Exploring Within and Between Subject Differences of the Role of Cervical Proprioception in the Postural and Spatial Orientation Perception of Young Healthy Adults

by

Sherri Lynn Thomson

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Examining Committee Membership

The following served on the Examining Committee for this thesis. The decision of the Examining Committee is by majority vote.

External Examiner	Dr. Kristin E. Musselman, PhD Assistant Professor University of Toronto
Internal-external Member	Dr. Bryan Tripp, PhD Associate Professor University of Waterloo
Supervisor	Dr. William McIlroy, PhD Professor University of Waterloo
Internal Member	Dr. Richard Staines, PhD Professor University of Waterloo
Committee Member	Dr. Michael Barnett-Cowan, PhD Associate Professor University of Waterloo

Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

A proportion of physiotherapy patients with neck pain, either from idiopathic or traumatic causes, will report symptoms of dizziness and postural imbalance in the absence of additional pathology. The term cervicogenic dizziness, used to describe this presentation of symptoms, remains a controversial diagnosis largely due to the lack of a diagnostic test and an apparent lack of consistency between neck pain and symptom severity. Although mounting evidence suggests that cervical proprioceptive information may play a larger role in balance control than previously believed, its precise role and the reason why some individuals seem more impacted when this information is disrupted, remains a topic of debate. Therefore, this thesis aimed to explore the fundamental understanding of how cervical proprioception information is used in the formation of a body schema and therefore may help in referencing the information provided by the visual, vestibular and body proprioceptive systems used for balance control. This current foundational work is delimited to a focus on healthy adults. The studies in this thesis sought to; 1) examine the impact of altered cervical proprioception on postural and spatial orientation perception and standing balance, 2) investigate the importance of between subject differences in cervical proprioception as it relates to balance control and 3) explore person specific characteristics that may impact on cervical proprioception and the extent to which it impacts on balance control at a person specific level. There were three predominant findings in this thesis. The first was that altering cervical proprioception using unilateral dorsal neck vibration significantly impacts on postural and spatial orientation perception involving the perception of head and elbow orientation, and visual vertical perception. The second finding is the existence of significant between subject differences in cervical proprioception performance, as measured by joint position error mean and SD. The third main finding from this thesis is that person specific characteristics may impact on cervical proprioception, as seen in differences in cervical JPE as well as the extent to which neck vibration impacts on cervical JPE. In addition, this thesis also explores the use of portable technology as tools for evaluating cervical JPE and visual vertical perception error, while suggesting how this information may be used to inform on physiotherapy assessment and treatment of individuals with suspected cervicogenic dizziness in a clinical setting.

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List of Abbreviations

ANOVA	Analysis of Variance
AP	Anteroposterior
ATNR	Asymmetrical Tonic Neck Reflex
BMI	Body Mass Index
CCR	Cervicocollic Reflex
CNS	Central Nervous System
COM	Center of Mass
COP	Center of Pressure
COR	Cervico-ocular Reflex
DC	Direct Current
EC	Eyes Closed
EO	Eyes Open
Ext	Extension
FHP	Forward Head Posture
Flex	Flexion
fMRI	Functional Magnetic Resonance Imagery
Hz	Hertz
IMU	Inertial Measurement Unit
JPE	Joint Position Error
JPE(30)	Joint Position Error to 30 Degrees
JPE (90)	Joint Position Error to 90 Degrees
JPE(SSA)	Joint Position Error to Subjective Straight Ahead

List of Abbreviations *(cont'd)*

kgf	Kilograms of Force
L	Left
LCD	Liquid Crystal Diode
LED	Light Emitting Diode
ML	Mediolateral
MRI	Magnetic Resonance Imagery
msec	Millisecond
No Vib	No Vibration
OKR	Optokinetic Reflex
OPE	Orientation Perception Error
PET	Positron Emission Tomography
PL	Path Length
R	Right
RMS	Root Mean Squared
ROM	Range of Motion
Rot	Rotation
SD	Standard Deviation
sec	Second
SEM	Standard Error of Measurement
SF	Side Flexion
STNR	Symmetric Tonic Neck Reflex
VCR	Vestibulocollic Reflex

List of Abbreviations *(cont'd)*

Vib	Vibration
VOR	Vestibuloocular Reflex
VSA	Visual Straight Ahead
VVPE	Visual Vertical Perception Error
WAD	Whiplash Associated Disorder

Chapter 1: Literature Review

1.0 Introduction

Neck pain and dysfunction are common complaints among patients seen by physiotherapists. The causes of neck pain include trauma such as whiplash or concussion injuries or non-traumatic causes including muscle tension, nerve root irritation or degenerative changes in the cervical vertebrae and discs (Ahn et al., 2007). Among patients with neck pain from either traumatic or non-traumatic sources, a subset will report additional symptoms such as dizziness, nausea or feelings of unsteadiness (Colledge et al., 1996; Hansson et al., 2006; Heikkilä & Wenngren, 1998; Morinaka, 2009; Treleaven, 2008). Among individuals with whiplash, it is reported that a significant proportion, as much as 48% in some studies, experience some degree of dizziness. (Ferrari et al., 2005). The differential diagnosis for dizziness is extensive and includes central nervous system disease and dysfunction, vertebrobasilar insufficiency, vestibular or visual dysfunction, hypotension, polypharmacy and many others (Brandt & Bronstein, 2001; Reiley et al., 2017). However, for a proportion of patients with neck pain coinciding with dizziness or imbalance, in the absence of these alternative diagnoses, the source of the problem may be the cervical spine (Kristjansson & Treleaven, 2009; S. Reid et al., 2012; Ryan & Cope, 1955). The terms cervicogenic dizziness and cervical vertigo have been used to describe a hypothesized diagnosis for dizziness and imbalance due to altered afferent input from the cervical spine (Brandt & Bronstein, 2001; Ryan & Cope, 1955; Treleaven, 2008; Wrisley et al., 2000). For the remainder of this thesis the term cervicogenic dizziness will be used although the terms have been used interchangeably in the literature. The idea that sensory information from the cervical spine may play a role in balance control and hence may contribute to its disruption and associated symptoms when altered, has been investigated since the mid eighteen hundreds with animal studies (Abrahams & Falchetto, 1969; Cohen, 1961; de Jong et al., 1977). Over the past century, additional human case studies, neuroanatomical investigations, balance, gait and perceptual laboratory experiments and examinations of clinical populations with whiplash injury, torticollis and vestibular loss have provided significant evidence in support of the possibility of cervicogenic dizziness (Anastasopoulos et al., 1998; Bove, Diverio, Pozzo, & Schieppati, 2001; de Jong et al., 1977; Taylor & McCloskey, 1991; Treleaven, 2008; Wrisley et al., 2000). However, to this day, cervicogenic dizziness remains a controversial diagnosis in the medical community (Brandt & Bronstein, 2001; Hain, 2015; Magnusson & Malmström, 2016). Those arguing against cervicogenic dizziness as a true diagnosis point to the fact that it remains a diagnosis of exclusion with no specific diagnostic test (Brandt & Bronstein, 2001; Magnusson & Malmström, 2016). Some argue that the non-specific nature of the symptoms produced by cervicogenic dizziness may be the result of other undiagnosed conditions such as benign paroxysmal positional vertigo (BPPV), rather than a unique entity (Brandt & Bronstein, 2001). Additionally, cervicogenic dizziness is not reported by everyone suffering a neck injury, or neck pain, which prompts the question as to why certain individuals experience cervicogenic dizziness while others do not (Brandt & Bronstein, 2001). Despite the continued controversy, the growing body of literature from multiple disciplines does support the likelihood that afferent information from the cervical spine does play a greater role in human balance control than previously believed (Kristjansson & Treleaven, 2009; Takahashi, 2018; Treleaven et al., 2003). However, to date, the specifics of this role remain unclear. As such, the overarching objective of this thesis is to explore the role of cervical spine proprioception in balance control in order to inform on the assessment and treatment of individuals with suspected cervicogenic dizziness in a clinical setting.

The overall aims of the thesis are to:

1. Advance understanding of the link between cervical spine proprioception and the control of upright balance.
2. Explore the between subject variability on the impact of altered cervical proprioception in balance control.
3. Propose improved clinical procedures to examine neck proprioception ability and its impact on balance control in order to inform on diagnosis and treatment of patients seen in a physiotherapy clinic with suspected cervicogenic dizziness.

These aims will be met by a review of the existing literature exploring the history of cervicogenic dizziness research, the controversy surrounding it as a differential diagnosis and the evidence supporting the role of cervical spine proprioception in balance control. A conceptual model will be proposed to explain the possible role of neck proprioception as part of multisensory integration used for balance control. Application of this model in the form of four completed studies will be presented to meet the objectives.

1.1 Balance Control

Balance control or postural control requires the ability to perform two essential tasks, postural equilibrium and postural orientation (Horak, 2006). Postural equilibrium is the ability to maintain one’s center of mass over their base of support under varying task requirements and environmental conditions (Horak, 2006). Postural orientation involves the controlled and organized alignment of the body and its segments in a desired configuration and the maintenance of this alignment under varying task and environmental conditions (Horak, 2006). These processes are guided by sensory information from three systems; visual, vestibular and somatosensory. The visual system provides information about the environmental surroundings and the body's position within that environment (Kotecha et al., 2012; Paulus et al., 1989). Visual identification of surface characteristics and orientation allows the individual to prepare for any perceived challenges to balance associated with that surface (Lee & Kalmus, 1980). Vision also allows for the identification of potential hazards within the environment that may pose a threat to balance (Lee & Kalmus, 1980). Peripheral vision is thought to be important for generating and updating an internal representation of the body within the environment that may be used to generate appropriate balance reactions such as stepping in an appropriate direction or grasping a nearby surface following an unexpected perturbation (Akram et al., 2013; King et al., 2010; Zettel et al., 2005). The vestibular system provides information about the acceleration of the head in any of the three planes, as well as the position of the head with respect to gravity. In addition, the vestibular system is highly linked to the visual system by way of reflexes such as the vestibuloocular reflex (VOR) that stabilizes images on the retina during head movements (Angelaki & Cullen, 2008; Armstrong et al., 2008). The third sensory system providing information used to control balance is the somatosensory system. This system detects tissue loading by way of proprioceptors and mechanoreceptors located within muscles, tendons, joint surfaces and soft tissues of the body, including the cervical spine (Armstrong et al., 2008; Briggs & Galea, 2002). These sensory organs relay information about joint position, loading and movement, in addition to detecting the nature of the contact between the environment and the body such as temperature, pressure and vibration. The lower extremity has been the most extensively investigated source for somatosensory information for balance control, as it provides information about the characteristics of the support surface (texture, movement, orientation) as well as feedback from the muscles around the ankle responsible for making fast necessary adjustments in order to maintain standing balance (Kars et al., 2009; Kotecha et al., 2012). However, somatosensory information from the cervical spine has also been suggested to play a role in the maintenance of effective balance control, movement co-ordination and gait (Bove et al., 2001; Bove, Brichetto, Abbruzzese, Marchese, & Schieppati, 2004; Treleaven, 2008).

1.2 Cervicogenic Dizziness

The notion that the cervical spine could contribute to balance, postural control and mobility was examined as early as the mid-1800s by researchers such as Longet et al. (1845) and Claude Bernard (1865), who reported that damage to the cervical muscles in a wide array of animals including horses, rabbits, dogs and cats, could impart ataxia and abnormal movement (de Jong et al., 1977). Further animal studies in the middle of the 1900s continued to confirm that the cervical spine had a role to play in postural control. Cohen (1960) examined the contribution of neck and eye proprioception on postural orientation and body co-ordination in monkeys by injecting anesthetic into extraocular muscles of the eye and the first three dorsal roots of the cervical spine (C1,2,3) (Cohen, 1961). Although no striking movement impairments were noted with impaired ocular proprioception, he reported severe disturbances to balance control and co-ordination in the animals with dorsal root blocks including, staggering uncoordinated ataxic gait, gross errors in coordinated movements such as climbing and inaccurate reach to grasp movements. These impairments were described as being similar to those displayed by animals with bilateral labyrinthectomies. Cohen (1961) concluded that neck proprioception "plays a very important role in maintaining proper orientation, balance and therefore motor co-ordination of the body" (Cohen, 1961). These findings were supported by subsequent researchers including Abrahams and Falchetto (1969), who sectioned the nerves supplying the head extensor muscles in cats, and reported subsequent ataxia in the hind limbs (Abrahams & Falchetto, 1969). They concluded that cervical spine muscle input might be important for postural reflex generation. De Jong and de Jong (1969) experimented on rabbits, cats, monkeys and humans by injecting anesthetic solution into the upper cervical region of the neck. They also found that ataxia was produced by cervical anesthetic injection across all species tested, with a strong sense of tilting/falling over towards the injected side reported by the human subjects (de Jong et al., 1977). Nystagmus was produced following injection of rabbits, cats and monkeys but not in the human subjects. The researchers also noted the presence of altered upper extremity co-ordination in the form of past-pointing or missing objects during reaching as well as hypotonia in the ataxic side limbs as was noted previously by Cohen (1960). These animal studies and many others provide evidence to support the theory that altered cervical afferent information can impact on balance control.

Around this time, Ryan and Cope (1955) described a collection of symptoms including vertigo, dizziness and altered balance, that they observed in a sample of patients following cervical spine trauma, traction injury or severe spondylosis (Ryan & Cope, 1955). They termed this condition cervical vertigo and hypothesized that their clinical observations were the result of trauma to the upper cervical spine proprioceptors, resulting in altered input to the vestibular nucleus and possibly the cerebellum and producing symptoms similar to those of vestibular disease (Ryan and Cope 1955).

Over the past few decades researchers have explored the characteristics of individuals with suspected cervicogenic dizziness in an attempt to better characterize this hypothesized condition (Malmström et al., 2007). Cervicogenic dizziness has been more specifically defined as a “non-specific sensation of altered orientation in space and disequilibrium originating from abnormal afferent activity from the neck” (Wrisley et al., 2000). Malmström et al. (2007) examined the musculoskeletal findings of individuals with suspected cervicogenic dizziness. In general, these individuals had bilateral dorsal neck muscle tenderness, increased tightness of the trapezius and suboccipital muscles, multiple zygapophyseal joint tenderness, more commonly in the higher cervical levels, altered postural alignment, normal or greater than expected cervical active range of motion and reduced dynamic stabilization capacity in the cervical and trunk muscles (Malmström et al., 2007). Treatment approaches including manual therapy techniques for the cervical spine, head proprioceptive training, balance exercises and gaze stability exercises have been proposed as rehabilitation options for this population (Kristjansson & Treleaven, 2009; Lystad, Bell, Bonnevie-Svendsen, & Carter, 2011; Reid & Rivett, 2005; Reid et al., 2012). However, despite the early experimental and proposed clinical support for the existence of cervicogenic dizziness as a diagnosis, there remains controversy about its existence as a unique entity. There remain 3 arguments perpetuating this controversy. 1: Lack of specificity. Some argue that the symptoms of cervicogenic dizziness could be explained by another missed diagnosis. 2: No diagnostic test. Cervicogenic dizziness remains a diagnosis of exclusion, eliminating all other differential diagnoses through a battery of testing. 3. The lack of consistency between neck pain/trauma severity and generation of cervicogenic dizziness symptoms. It currently remains unclear why some individuals are more impacted by neck pain/dysfunction than others. Regardless of this ongoing controversy, evidence continues to mount from various disciplines in support of the importance of cervical proprioception in balance control.

1.3 Cervical Spine Anatomy and Neuroanatomy

Evidence for the role of the cervical spine proprioception in balance control can be found in the anatomy, neuroanatomy and afferent pathways of the neck. At a fundamental level, the anatomy of the cervical spine and the neurological connections and pathways between afferent sensory receptors, spinal nuclei, subcortical structures and cortical centers provides evidence for a complex multisensory integration of cervical proprioceptive information for postural orientation and equilibrium, co-ordination of eye movements for gaze stability and maintenance of head stability and body orientation functions (Armstrong et al., 2008; Bottini, 2001; Schieppati, Nardone, & Schmid, 2003; Taylor & McCloskey, 1988; Treleaven, 2011).

The cervical spine is a complex collection of 37 separate joints, muscles, tendons, neural and vascular tissue that supports and moves the relatively heavy 10-15lb head, while protecting the vital neural connections of the spinal cord, and vascular pathways of the vertebral and carotid arteries and returning jugular veins. The cervical spine is a unique part of the body in a number of ways, including its highly mobile structure and vital function in orienting the visual, vestibular, auditory, and olfactory sensory systems housed within the head. The skeletal portion of the cervical spine consists of seven cervical vertebra that bridge the area between the skull and the thorax (Bogduk, 2016; Magee, 2002). This area of the spine is unique from the thoracic and lumbar portions in both shape and orientation. The 45 degree angle of the articulating zygapophyseal (z-joints) joints in the mid to lower section of the cervical spine vertebra, combined with the unique condylar articulation of the atlantooccipital joint and rotational capacity of the atlanto-axial joint at C1/2, allows for significant flexibility of the neck and large range of motion potential into each of the three degrees of movement freedom (Magee, 2002). Flexion in the entire cervical spine is approximately 80-90 degrees with extension reaching approximately 70 degrees (Magee, 2002). Side flexion and rotation reach approximately 20-45 degrees and 70-90 degrees respectively (Bogduk, 2016; Magee, 2002). High mobility of the cervical spine is an evolutionary benefit enabling for a greater potential for visual information collection through head turning, and improved sound and scent localization (Sefton et al., 2016). All of which in theory would improve the likelihood of efficient and successful interaction with the environment. The high mobility of the cervical spine compared to the rest of the spinal column comes at the cost of stability and as a result, highly developed muscular and ligamentous control mechanisms are in place in this region to monitor and control movement of the head (Bogduk, 2016; J. L. Taylor & McCloskey, 1988). In addition, because the neck separates the sensory systems housed in the head from the rest of the body, precise co-ordination between neck movement and visual and vestibular information is vital for efficient and effective multisensory integration and balance control.

Some of this precise co-ordination occurs by way of cervical reflexes. The cervico-ocular reflex (COR) is part of a group of multiple reflexes responsible for stabilizing visual images on the retina during movement. The COR is initiated by movement of the head with respect to the trunk and works in conjunction with the VOR and optokinetic reflex (OKR) to prevent retinal slip for gaze stabilization (Ischebeck et al., 2016; Kelders et al., 2003). Studies have shown that unlike the VOR and the OKR which both decrease (less gain) with age, the COR gain increases as we age, possibly to help compensate for deterioration of the other gaze stability reflexes (Kelders et al., 2003) It has also been shown that COR gain is increased in both patients with vestibular loss and those with neck pain from both traumatic and non-traumatic causes, suggesting an increased importance of this reflex in these populations (de Vries et al., 2016; Ischebeck et al., 2016; Maurer et al., 1998).

The cervicocollic reflex (CCR) works intricately with the vestibulocollic reflex (VCR) to stabilize the head with respect to the body and the environment (Reynolds et al., 2008). The CCR is initiated by stretch receptors in the neck which will in turn result in contraction of the stretched muscles to prevent further movement. The VCR is initiated by the vestibular system so that muscles contralateral to the direction of movement will be initiated to maintain head stability (Goldberg & Cullen, 2013). The actions of the CCR and VCR essentially oppose one another and so the CNS must continuously adjust the gain of each reflex depending on the immediate task goals and environmental constraints (Reynolds et al., 2008).

Other cervically driven reflexes exist, predominantly in human infancy, that impact muscular tone in the body. The asymmetrical tonic reflex (ATNR) produces extension and increased tone of the ipsilateral limb and decreased extensor tone to contralateral muscles with head rotation in the transverse plane (yaw) (Konicarova & Bob, 2013). The symmetric tonic neck reflex (STNR) produces increased tone to the extensors when the head is extended in the sagittal plane and increased flexor tone when the head is flexed (Bruijn et al., 2013). Normally the expression of these primitive reflexes dissipates in early infancy except in cases of neurological impairment such as cerebral palsy (Blasco, 1994). However, more recent evidence suggests that these reflexes are measurable, although small, into childhood and in some individuals into early adulthood (Bruijn et al., 2013). The implications of the persistence of these primitive reflexes possibly into adulthood is not yet clear.

1.3.1 Cervical Proprioception and Kinesthesia

It is believed that cervicogenic dizziness is caused by altered proprioceptive information from the neck. Proprioception and kinesthesia are the ability to discern the position and movement of body segments using specialized sensory receptors (Kröger, 2018; Stillman, 2013). Proprioceptors are sensory mechanoreceptors that provide information about the forces acting on a joint thereby allowing for the ongoing awareness of limb and joint position and motion. These proprioceptors include muscle spindles, golgi tendon organs and joint receptors (Stillman, 2013). Muscle spindles are encapsulated receptors located within muscle tissue that provide information about muscle length and the speed of muscle length change (Boyd-Clark et al., 2002). They are innervated by both afferent and efferent neurons (sensory - type I and IIa afferent; motor -gamma motor neurons). Lengthening of a muscle results in stimulation of these sensory afferents, sending signals to both the brain and also to alpha motoneurons that supply the muscle housing the spindle, contributing to the mono-synaptic stretch reflex (Wang et al., 2012). It is now widely believed that muscle spindles are likely the primary proprioceptor receptors (Boyd-Clark et al., 2002; Liu, Thornell, & Pedrosa-Domellöf, 2003; Taylor & McCloskey, 1988). Researchers have shown that the number and organizational structure of muscle spindles within particular muscles of the body relate to their use, with higher densities located in muscles used for specialized activities requiring precise motor control and movement monitoring (Boyd-Clark et al., 2002; Kulkarni et al., 2001). The lumbricals of the hand, masseter muscles of the jaw and intrinsic muscles of the foot are examples of muscles used for very specific tasks requiring intricate movement monitoring (Liu et al., 2003; Peck & Nitz, 1984). Given the monumental balancing task of supporting and moving the head, it is unsurprising that the musculature in the cervical spine also contains some of the highest densities of spindle fibers in the body. The deep suboccipital muscles (rectus capitus posterior major and minor and oblique capitus superior and inferior have been found to have significantly higher concentrations of muscle spindles than other skeletal muscle on the order of 35/g (Kulkarni et al., 2001; Liu et al., 2003; Peck & Nitz, 1984). It has been suggested that given the high density of muscle spindles in this area that the deep suboccipital muscles may be primarily used to monitor movement (muscle length changes) of the head similar to the role played by the lumbricals in the hand that are believed to monitor joint movement rather than contributing significantly to force generation or joint movement (Kulkarni et al., 2001). Spindle density has been examined in other muscles believed to be important for postural maintenance and cervical stability including the multifidus and longus coli muscles. The longus coli muscle was found to have density of 48.6/g and multifidus at 24.3/g (Boyd-Clark et al., 2002). Proprioception receptors in other tissue of the cervical spine may also contribute afferent information. Encapsulated mechanoreceptors have been found in the zygapophyseal joint capsules in the cervical spine, indicating that the forces acting on the capsule is likely being monitored continuously by the central nervous system (McLain, 1994). Additionally, mechanoreceptors in the cervical spine discs have been investigated in individuals with cervical spondylosis and vertigo and researchers have reported a positive association between increased numbers of mechanoreceptors, specifically ruffini corpuscles, in the discs of individuals reporting vertigo who had spondylosis (Peng, 2018).

1.3.2 Somatosensory Pathways in the Neck

Afferent information from the cervical spine receptors travel to the dorsal horn of the spinal cord via the dorsal root where they synapse. Somatosensory information from the neck, C1-C4, has been shown to terminate in the spinal cord at lamina 3 and also in the central cervical nucleus and the ventral horn (Berthoz et al., 1992). From the spinal cord synapses, proprioceptive information travels to supraspinal structures by way of the dorsal columns where they are believed to synapse at the ventrobasalar thalamus with projections to the primary somatosensory cortex and cerebellum. Additionally, paravertebral muscle spindle information from the upper cervical region has been shown to excite vestibular nucleus neurons, suggesting direct connections between cervical afferent information and the vestibular system (Bottini, 2001). Studies in the cat have suggested that sensory cervical information may also project to the anterior suprasulvian cortex. Vestibular information is also believed to synapse here, suggesting that this area may be an association cortex (Landgren & Silfvenius, 1968).

Although a limited number of studies exist, positron emission tomography (PET), magnetic resonance imagery (MRI) and functional magnetic resonance imagery (fMRI) neuroimaging studies have explored multisensory connections between cervical afferent information and both the vestibular and visual processing centers in the brain. Bottini et al. (2001) performed PET studies during stimulation of cervical afferents with vibration and during caloric stimulation of the vestibular system, in the hopes of locating areas of the brain contributing to the generation of egocentric spatial representation. In this study, increased cerebral blood flow under both sensory stimulations was observed in the insula, retroinsular cortex, somatosensory area two and the temporoparietal junction, leading the researchers to propose these areas of the cortex as being involved in the generation of egocentric spatial representation (Bottini, 2001). Additionally, Fasold et al. (2008) used fMRI to evaluate cervical afferent multisensory connections in the cortex and found that cervical afferent stimulation evoked activity in the intraparietal sulcus, frontal eye fields, motor and premotor cortex during neck vibration (Fasold et al., 2008). To explore visual and cervical proprioceptive interactions in the cortex, Cutfield et al. (2014) used fMRI to evaluate normal healthy subjects and those with bilateral vestibular loss during simultaneous visual and cervical proprioceptive (vibration) stimulation. This study found overlapping areas in the cortex during proprioceptive and visual processing. Additionally, they reported an inhibition of visual motion related cortical areas during simultaneous cervical proprioceptive stimulation, giving functional imaging support to the theory that cervical afferent information is upweighted by individuals with vestibular loss (Cutfield et al., 2014). Overall, electrophysiological studies in animal models and recent functional neuroimaging studies in humans gives evidence to support the existence of 'polysensory' cortical networks for balance and spatial orientation processing of which cervical proprioception plays and important role (Bottini, 2001; Cutfield et al., 2014; Fasold et al., 2008).

1.4 Evidence for the Role of Cervical Proprioception from Clinical Populations

The following section reviews several clinical conditions that provide some insight into the potential role for cervical proprioception in human postural orientation and spatial orientation perception.

1.4.1 Whiplash Associated Disorder (WAD) and Dizziness

Evidence from several clinical populations supports an important role for neck proprioception in balance control. The most extensively investigated population are those with whiplash associated disorder (WAD) following a motor vehicle accident. Whiplash injuries involve the rapid hyperextension and flexion of the cervical spine during rapid acceleration and deceleration of the body, typically as the result of a rear or side impact collision (Pastakia & Kumar, 2011). During a typical rear end collision, the acceleration of the thorax and inertia of the head results in an atypical S shaped curve in the cervical spine involving the extension of the mid cervical spine and upper cervical flexion (Grauer et al., 1997; Panjabi et al., 2004). As the thorax continues forward the neck is forced into hyperextension. The result is the potential injury to a wide variety of cervical structures including: the cervical facet joints, ligamentous supports, cervical muscles, intervertebral discs, dorsal root ganglion, spinal cord and vertebral artery in the neck (Panjabi et al., 2004; Sterling et al., 2003). Although whiplash injuries are complex and there is potential for overlapping injuries to multiple sensory and tissue systems, a subgroup of individuals with WAD do report dizziness and imbalance that seem to correlate with neck pain and dysfunction (Treleaven et al., 2003). Several studies have attempted to explore the differences between people with WAD who experience dizziness and those who do not. Although in general individuals with WAD demonstrate increased cervical joint position error WAD sufferers who report dizziness perform significantly worse, displaying poorer kinesthesia than those without dizziness (Treleaven et al., 2003, 2005). Similar to JPE testing, individuals with WAD generally exhibit altered balance control with increased COP sway (Kristjansson & Treleaven, 2009). Individuals with WAD and dizziness perform significantly worse during balance testing than those without dizziness (Treleaven et al., 2003). The authors have attributed the differing kinesthesia and balance control between WAD sufferers with and without dizziness to altered cervical afferent information. Despite the evidence that WAD can alter JPE, balance and gaze stability, and that those who also report dizziness demonstrate poorer performance, due to the complex pathophysiology of WAD injuries it is difficult to attribute causality to damaged cervical proprioception.

1.4.2 Vestibular Loss

Individuals with vestibular sensory loss provide an excellent clinical population in which to examine the impact of cervical proprioception on balance control. Vestibular dysfunction may be the result of peripheral or central disease processes and may result in unilateral or bilateral vestibular sensory loss (Kerber, 2016). In response to vestibular loss patients gradually adapt and typically experience improved symptoms. It is known that in response to altered VOR, the COR response in patients with vestibular loss increases as a compensatory strategy (Maurer et al., 1998). Additionally, it is believed that compensatory processes in multisensory integration in the brain is a likely factor for adaptation after vestibular loss, however the specifics of these processes is not yet understood. In a recent study by Cutfield et al. (2013) functional MRI was used to investigate the adaptation processes in bilateral vestibular loss patients. More specifically, the researchers were interested in exploring how proprioceptive information from the cervical spine is used differently in these individuals for the purposes of visual processing. During MRI imaging, vibration stimulation of the dorsal neck muscles in the presence of visual stimulation resulted in attenuation of activation in visual motion induced cortical areas of the brain (Cutfield et al., 2014). The researchers suggest that this may be evidence of inhibitory processes between cervical proprioception information on head motion and visual cues and may represent an overall upregulation of proprioceptive sensory weighting for multisensory integration processes to compensate for vestibular loss (Cutfield et al., 2014). The authors also suggest visual processing areas as a potential site of multisensory integration between cervical proprioception and vestibular information.

1.4.3 Torticollis

Additional evidence for sensory re-weighting processes in the event of diminished or un-reliable sensory information can be seen in individuals with spasmodic torticollis. Spasmodic torticollis or cervical dystonia involves the involuntary contraction of cervical muscles resulting in unintentional head turning and posture (Bove et al., 2004). The head may become rotated, flexed, extended or side flexed, or in the majority of cases, some combination of these (Velickovic et al., 2001). The underlying mechanisms responsible for this condition are not fully understood. However, genetic contributions and decreases in centrally generated reciprocal inhibition mechanisms may be involved (Velickovic et al., 2001). Of interest in this population is the way in which cervical afferent information may be used in spatial orientation, given that muscle tension and “neutral” head position is frequently altered from that of individuals without torticollis. A study by Anastasopoulos et al. (1998) examined how people with cervical dystonia perceive subjective visual straight ahead (VSA) by asking participants to indicate VSA following coupled head and trunk movement or uncoupled trunk on head (neck proprioception) or head on trunk (vestibular and neck proprioception stimulation) movements. Interestingly individuals with cervical dystonia reported VSA consistent with the control group when the head and trunk were coupled. However, when the trunk and head were uncoupled, VSA was shifted towards the trunk midline. They authors theorize that this might indicate be a de-weighting of cervical afferent information and the use of a trunk egocentric reference frame due to the un-reliability of cervical afferent information in this population (Anastasopoulos et al., 1998). This hypothesis is supported by the work or Bove et al. (2007). They investigated the postural sway of individuals with and without cervical dystonia in response to neck muscle vibration. In quiet standing the cervical dystonia group displayed increased postural sway when compared to controls, however postural sway responses were negligible in response to neck vibration, compared to those of the control group. The authors suggest this is further evidence for de-weighting of cervical afferent information for balance control in this population (Bove et al., 2007).

1.5 Evidence from Experimental Manipulation of Cervical Proprioception Studies

Experimentally manipulated cervical spine proprioception in a laboratory setting has provided a wealth of support for an important role for this sensory information in balance control. Although many methods of cervical proprioception manipulation have been reported including the use of cervical collars, taping techniques and induced muscle fatigue, vibration stimulation to the neck muscles is perhaps the most frequently cited.

1.5.1 Vibration Studies

The impact of vibration on muscle tissue has been examined since the 1860's when it was first noted that vibrating the handle of a tool could stimulate an unintentional gripping response in the hand (Carlsöö, 1982). Vibration has since been shown to stimulate muscle tissue in a similar manor to a stretch reflex and this involuntary contraction has been termed the tonic vibration reflex (Carlsöö, 1982; Eklund, 1972; Goodwin et al., 1972). The extent to which vibration stimulates muscle contraction has been shown to be influenced by factors such as the degree of muscle stretch (joint position), the amplitude and frequency of the vibration stimulation and the temperature of the muscle when vibrated (Goodwin et al., 1972). It is believed that vibration stimulates the muscle spindles, and that this increased afferent input from the stretch receptors is what triggers this tonic vibration reflex (Goodwin et al., 1972). It is known that the application of vibration to muscles involved in joint movement can impair the detection of true joint position. Goodwin et al. (1972) explored the impact of muscle vibration (biceps, or triceps) on a subject's ability to accurately track elbow joint angles using the non-vibrated limb. In an unrestrained test arm, vibration to the biceps brachii tendon induced contraction of the muscle and flexion of the elbow joint. When subjects were asked to track the positional changes of the test arm with the non-vibrated limb, they produced considerable errors in perceived joint position. Despite these errors, when the vibrated limb was unrestrained, subjects could still discern the direction of the perceived movement correctly. However, when the elbow joint was prevented from flexing in response to the bicep tendon vibration, the participants reported a sudden perception of the joint movement reversing directions. They perceived the elbow joint extending as indicated by a change in the direction of the joint angle of the tracking arm despite the fact that the elbow remained stationary (Goodwin et al., 1972).

Perceptual illusions from muscle vibration aren't limited to joint position sense. Numerous authors have reported that dorsal neck muscle vibration will result in visual illusory movement of a fixated illuminated target in the absence of additional visual information. Biguer et al. (1988) investigated this perceptual visual illusion in two studies. In the first study subjects seated in a dark room were asked to point to an illuminated target on a screen with an unseen hand, with and without the application of left sided dorsal neck vibration. Subject pointing error was calculated by comparing the actual target location with the subject's perceived target location. In four of the subjects the head was not held in a fixed position, whereas the others' head position was kept constant using a bite plate. The results of this study showed that unilateral dorsal neck muscle vibration can produce the illusion of visual target movement in the direction opposite the vibrated side. Additionally, the authors demonstrated that the perception of target location, as shown in a pointing task, was also displaced in the same direction. Of note, the authors identified that some participants described feeling dizzy from the testing procedure and there was no reported difference in the performance of subjects using the bite plate and those instructed to “keep the head still”. The results of this study have been replicated by others with similar results (McIntyre & Seizova-Cajic, 2007; Taylor & Mccloskey, 1991).

In addition to visual and joint perceptual studies, neck muscle vibration has also been used to investigate the impact of altered cervical proprioception on balance control, gait and sensory motor function. Bove et al. (2001) explored the impact of neck vibration on gait trajectory and standing postural control. In their study, neck vibration was applied either before or during measurements of standing balance or straight trajectory walking (Bove et al., 2001). Vibration applied to right unilateral dorsal neck muscles during gait resulted in a systematic shift in walking trajectory in a direction opposite to the side of vibration, a slowing of velocity and undershoot of the intended target. Vibration applied prior to the walking task resulted in a non-systematic shift in walking trajectory. During stance, the authors found that vibration applied during the trial shifted the mean center of foot pressure to the side contralateral to neck vibration, whereas vibration applied prior to the stance trial did not impact mean center of foot pressure. The authors hypothesized the vibration induced gait disturbances could be the result of altered cervical spine proprioceptive information impacting on the execution and updating of the motor program to the intended target. Vibration applied before the walk may have impaired the sense of subjective straight ahead, preventing the formulation of an accurate frame of reference before the walk and hence leading to non-systematic errors in trajectory. Whereas, the application of vibration during the walk may represent a use of faulty neck proprioceptive information into the online motor control program and hence producing systematic deviation away from the vibrated side in corresponding to the illusion of muscle lengthening of the vibrated muscles (Bove et al., 2001).

A subsequent study by Bove et al. (2002) again used vibration of cervical spine musculature to investigate the role of altered cervical proprioception on body orientation. This time a stepping task was employed during which participants were to march on the spot in the absence of vision during no vibration, vibration during stepping, or vibration before stepping. The results of their investigation showed a systematic deviation of stepping orientation with rotation towards the side contralateral to the neck vibration with a velocity of about 1degree/second (Bove et al., 2002). These two studies taken together provide support for the notion that cervical proprioceptive information may be used to contribute to a reference system that informs on postural orientation.

1.5.2 Stimulation of Nociceptors

To explore the role of neck pain in the generation of sensory motor disturbances such as joint position error, previously described in clinical patients such as those with WAD, Malmstrom et al. (2013), experimentally induced pain in the cervical spine of subjects using hypertonic saline injections into C2/3 splenius capitis muscle (Malmström et al., 2013). Pain experienced by each subject was accompanied by a significantly increased joint position error to a target at 30 degrees but not to a neutral head position. They concluded that this increase in reposition error represented a pain related alteration of cervical proprioception and thus impacted the sensorimotor control of the neck. Of interest, the authors identified that one subject was unable to complete the study due to the development of symptoms of presyncope, dizziness, blurred vision following the hypertonic saline injection and an additional 4 subjects also identified symptoms of either dizziness, unsteadiness, nausea or presyncope during the study (Malmström et al., 2013). Vuillerme and Pinsault, (2008) also investigated the impact of induced cervical pain on balance control by painfully electrically stimulating bilateral muscle bellies of the upper trapezius muscle and examining the impact of pain on measures of standing balance including COP sway, COM displacement, sway velocity, length and frequency. Induced cervical spine pain resulted in increased AP sway, path length, higher COP sway frequency and increased COM variance (Vuillerme & Pinsault, 2009). The authors concluded that electrically induced cervical neck pain has a destabilizing effect on balance control that corresponds to the balance control challenges displayed by clinical populations with neck pain. The possible mechanisms of cervical pain driven postural control changes are discussed by the authors and include a change in attentional resources towards the painful stimuli and away from balance control, a possible increase in anxiety or arousal in the painful condition which is known to modify balance control and the modification of sensory motor function (cervical proprioceptive input) as a result of pain mechanisms (Vuillerme & Pinsault, 2009). Support of this third hypothesis comes from additional studies in which induced joint pain was shown to impair proprioceptive ability at both the thumb and ankle (Matre et al., 2002; Weerakkody et al., 2008).

1.5.3 Muscle Fatigue Studies

In addition to vibration and induced neck pain, researchers have employed additional experimental methods to evaluate the impact of cervical proprioception in balance control.

Muscle fatigue is known to reduce proprioceptive ability and cervical muscle fatigue has been shown to increase cervical joint position error (Pinsault & Vuillerme, 2010). Schiepatti et al. (2015) examined the impact of dorsal cervical muscle fatigue on standing balance. The results of their study suggested a destabilizing impact of cervical muscle fatigue on postural control as indicated by statistically significant increases in postural sway area under no vision and to a lesser (not statistically significant) extent full vision conditions (Schiepatti et al., 2015). The authors hypothesize that the effects of cervical muscle fatigue may be due to altered afferent firing from fatigue related metabolic changes and that this in turn could alter an internal reference system for balance. Gosselin et al. (2004) also examined the impact of muscle fatigue on standing balance in healthy individuals and found that prolonged isometric contraction of dorsal neck muscles resulted in significant increases in sway path length, CoP sway in an AP direction and sway velocity (Gosselin et al., 2004).

1.6 Summary

In summary, the series of experimental studies using vibration, nociceptors activation, muscle fatigue and clinical studies have collectively revealed a link between cervical sensory inputs and the control of movements such as balance. The current work seeks to provide more clarity about the specific role of cervical proprioception and control of movement and balance.

1.7 Research Objectives

As outlined above, the overarching objective of this thesis is to explore, in healthy adults, the role of cervical spine proprioception in balance control in order to eventually inform on the assessment and treatment of individuals with suspected cervicogenic dizziness in a clinical setting. The overarching hypotheses are that:

1. In addition to its role in reflex generation used to co-ordinate visual and vestibular sensory systems for the purposes of gaze stability and postural stability, cervical proprioceptive information is used to inform on visual and vestibular sensory information at a higher level in the generation of a body schema from which motor planning for task performance may be derived.

2. Individual variability exists in the weighting of cervical proprioceptive information used in this multisensory integration and this will therefore impact on the extent to which altered cervical proprioception impacts on balance control.

3. Person specific characteristics, experience and training may impact the extent to which individuals weight cervical proprioceptive information for balance control and therefore between subject differences in cervical proprioception function and the extent to which individuals are impacted when it is altered, may be related in part to these characteristics. Individuals at greater risk for developing cervicogenic dizziness may therefore be those with a greater weighing of cervical proprioception information for balance control.

This document is comprised of four studies with the following objectives:

<u>Study 1:</u> *Examining reach to point target accuracy in response to unilateral left sided neck vibration without vision*

The objective of this study was to explore the idea that cervical proprioception information acts as a frame of reference for visual spatial orientation. To achieve this goal a reach to target task was utilized in which participants were required to reach towards a remembered target on a touch screen computer without vision. To investigate the role of cervical proprioception in localizing the remembered target, unilateral dorsal neck muscle vibration was used to alter cervical proprioceptive information following the presentation of the target and during the reach to target movement. Pointing error was compared between vibrated and non-vibrated conditions.

The results of this study prompted the question as to the importance of between subject variability in cervical proprioception and the extent to which individuals varied in their response to the cervical muscle vibration stimulus.

<u>Study 2:</u> *The effect of posterior neck muscle vibration subjective straight ahead*

The objective of study 2 was to explore the between subject variability in cervical kinesthesia by measuring cervical JPE to subjective straight ahead (SSA) and the extent to which between subject variability existed in the response to dorsal muscle vibration. This objective was achieved by examining participant performance in relocating subjective straight ahead with and without neck muscle vibration. In addition, between subject variability of unilateral neck muscle vibration on the maintenance of a static head position was explored.

The results of study 1 and 2 demonstrated that individuals varied significantly in their task performance with and without neck vibration (reach to point accuracy in the absence of vision, and cervical JPE (SSA) in the absence of vision).

Study 3: *Understanding the determinants of within and between subject variability in cervical JPE with and without neck vibration*

Study 3 had two main objectives. 1) To examine the consistency of cervical JPE across different movement direction, target orientations, neck vibration side and testing day. 2) To explore person specific characteristics with the potential to impact on cervical JPE performance and the extent to which it was impacted by neck vibration.

Study 4: *Exploring the between subject differences in the role of neck proprioception on contributions to balance control*

Study 4 set out to explore the impact of unilateral dorsal neck muscle vibration on body and spatial orientation perception and standing balance. More specifically, whether individuals who demonstrated greater perceptual error in relocating subjective straight ahead because of neck vibration would also be impacted to a greater extent in the perception of body orientation, visual vertical and standing balance.

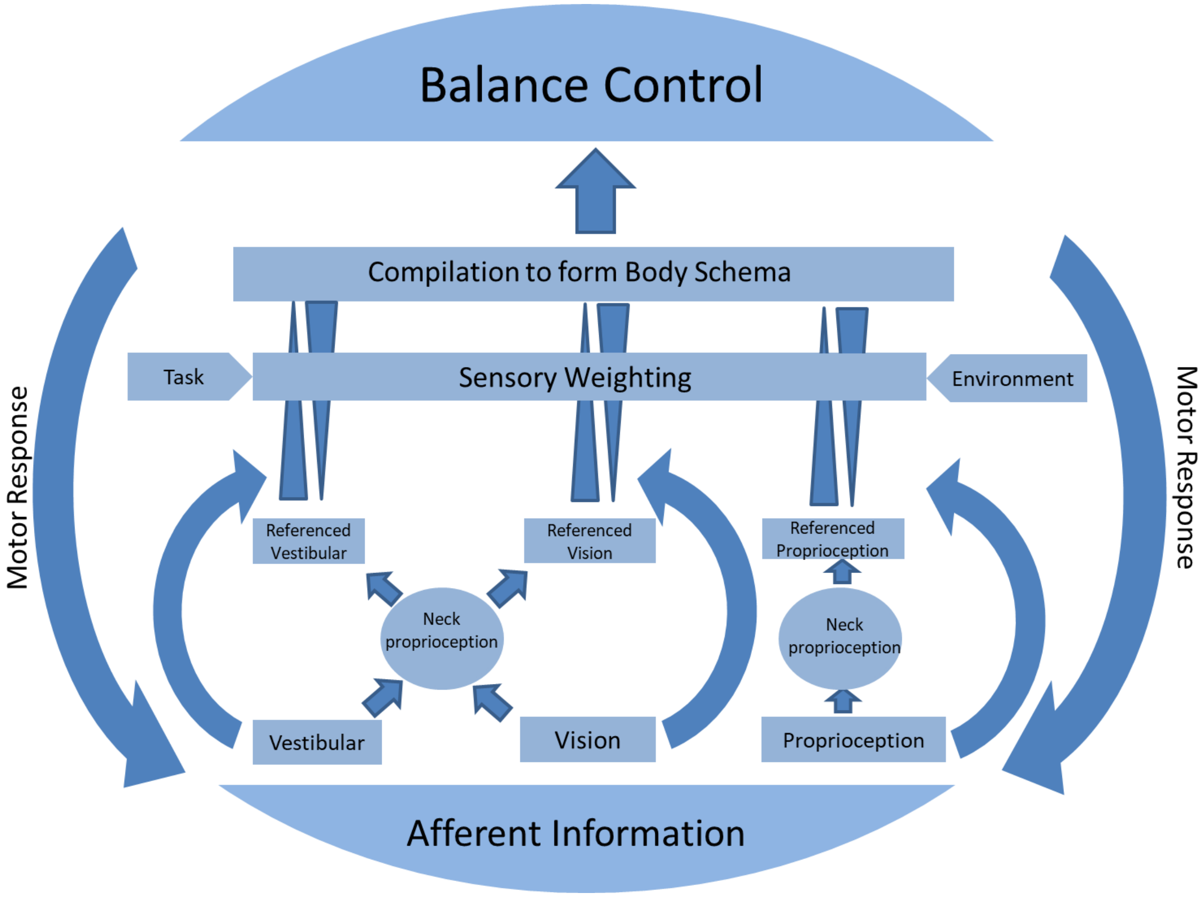

Figure 1: Conceptual schematic diagram of the potential role of cervical proprioception for the use of balance control. In this model afferent information from vestibular, visual and proprioceptive sources is contextualized (informed) by cervical proprioceptive information then used in the construction of a body schema for balance control. Sensory weighting can occur depending on the task or environmental conditions.

Chapter 2. Study 1: Examining reach to point target accuracy in response to unilateral left sided neck vibration without vision

2.1 Introduction:

Multisensory co-ordination between visual and proprioceptive sensory systems is vital for successful interaction with our environment (Horak, 2006; Peterka, 2002). High acuity in goal directed end point reaching relies on the successful co-ordination of visual information about the spatial location of a target of interest and proprioceptive information about current and online multi-joint position and movement in order to achieve accurate target acquisition (Berkinblit et al., 1995; Desmurget et al., 1998; Vercher et al., 1994). It is believed that vision and proprioception have distinct roles to play during reach to target tasks. Visual information is believed to be important for creating and storing a visual map of the environment that can be used in planning goal directed reach to target tasks. Proprioceptive information is believed to be used to inform the motor plan used to carry out the goal directed task, about the position and orientation of the limbs and their current state (movement, muscle activation etc.) (Sarlenga & Sainburg, 2009). Both visual and proprioceptive information are required to construct a body scheme or representation of ourselves within our environment. The importance of limb proprioception and orientation as it relates to goal directed end point reaching has been well investigated in the literature. Studies have shown that without accurate afferent information about the starting point of the limb and its relationship to other body segments, accuracy and precision in goal directed movements suffer (Desmurget et al., 1998).

In contrast to limb proprioception, less attention has been given to the role of cervical spine proprioception and its impact on reach to point accuracy. It has been theorized that proprioceptive information from the neck may contribute to the maintenance of postural orientation by way of contextualizing visual and vestibular information, giving it relevance to the body position (Pettorossi & Schieppati, 2014). Cervical spine proprioception has the important role of discerning the orientation of the head relative to the trunk. As such, in the construction of an internal body schema used for motor planning, this information should theoretically be an important contributor. For example, the motor plan for a reaching movement towards an object in front of you would vary significantly between a head aligned with the trunk compared to a head on a rotated trunk. In theory, this information should be of great importance in planning and executing accurate reaching movements towards a visual target and even greater importance when reaching towards a remembered visual target in the absence of visual cues about head on trunk position.

To address the potential role of neck proprioception, previous work in this area has investigated the impact of neck vibration on reach to visual target tasks. These studies have investigated the impact on reaching towards a stationary visual target under the illusion of target motion known to be induced by unilateral neck vibration in a majority of subjects. As an example, Biguer et al. (1988) examined this neck vibration induced visual illusion and the accuracy of pointing to this illusory moving target during neck vibration. In their study, subjects pointing towards an illuminated red target in an otherwise dark room had increased target relocation error during left sided unilateral dorsal neck muscle vibration. In all but one subject, this error was systematic in nature with increases to the right of the actual target location although the size of this target relocation error was quite variable among the subjects (Biguer et al., 1988). The authors suggest that this is evidence for a role of neck proprioception in the perception of gaze direction (Biguer et al., 1998).

Similarly, Taylor and McCluskey (1991) examined the impact of neck vibration on the accuracy of reaching to a visual target and on the perception of head position. In their study, subjects sat with their heads secured by a bite bar while wearing a device over their field of vision, through which an illuminated target (LED light) could be cast (Taylor & McCloskey, 1991). A grid pattern on the bottom of the device was used in recording subjects' perception of their nose location. Similar to Biguer et al. (1998), the results of this study showed that the direction of the visual target motion was variable between subjects (three to the left, six to the right) but that overall, neck vibration resulted in displacement of reach to target error in the direction of the perceived motion. These observations were replicated by McIntyre and Seizova-Cajic, (2007). What was interesting in such studies was the between subject variability. In the study by Taylor and Mcluskey (1991) kinesthetic illusion measured by perceived nose position, was also variable from subject to subject. This was expressed not only by the different responses but also by the study inclusion and exclusion criteria. In the study by McIntyre and Seizova-Cajic (2007) only individuals in which a visual illusion could be induced by vibration were included. Of the 13 individuals initially included for the study, four were discarded due to lack of reported visual illusion from vibration (McIntyre & Seizova-Cajic, 2007).

The current study extends this previous work, to further our understanding of the role of cervical proprioception for spatial orientation. In these previous studies the systematic target relocation error towards the vibration induced visualized illusion suggesting a role for cervical proprioception in gaze orientation and head orientation perception. From these findings it was wondered how altered cervical proprioception might impact relocating a remembered rather than a visualized target. The current study theorized that cervical proprioception helps to contextualize visual and body proprioceptive information for the generation of an egocentric body schema used in generating a reach to target motor plan. Therefore, altering cervical afferent information after the visualization of a target and prior to the performance of the motor task should result in a systematic displacement in target relocation in accordance with this new sensory information.

Therefore, the purpose of this study was to examine the impact of unilateral dorsal neck muscle vibration on reach to point accuracy of a remembered target in the absence of vision.

1. The main hypothesis was that in the absence of vision, left sided unilateral dorsal neck muscle vibration would result in a systematic shift in target relocation error in both the vertical and horizontal axis, with increased upward and leftward target error during the vibrated trials. This error would be consistent with compensating for the perception of muscle lengthening during unilateral left sided muscle vibration.

2. It was hypothesized that any deviations would be unconsciously percieved and therefore response time between vibrated and non-vibrated trials would remain consistent across both conditions (vibration and no vibration). If subjects were uncertain of their performance, response time might be expected to increase during that trial.

2.2 Methods:

2.2.1 Participants:

Ten young healthy right-handed participants took part in this study (6 male, 4 female) with a mean age of 27.7 years (SD 5.2 years). Subjects completed a health status questionnaire, indicating that they were free from recent neck pain, injury or any neurological or musculoskeletal injury that could have impacted their ability to participate in the study. Informed consent was obtained from all participants prior to participation in the study, indicating that the study purpose, procedures, potential risks and benefits, voluntary participation and ability to withdraw from the study at any time had been fully explained. Ethics approval for this study was granted by the Office of Research Ethics at the University of Waterloo.

2.2.2 Protocol:

Subjects were seated in a dark soundproof booth facing a touch screen computer monitor. Participants sat in front of the monitor so that their body midline aligned with that of the monitor at a distance of 42cm from the screen (Figure 2.1). On the table in front of the participant was a wireless keyboard that was positioned so that the midline of the space bar was 10 cm to the right of the midline of the participant and 10 cm forward from the edge of the table. A piece of felt measuring 1cm x 1cm was adhered to the center point of the space bar, marking the start position. This ensured that participants kept the same start position from trial to trial. During the reach to point tasks participants were instructed to keep the tip of their index finger on the marked position of the space bar, holding down the space bar until a “go” tone was sounded. Participants also wore liquid crystal diode (LCD) voltage gated goggles which would open and close to prevent or allow vision during specific times during the study. A custom-made vibration unit was firmly affixed to the left sided dorsal neck muscles using medical tape as described below. This vibration unit supplied a vibratory stimulus during the vibration blocks of the experiment.

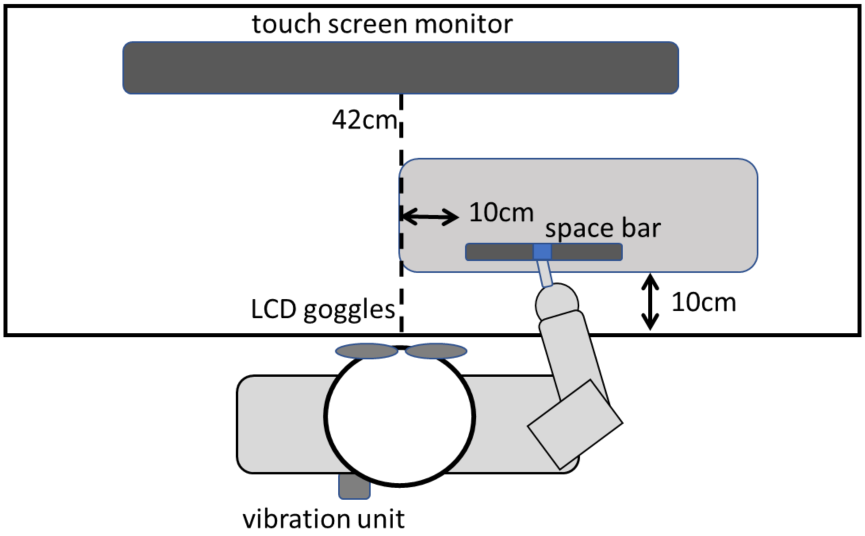

Figure 2.1: Experimental set up. Vibration was applied unilaterally and contralateral to the reaching arm. Liquid crystal diode (LCD) googles were used to manipulate the timing of the availability of visual inputs. The standardized starting position is shown, and subjects reached to point to the touch screen monitor when prompted by an auditory cue.

2.2.3 Task conditions:

There were 4 experimental conditions in the study: 1. Goggles open (full vision) no vibration 2. Goggles closed (remembered target) no vibration, 3. Goggles open vibration and 4. Goggles closed (remembered target) vibration. Trials were carried out in a randomized block design with two blocks of 30 trials receiving no vibration and two blocks of 30 trials receiving vibration. Each block contained equal numbers of goggles open and closed trials.

Prior to the first collected block of trials, participants were given a session of 18 practice reach to target trails without vibration but with both goggles open and goggles closed trials to familiarize themselves with the equipment and instructions. Participants were instructed to keep their index finger pressing down on the space bar at the designated start position. The goggles started off closed, preventing visualization of the target. After 5 seconds, a target would be presented on the touch screen monitor in one of 6 horizontal positions on the screen. (Figure 2.2) The target location was randomly selected. Targets were 1cm diameter grey circles on a black background and participants were instructed to relocate to the center of the target as accurately as possible. The glasses would open for 1 second, allowing for visualization of the target. Participants were instructed that when the target appeared to memorize, as best they could, the location of the target. The glasses would close again, and vibration stimulation would either turn on or remain off depending on the experimental block. Stimulation or no stimulation would occur for 2 seconds, then the glasses would either open or not open simultaneously with the presentation of a tone, prompting the participant to point toward the visualized or remembered target location as accurately as possible. As soon as the participant touched the screen, the glasses would close if they had been open, or remain closed and the next trial would begin. Each of the 4 blocks contained 30 trials for a total of 120 trials per participant (30 trials for each condition). (Figure 2.3 illustrates the study paradigm).

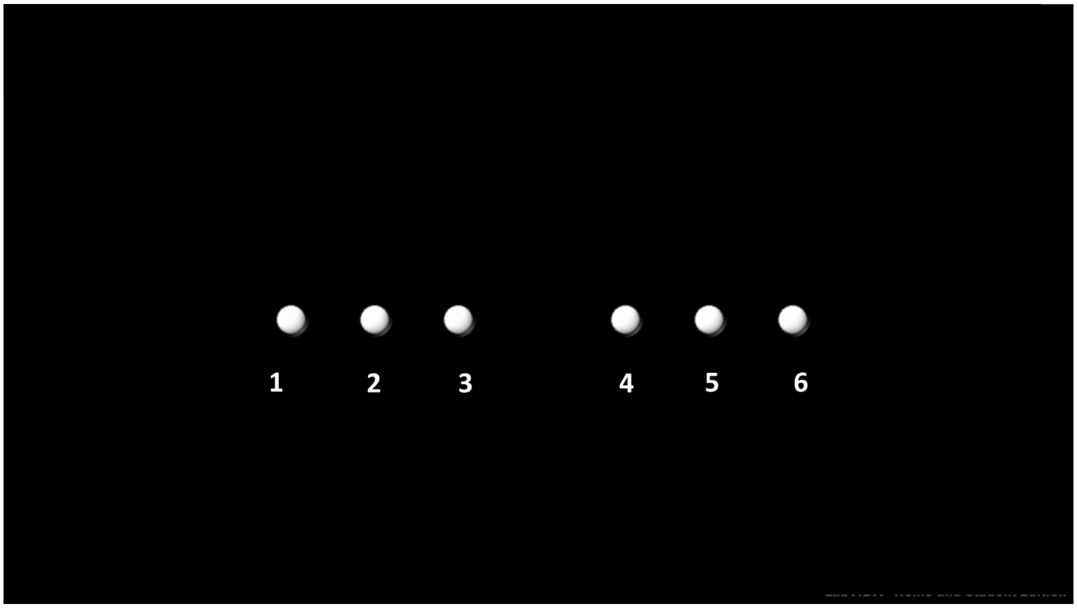

Figure 2.2: Target appearance and location on the screen. Targets would appear one at a time in random order without enumeration.

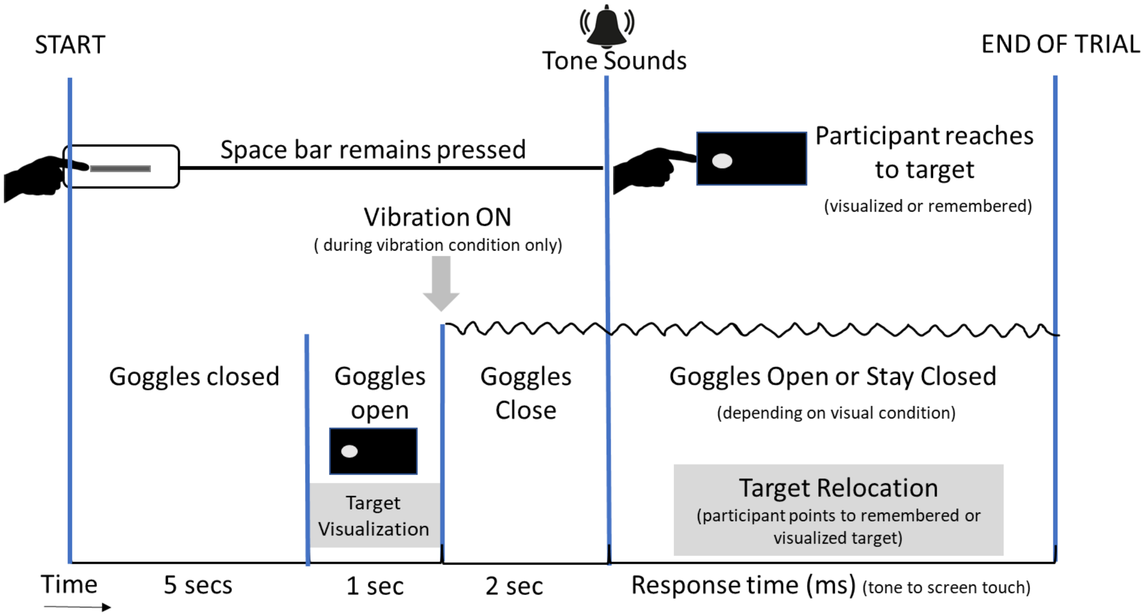

Figure 2.3: Study Paradigm.

2.2.4 Equipment

The touch screen computer monitor used was a 21.5-inch Dell ST2220T Multi-Touch Monitor with an average response time of 15 msec. The touch accuracy was reported as + 2.5 mm. Liquid crystal diode goggles were used which would switch from opaque to translucent with the application of a voltage. The vibration mechanism was a custom-made vibration unit comprised of a small direct current (DC) motor with an offset weight creating an oscillatory effect when a 2.5 Volt current was applied. This current resulted in vibration of the unit at approximately 80 Hz. The motor was encased in a 7.5cm x 2 cm plastic tube and affixed snuggly to the neck using medical tape. It remained in place throughout the entire study. The vibration unit was positioned over the left splenius capitus muscle approximately 2cm left of the midline between the cervical levels of C3 and C7.

2.2.5 Data acquisition:

The study was collected using a custom built LabView program (National instruments, Austin TX,) This program controlled the opening and closing of the liquid crystal goggles, the presentation of the pointing tone and the random presentation of pointing targets, while collecting the target relocation positions of each trial (screen touch) and calculating the horizontal and vertical error displacements. Response time was calculated as the time between the presentation of the tone and when the participant touched the screen to relocate the target.

2.2.6 Analysis

All statistical calculations were performed in SAS version 9.2. The main effect of vibration across all participants in the glasses open and glasses closed conditions was examined using a 2 factor repeated measures ANOVA with a value for statistical significance set at alpha= .05. Horizontal relocation error, vertical relocation error and a combined single displacement target relocation error and response time were analyzed with separate ANOVAs.

$$\text{Single Displacement Error} = \sqrt{[(\text{horizontal error})^2 + (\text{vertical error})^2]}$$

The study also focused on the responses within individual subjects to determine the nature of between subject differences. Subject specific difference in target relocation error (horizontal, vertical, single displacement vector and response time) between vibration and non-vibration conditions was compared using separate two-way ANOVAs.

2.3 Results:

2.3.1 Effect of vibration in the absence of vision on target relocation error

The main hypothesis of this study was that in the absence of vision, left sided unilateral dorsal neck muscle vibration would result in a systematic shift in target relocation error in both the vertical and horizontal axis with increased upward and leftward target error during the vibrated trials. Figure 2.4 shows the target relocations of all participants for all target locations in the full vision (goggles open) and remembered target (goggles closed) tasks between vibration and no vibration conditions. Under full vision conditions participants were able to accurately relocate the presented target with little error (single vector target relocation error = 3.82mm (±2.40mm) with no vibration and 3.85mm (± 2.31mm) with vibration). As expected, when relocating the remembered target there was increased relocation error across both the no vibration and vibration conditions (single vector target relocation error = 31.19mm (±16.28mm) no vibration and 32.04mm (± 19.77mm) with vibration. The repeated measures ANOVA did not reveal any statistically significant differences for the main effect of vibration in horizontal, vertical or single displacement vector relocation error in either the full vision or remembered target tasks. (Table 2.1). The means and standard deviations for vertical, horizontal and single vector relocation error for both full vision (goggles open) and remembered target (goggles closed) tasks in the vibrated and no vibrated conditions are presented in Table 2.2. The mean relocation error for vertical and horizontal planes, across all subjects, is displayed in Figure 2.5. The vertical relocation error towards the remembered target was increased in an upward direction in the vibrated condition, but it was not statistically significant. Across all participants in the full vision (goggles open) task, the SD between vibration and no vibration conditions was similar. However, as is shown in Figure 2.6, in the remembered target task the SD for vertical error and single vector error during the vibrated trials appears to be greater than during non-vibrated trials. This possible increased variability during the vibrated condition towards the remembered target prompted an examination of individual variability in response to vibration.

There was a statically significant interaction effect for target location and vibration (p=0.0205) for single vector error and a difference shy of significance for horizontal error (p=.0805). (Table 2.1). When reaching towards targets 2, 3, 4, 5 and 6, participants had increased relocation error during neck vibration, however, only target 4 reached statistical significance upon post hoc testing.

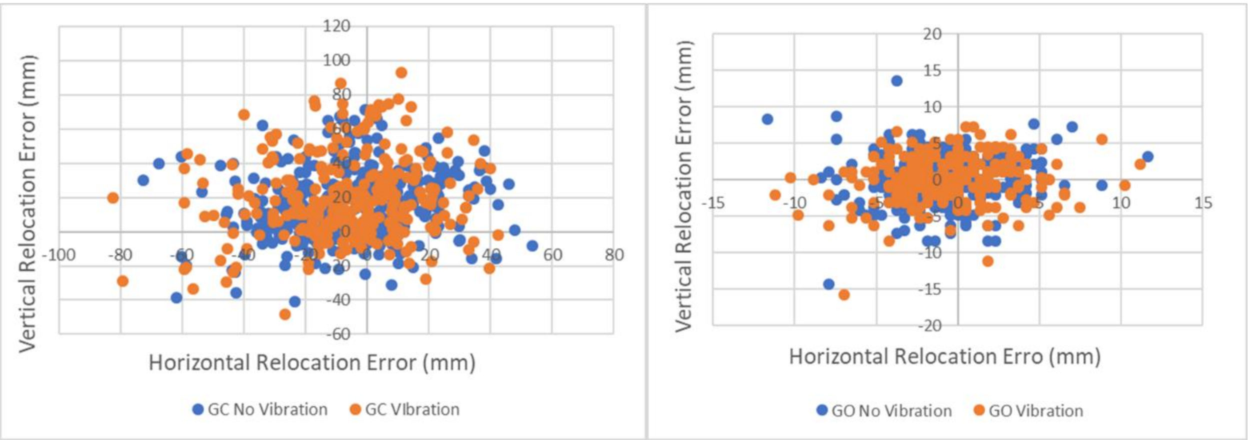

Figure 2.4: Target relocation across all subjects during Goggles Closed (A) and Goggles Open (B) conditions with and without vibration.

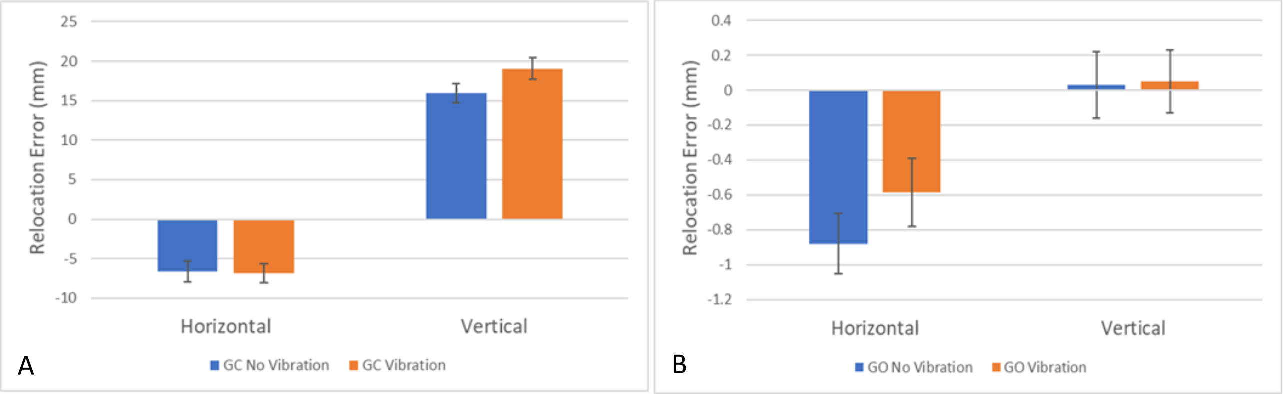

Figure 2.5: Target relocation error across all subjects during Goggles Closed (A) and Goggles Open (B) conditions with and without vibration.

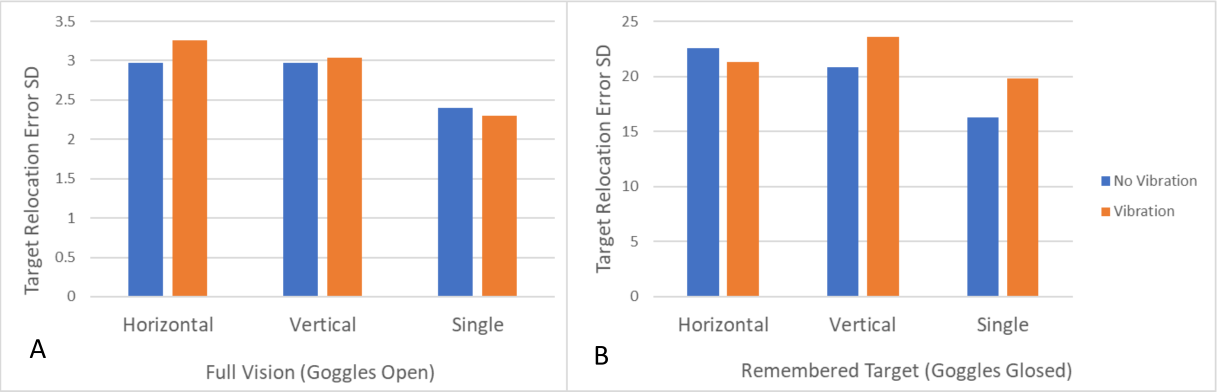

Figure 2.6: Standard deviation for Goggles Open (A) and Goggles Closed (B) conditions with and without vibration

	Vertical error	**Horizontal error**	**Single vector error**	**Response time**
Stim	p = 0.3410	p=.7276	p=0.9070	p=0.0699
Target	p= .3023	0.3089	p= 0.6639	p =0.0070
Vibration x Target interaction	p= 0.2546	p=.0805	p=0.0205	p= 0.4268

Table 2.1: Repeated measures ANOVA results for main effect of vibration on vertical, horizontal and single vector error as well as response time. Dark shaded boxes represent p values that reached statistical significance ($p \leq .05$). Light shaded boxes represent p values shy of significance.

	Horizontal Error (mm) ±(SD)		Vertical Error (mm) ±(SD)		Single Vector Error (mm) ±(SD)		Response Time Error (msec) ±(SD)	
	No Vibration	Vibration	No Vibration	Vibration	No Vibration	Vibration	No Vibration	Vibration
Full Vision (Goggles open)	-0.88 ±(2.97)	-0.59 ± (3.26)	0.03 ± (3.29)	0.05 ± (3.03)	3.82 ± (2.40)	3.85 ± (2.31)	1479.83 ± (332.64)	1497.91 ± (432.41)
Remembered Target (Goggles closed)	-6.62 ± (22.53)	-6.84 ± (21.28)	15.91 ± (20.86)	19.04 ± (23.60)	31.19 ± (16.28)	32.04 ± (19.77)	1863.20 ± (664.92)	1748.34 ± (427.34)

Table 2.2: Means and standard deviations (SD) for horizontal, vertical and single vector error and response time across all participants for full vision (goggles open) and remembered target (goggles closed) tasks during vibration and no vibration conditions.

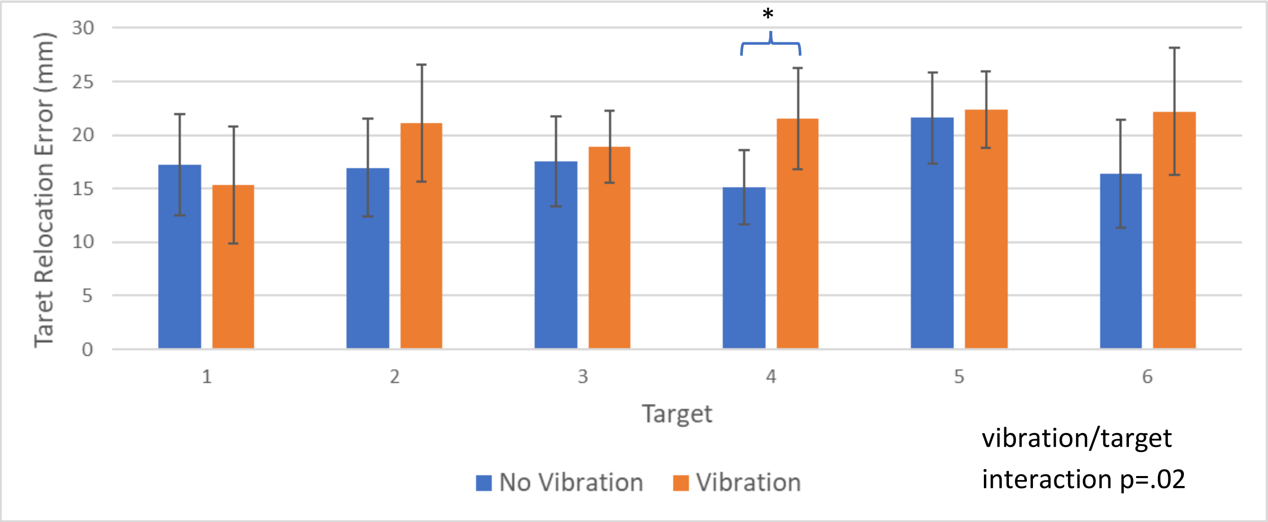

Figure 2.7: Single vector target relocation error in remembered target (goggles closed) task by target and vibration condition.

2.3.2 Response Time

Overall, participants completed the reach to target task significantly slower when reaching towards the remembered target (goggles closed). (Figure 2.8). During the full vision (goggles open) task, the average response time and standard deviation for no vibration and vibration trials were similar at 1479.83±332.64msec and 1497.91±432.42msec respectively. When relocating towards the remembered target, participants responded more slowly during the non-vibration vs vibration condition, with response times of 1836.45±482.92msec and 1748.34±427.34msec respectively, though this difference in response time was not significant. (See Figure 2.8 and Table 2.1 for summary of repeated measures ANOVA results). There was a statistically significant effect of target location on response time (p=.0044) across participants during the remembered target (goggles closed) task. (Figure 2.9)

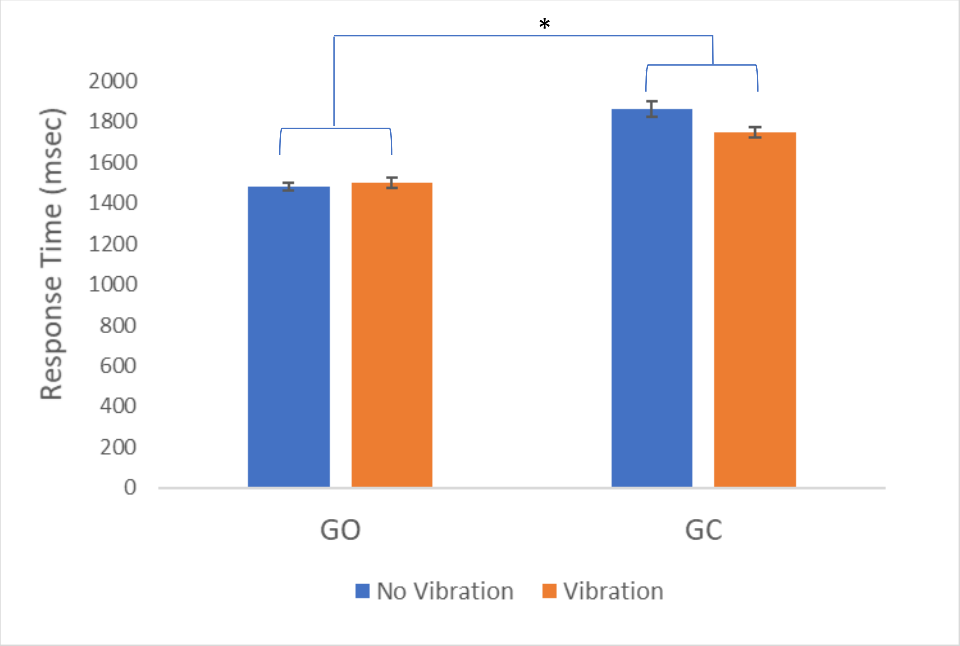

Figure 2.8: Average response time across all participants and targets during vibration and no vibration conditions with goggles open and closed. (Error bars represent SE)

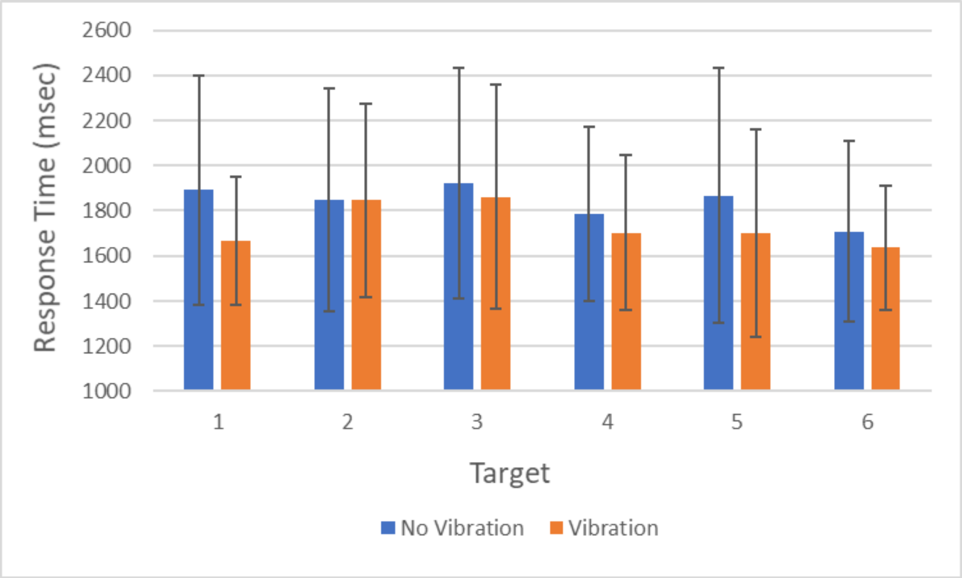

Figure 2.9: Average response time towards remembered target (goggles closed) across all participants by target and vibration condition (Error bars represent SD)

2.3.3 Within subject differences:

While there were no overall differences across all participants, with respect to the effect of vibration on relocation error, there was considerable variability between individuals when reaching towards the remembered target (Figure 2.10). Overall, regardless of the vibration condition, some participants were innately more accurate and precise than others as is seen in the larger overall differences in mean relocation error and SD between participants. For example, participant 5 and participant 10 had small relocation error in both horizontal and vertical directions versus participant 2 and 6 who had relatively larger vertical relocation error and participants, 1, 4 and 6 who had relatively larger horizontal error towards the remembered target (goggles closed). Interestingly, there also appeared to be great variability between subjects for target relocation error between the no vibration and vibration conditions despite no significant group effects. As is seen in Figure 2.10 some participants such as participant 5, 6, 8, 9, and 10 the target relocation error in either the vertical or horizontal direction was considerably different between the vibrated and non-vibrated condition. As a result, we examined the impact of vibration on target relocation (horizontal error, vertical error, single vector error) at a subject specific level using separate repeated measures ANOVAs for each participant. When the effect of vibration was examined within participants, 5/10 varied significantly in either vertical (participants 3, 6, 10) horizontal (participants 8,9) or single vector (participants 6, 10) error with one more participant (participant 3) near statistical significance in vertical error (p=.0505) Table 2.3 presents the means, standard deviations and *p*-values for the within subject repeated measures ANOVAs for vertical, horizontal and single vector relocation error. Significant findings are visualized in Figure 2.10 by subject. To further visualize the differences in target relocation error towards a remembered target (goggles closed) between subjects, individual trial target relocation error and mean error was plotted for each participant in Figure 2.11. Subject 6 and 10 demonstrated the pattern of target relocation error during unilateral neck vibration that was hypothesized, with upward and leftward displacement of error when relocating the remembered target location during vibration.

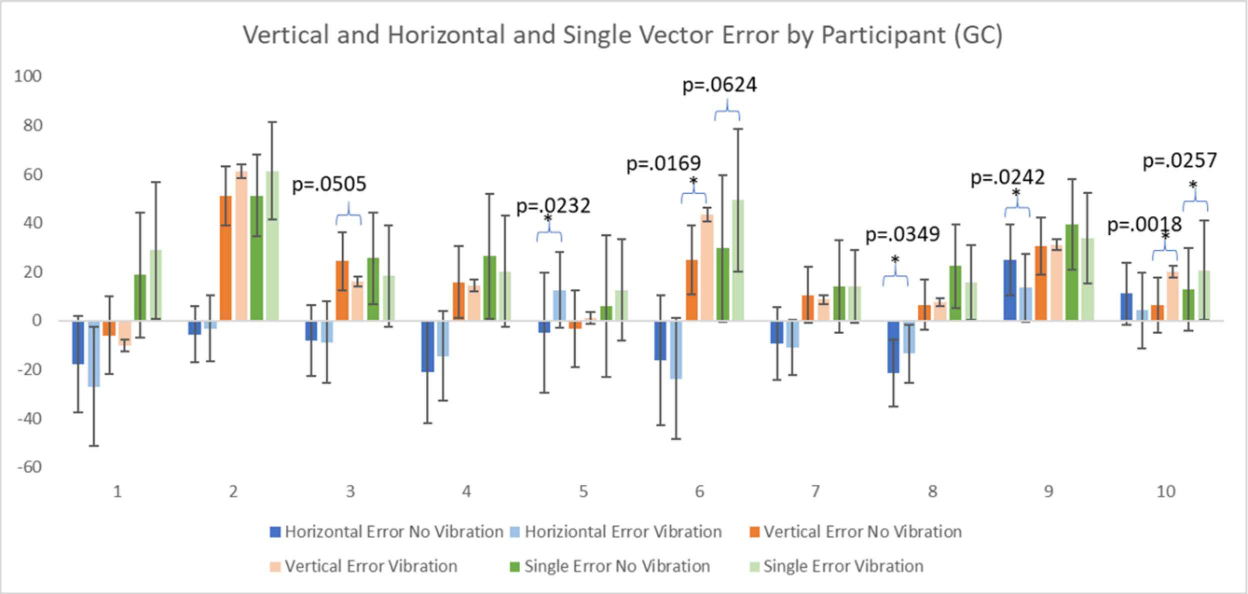

Figure 2.10: Within subject differences in target relocation error to a remembered target (horizontal error (blue), vertical error (orange) single vector error (green) between no vibration (dark) and vibrated (light) conditions. Individual ANOVA comparisons showing significance indicated. Error bars represent SD.

ID		Vertical Error			Horizontal Error			Single vector		
		Mean	**SD**	**p =**	**Mean**	**SD**	**p =**	**Mean**	**SD**	**p =**
1	**no vib**	-5.98	15.97	0.1189	-17.75	19.87	0.4718	18.73	25.49	0.2903
	vib	-10.25	13.60		-26.89	24.44		28.78	27.97	
2	**no vib**	51.04	12.16	0.3277	-5.51	11.48	0.9780	51.34	16.72	0.2499
	vib	61.28	14.85		-3.20	13.50		61.36	20.07	
3	**no vib**	24.38	11.90	0.0505	-8.15	14.46	0.7730	25.71	18.72	0.1338
	vib	16.09	11.87		-8.74	16.85		18.31	20.61	
4	**no vib**	15.74	14.77	0.7552	-21.19	20.94	0.1355	26.39	25.63	0.2220
	vib	14.33	13.59		-14.38	18.48		20.30	22.94	
5	**no vib**	-3.28	15.65	0.3381	-5.05	24.55	0.0232	6.02	29.11	0.1405
	vib	1.175	13.74		12.50	15.55		12.55	20.75	
6	**no vib**	24.92	13.95	0.0169	-16.11	26.55	0.3071	29.67	30.00	0.0677
	vib	43.46	15.34		-23.70	24.87		49.50	29.22	
7	**no vib**	10.56	11.48	0.2448	-9.38	14.97	0.5008	14.05	18.87	0.5268
	vib	8.76	9.80		-10.99	11.30		14.12	14.96	
8	**no vib**	6.56	10.29	0.5872	-21.44	13.68	0.0349	22.42	17.12	0.1248
	vib	7.61	9.60		-13.52	11.94		15.52	15.32	
9	**no vib**	30.57	11.64	0.7735	24.94	14.42	0.0242	39.45	18.53	0.1421
	vib	31.07	12.18		13.56	13.86		33.90	18.45	
10	**no vib**	6.37	11.13	0.0081	11.06	12.78	0.2204	12.76	16.95	.0403
	vib	20.19	13.30		4.29	15.50		20.64	20.42	

Table 2.3: Means and standard deviations for horizontal, vertical, and single relocation error between vibration and no vibration condition. *p*-values are presented for the repeated measures ANOVA results to look for within participant differences between vibration and no vibration conditions for target relocation error in remembered target task. (Dark shaded boxes represent statistical significance (p>.05) between no vibration and vibration conditions and lightly shaded boxes represent differences nearing significance).

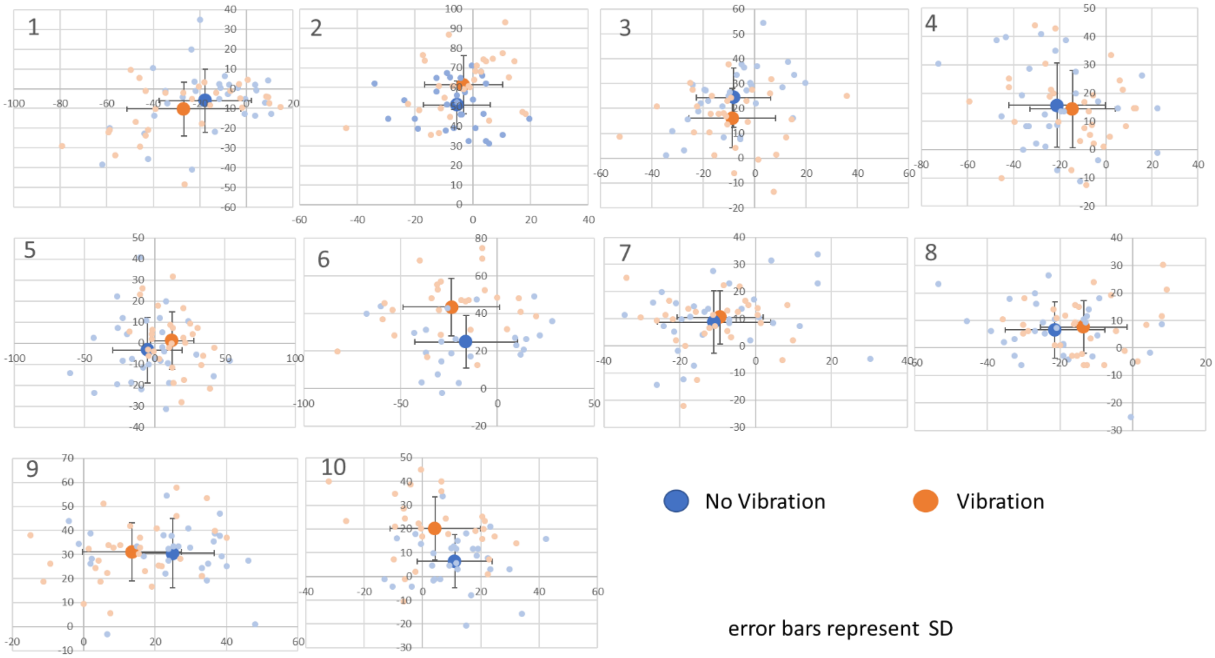

Figure 2.11: Individual target relocation error by trial, conditions (vibration or no vibration) for each participant (1-10). Small light coloured dots represent individual trails (blue= no vibration condition, orange= vibration condition). Larger dots represent overall average across all targets for each condition (blue= no vibration, orange= vibration). Error bars represent the standard deviation of the mean within each condition.

2.4 Discussion

The purpose of this study was to determine the effect of unilateral dorsal neck muscle vibration on reach to point accuracy to a visualized and remembered target. It was hypothesized that vibration would have little impact on reach to point accuracy in the full vision condition, but that reaching towards the remembered visual target during neck vibration would induce a systematic deviation with increased vertical and left horizontal target relocation error. Overall, the current study did not find significant differences across participants with respect to the application of vibration on reaching errors or response time. The work did however reveal significant between subject differences that may well have contributed to the absence of group differences.

With respect the first hypotheses the current study failed to find any statistical differences in target relocation error (horizontal, vertical, single displacement) between the vibration and no vibration conditions. These results differed from previous work in which a systematic increase in reaching towards a visualized target did occur. The lack of main effect of neck vibration on the remembered target relocation error is likely due to several factors. The first is the possibility that unilateral left sided neck vibration does not impact the accuracy of relocating a remembered target. However, given the previous literature in support of an effect of muscle vibration on spatial orientation and that our vibration stimulus was similar to that of previous studies, it is likely that other factors may have contributed to the lack of significant findings.

One explanation is that the experimental task employed in this study was not sensitive enough to detect any small vibration related effects. It is known that reaching accuracy declines as sensory information is removed (Berkinblit et al., 1995). The presence of both visual and proprioceptive information at the start and throughout a reaching task improves accuracy (Sarlenga & Sainburg, 2009). Pointing to a remembered target significantly decreases pointing accuracy and it has been reported that constant errors in reaching accuracy in this condition can reach 4-8cm or 9cm by some authors (Berkinblit et al., 1995; Darling & Miller, 1993). Therefore, additional small effects from vibration on reaching accuracy might not have been distinguishable from the variability in responses in the control condition. The magnitude of the neck vibration effect on reaching towards the visual target in previous studies was reported to be between 2.7-8.4 degrees of visual angle by Biguer et al. (1988), 4 degrees (4.2 cm displacement) by McIntyre and Seizova-Cajic (2007) and 3.3-7.5 degrees of visual angle by Talor and McCluskey (1991). It was believed, that given the magnitude of the previously reported systematic effects of vibration on pointing accuracy, that despite the increased inaccuracy of pointing to a remembered target, any vibratory effects would be observable.

2.4.1 Vibration unit position

Although great care was given to standardize the placement of the vibration device from participant to participant, it is possible that the lack of significant findings may be related to differences in the muscle vibration location between participants. The current study used a vibration placement strategy similar to that reported by several authors (Courtine, De Nunzio, Schmid, Beretta, & Schieppati, 2007; Ivanenko, Grasso, & Lacquaniti, 2000; Verrel, Cuisinier, Lindenberger, & Vuillerme, 2011) To vibrate posterior left sided dorsal neck muscles (primarily splenius capitus and upper trapezius) the placement position for the vibration unit was found by palpating the spinous process to discern vertebral level, palpating the dorsal neck musculature approximately 2 cm lateral to the spinous process at C3 and placing the securing the vibration unit with medical tape snuggly into a vertical position between C3 and C7 over the palpated muscles of interest. Although it has been reported that subtle changes in vibrator position on the muscles can alter the vertical or horizontal direction of a reported illusory target movement, given that we were not investigating this visual illusion perception we chose to standardize our vibration unit position based on physical landmarking rather than visual illusion findings. It is therefore possible that individual differences in muscle size and morphology could have resulted in differences in the precise location of muscle vibration possibly leading greater vertical versus horizontal target relocation error or vice versa from person to person.

This possibility was examined by looking at the individual target relocation error results in both vertical, horizontal and a single displacement vector (Figure 2.11). This allowed us to explore the possibility that the way in which subjects responded to the vibration condition may have been variable, as indicated by directional differences in target relocation displacement (vertical or horizontal). In the examination of between subject differences it was found that 5 of the 10 subjects performed significantly differently under vibrated conditions (as indicated by significant differences in target relocation error in either vertical, horizontal or single vector). However, the direction of effect was variable from subject to subject. For example, subjects 6 and 10 demonstrated significant changes in target relocation error in an upward direction during the vibration condition, but subject 3 had near significant downward target relocation error during vibration. Subjects 5 and 8 had significant rightward target relocation error during vibration while subject 9 demonstrated significant leftward relocation error. It is unclear why this variability in both effect size and direction between subjects exists. Although as previously described great care was taken to ensure consistent vibration placement and attachment on each subject, it is possible that directional differences represent stimulation of different muscles to a greater or lesser extent between subjects. The vibration stimulus could have spread to unintended muscles such as the sternocleidomastoid muscle. Due to its insertion at the mastoid process and its oblique lateral position in the neck it is possible that vibration could have stimulated muscle spindles in this muscle resulting in the perception of head movement into left rotation and extension rather than right rotation and flexion as would be the case with spindle stimulation in the left sided splenius muscle. The finding of between subject differences in direction has been reported in other studies. Biguer et al. (1988), and Taylor and McCloskey (1991) both reported subjects with visual illusions not always in the hypothesized direction during vibration. In the case of Taylor and McCloskey (1991), 3/9 subjects had leftward illusory movement of the stationary target and 6/9 reported rightward target movement during left sided neck vibration. This variability speaks to the need for either better standardization in the placement of the vibration unit, or analysis of not only group effects but also between subject differences in future studies.

Lastly, in the current study, the effect size of vibration on target relocation error towards the remembered target was variable from subject to subject. As is shown in Figure 2.11 and Table 2.3, comparison of the target relocation error in both vertical and horizontal directions during the vibration and no vibration conditions shows that vibration may have had a greater effect in some individuals than others. For example, the vertical difference in target relocation error between no vibration and vibration was 18.54mm (upwards) and in subject 10 this difference was 13.82mm. It is unclear why certain participants seem to have an increased effect from the vibration, however this too has been reported by both Biguer et al. (1988), and Taylor and McCloskey (1991). It should be noted however that both of these authors reported substantially larger effect size (as described previously) from vibration than was observed in the current study.

2.4.2 Conclusion:

In the current study, unilateral left sided neck muscle vibration did not affect the target relocation accuracy during a reach to point task during either a full vision or remembered target condition. However, the results of this study did identify significant between subject differences in both the direction and magnitude of relocation error to the remembered target in 5 of our 10 participants. This finding prompts the question as to whether cervical proprioception is altered to a varying degree by muscle vibration between subjects, and why these between subject differences might occur.

Chapter 3 Study 2: The effect of posterior neck muscle vibration on subjective straight ahead

3.1 Introduction:

The control of upright balance is influenced by afferent information from many systems including the visual, vestibular, and body proprioception systems. Lower limb proprioception from the foot and ankle has been regarded as the primary contributor of proprioceptive information for postural stability. However, more recent evidence from studies of postural imbalance in individuals with cervical spine dysfunction indicates that proprioceptive information from the neck may have a more significant role in balance control than previously believed (Courtine et al., 2007; Treleaven, 2008; Verrel et al., 2011). Neck proprioception enables the determination of head position relative to the trunk. One way to examine neck proprioception is to measure head position sense by examining joint position error (JPE). Joint position error is the difference between an intended joint position and an actual joint position in a specified task. In the case of the cervical spine, joint position error testing is often performed to a head neutral position also known as subjective straight ahead (SSA) in which the head is perceived to be centered over the trunk. This testing is sometimes called either the subjective straight-ahead test (SSAT) or cervicocephalic relocation test (Kristjansson & Jull, 2001). One method to perform this test originally described by Revel et al. (1991), examines a person's ability to accurately return their head to a neutral head position or SSA position following a rotation of the head in the absence of vision (Revel et al., 1991) . In the original test a laser pointer attached to the head is used to record starting and relocation positions using horizontal, vertical and global (single vector) co-ordinates. The difference between the starting subjective straight-ahead position and the final head position is deemed joint position error. It is typically reported as both variable and absolute error and is used as a proxy for proprioceptive ability with higher error reflective of poorer proprioception (Revel et al., 1991; Treleaven et al., 2005). The subjective straight-ahead test has been shown by some to have favorable test-retest reliability (Pinsault et al., 2008). Additionally, individuals with idiopathic neck pain and whiplash injury have been shown to demonstrate increased joint position error during this test when compared to both healthy controls and those with bilateral vestibular dysfunction (Beinert et al., 2015; Rix & Bagust, 2001). A relocation error greater than 4.5 degrees has been suggested to be of clinical significance (Treleaven et al., 2005). Although administering the test in its original form using the laser pointer method is cost effective, as it requires inexpensive equipment, manually marking the location of laser pointer dot locations on a wall and the subsequent calculations required to determine the joint position error can be a barrier to use. In addition, the subjective straight-ahead test in its original form limits the analysis of the test simply to vertical and horizontal relocation co-ordinates. With the advent of relatively inexpensive wireless technology it may be possible to administer joint position error testing such as the subjective straight-ahead test using tri-planer accelerometers/ gyroscopes in order to discern head relocation error in roll, pitch and yaw angular displacements in addition to capturing other potentially important metrics related to joint repositioning such as movement velocity or acceleration.

To investigate the impact of altered proprioception on joint position error in a healthy population, neck proprioception can be influenced experimentally in a number of ways such as: prolonged isometric contraction, extended use of a soft collar and muscle vibration stimulation.

(Courtine, Papaxanthis, Laroche, & Pozzo, 2003; Gosselin et al., 2004; Karnath, Reich, Rorden, Fetter, & Driver, 2002; McIntyre & Seizova-Cajic, 2007; McKenna, Peng, & Zee, 2004; Schieppati et al., 2003; Verrel et al., 2011). As discussed previously in this document, vibration stimulation alters the activity of muscle spindle fibers, creating the illusion that the effected muscle is lengthening or on stretch (Eklund, 1972; Gilhodes & Tardy-Gervet, 1986). Vibration has been used extensively in the literature to modify proprioception in many body joints including the cervical spine. Subsequently, it has been suggested that participants undergoing neck muscle vibration readjust their head position or body posture accordingly to correct for this illusory muscle lengthening (Eklund, 1972; Karnath et al., 2002). In standing, bilateral dorsal neck muscle vibration induces a forward body lean, whereas in sitting this results in neck extension (Karnath et al., 2002; Verrel et al., 2011). In sitting, unilateral posterior neck muscle vibration will induce a rotation towards the vibrated side (Ceyte et al., 2006).

Although the use of vibratory stimulation on neck musculature is widely used, there is evidence to suggest that significant between subject variability exists in the effects of cervical muscle vibration on outcomes such as target relocation accuracy and the presence, magnitude and direction of induced visual target motion. As previously discussed in Study 1, studies by Bieguer et al. (1988), Taylor and McCluskey (1991) and McIntyre and Seizova-cajic (2007) all reported significant variability between subjects in the magnitude of visual illusion perception and head position perception (as indicated by pointing to one’s nose) (McIntyre & Seizova-Cajic, 2007; Taylor & McCloskey, 1991). Interestingly, visual illusions could not be elicited by vibration in a proportion of subjects in each of these subjects, and as such, these “non-responders” were excluded in two of the studies. This prompts the question of why such a discrepancy in response to vibration may exist and could this difference help to explain why in clinical populations certain individuals appear to be affected more by neck pain and neck injuries than others. Additionally, the experimental procedure of using muscle vibration to alter cervical afferent information varies from study to study. In some instances, vibration is applied prior to the task of interest. In other instances, it is used during a specified task, however, differences in the impact of vibration used prior to or during joint repositioning of the head has not been well studied.

The purpose of this study was to examine the timing and size of the effect of vibration on neck proprioception during both a static and dynamic subjective straight-ahead test measured using tri-planer (roll, pitch, yaw) wireless accelerometer/gyroscope technology that has the potential to be employed in a clinical setting. The current study aimed to replicate the findings of Karnath et al. (1994) who reported ipsilateral displacement in the dynamic subjective straight ahead of participants following the application of unilateral posterior neck muscle vibration towards the vibrated side. By examining the effect of vibration on static head position, this study aimed to investigate the timing onset of altered head position with the onset and offset of vibration in order to inform on the methodology of using neck muscle vibration in future studies.

Therefore, the three main objectives of this study were:

1. To assess the extent to which unilateral dorsal neck muscle vibration alters transverse head rotation sense using a head repositioning task to neutral.
2. To assess the extent to which bilateral dorsal neck muscle vibration alters sagittal head position sense using a head repositioning test to neutral.
3. To determine the temporal characteristics (onset and resolution) of any head position changes following the application and termination of posterior neck muscle vibration.

It was hypothesized that:

1) The application of unilateral dorsal neck muscle vibration will result in head position error in yaw (towards side of vibration) during head repositioning (left).
2) Bilateral dorsal neck muscle vibration will result in joint position error (increase pitch, specially neck extension) during head repositioning task.
3) Altered head position sense will occur within the first 30 seconds of vibration stimulation and resolve within 2 minutes of the termination of neck muscle vibration stimulation.

3.2 Methods:

3.2.1 Participants:

Fourteen participants completed the study. The 7 male and 7 female participants were between 19 and 33 years old with an average age of 24 years. Prior to study collection participants completed a health status questionnaire in order to exclude participants with cervical spine dysfunction, previous neck injury, neck pain, concussion or whiplash injury or any other neurological dysfunction or condition that could affect their baseline neck proprioception or ability to participate in the study. Prior to participation in the study, participants signed a consent form indicating that the study purpose, procedures, potential risks and benefits, voluntary participation and ability to withdraw from the study at any time has been fully explained. Ethics approval for this study was granted by the Office of Research Ethics at the University of Waterloo.

3.2.2 Experimental set-up:

Participants were seated in a high back ridged chair that prevented trunk rotation during the study. In addition to wearing the wireless accelerometer on their head and the vibration unit secured to the neck, participants also wore noise cancelling headphones which provided them with a tone to indicate when to move their head for the relocation task while preventing external audio cues that could have aided in orientation knowledge. Opaque goggles were also worn to prevent visual input during the experiment.

Vibration stimulation was applied to unilateral or bilateral dorsal neck muscles using a custom-made vibration unit that consisted of a small DC motor with an offset weight that created an oscillatory effect when a voltage was applied. The motor was encased in a 7.5cm x 2 cm plastic tube and affixed to the neck using adhesive Velcro applied to the skin on top of medical tape. This method of affixing the vibration unit was used rather than a strap or band fastened around the neck, to minimize somatosensory cues that might provide insight into head position during rotational movements from tightening and slackening of a band. A power of 2.5 volts was determined to result in a vibration frequency of approximately 80Hz. The vibration unit was placed in one of two locations depending on the part of the experiment being conducted. In part 1 and 3 the vibration unit was positioned over the left splenius capitus and upper trapezius muscle approximately 2cm left of the midline between the cervical levels of C3 and C7. In part 2 of the experiment to examine the effect of bilateral dorsal neck muscle vibration on joint position errors in the sagittal plane the vibration unit was positioned horizontally and centered at approximately the level of the C3-4 spinous process. (Figure 3.1 depicts a schematic of the experimental set up)

Head position was measured using a tri-planer wireless accelerometer/gyroscope (Xsens). This device provided information about head orientation (role, pitch and yaw) during the subjective straight-ahead test (Figure 3.2). The accelerometer measures 47 x 30 x 13 mm and was worn on the center of the forehead using a comfortable head band. Head position data was collected using the 3D orientation software provided by the Xsens platform with a sampling rate of 120hz. The output data was presented in degree angles for roll pitch and yaw. Timing for vibration onset and vibration offset as well as the timing of cuing tones was collected using a sync pulse supplied by the custom LabVIEW program that was used to trigger the collection of the Xsens device. This sync pulse was used in the calculation of timing responses to vibration.

3.2.3 Protocol:

There were three tasks in this study and a randomized block design was used to determine the ordering of tasks for each participant. The order of each study part was randomized and within each block the order of tasks (vibration or no vibration trials) was also randomized. A "washout" period of 5 minutes was provided between each task to allow for the dissipation of any effects of muscle vibration.

Task 1: Influence of unilateral vibration on transverse rotation (yaw)

In this part of the study participants were asked to adopt a neutral head position or a subjective straight-ahead position, in the absence of vision following three active head rotations (yaw) to the right. This position became the reference position and in each trial the participant was asked to try and return their head to this reference position as accurately as possible. At the sound of a tone participants were instructed to rotate their head to the right as far as was comfortable and hold that rotated head position for approximately 3 seconds before returning back to the initial reference position as accurately as possible upon hearing a second tone. Twenty consecutive trials were performed with no stimulation applied and 20 trials were performed with the unilateral dorsal neck muscle vibration applied continuously throughout the entire 20 trials. Vibration began 5 seconds prior to the first relocation trial. Immediately following the vibrated trials, 20 additional “recovery” trials were performed consecutively to evaluate the aftereffects of vibration on subjective straight-ahead relocation.

Task 2: Influence of bilateral vibration on sagittal plane rotation (pitch)

In this part of the study the experimental set up was the same as in part 1 except the vibration unit was placed horizontally and centered over C3 in order to provide bilateral dorsal neck muscle stimulation and assess its impact on subjective straight ahead testing in the sagittal plane (pitch). Participants were again asked to adopt a neutral head position or subjective straight-ahead position in the absence of vision, but this time after performing three head flexion movements. Participants were instructed to flex their head, “bring your chin towards your neck”, using neck movements and not trunk movements. Participants were allowed to practice moving this way until they felt comfortable with the task. Upon assuming the starting reference position, participants were instructed to gently flex their head as far as was comfortable upon hearing a tone and return their head to the reference position as accurately as possible upon hearing a second tone. 20 consecutive trials were performed with no stimulation and 20 trials were performed with vibration applied continuously throughout the entire 20 trials. Immediately following the vibrated trials, 20 additional “recovery” trials were performed consecutively to evaluate the aftereffects of vibration on subjective straight-ahead relocation.

Task 3: Examining the temporal characteristics of dorsal neck muscle vibration

In order to examine the temporal characteristics of the head movement response to dorsal neck muscle vibration. As before, subjects performed a head reposition task (subjective straight-ahead position following 3 right sided head turns) and maintain this position throughout the duration of the 6 minutes task in the absence of vision. During the first 2 minutes participants sat quietly maintaining their subjective straight-ahead position after which vibration was started on the left sided unilateral posterior neck muscles and remained on for 2 minutes. Participants continued to sit for an additional 2 minutes following the offset of vibration to evaluate the aftereffects of vibration on subjective straight ahead.

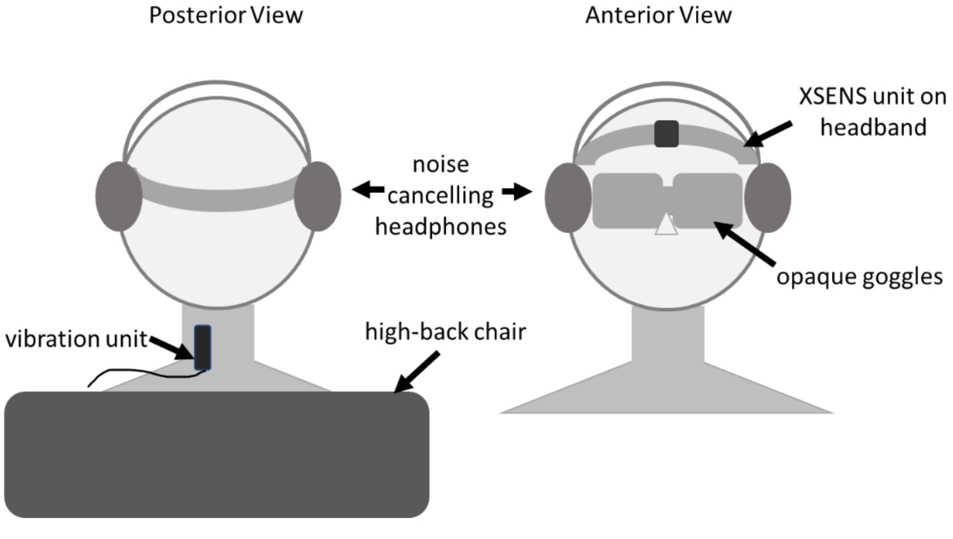

Figure 3.1: Experimental set up

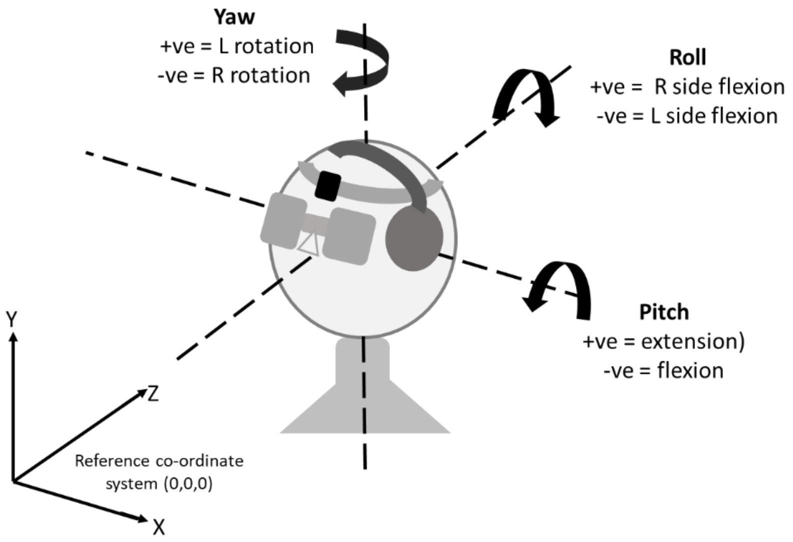

Figure 3.2: Roll, pitch and yaw orientation and axes of rotation

3.2.4 Analysis:

All head position output data from the Xsens collection was viewed and evaluated using a custom LabVIEW program. Relative and absolute joint position error was determined by subtracting the initial starting position (roll, pitch and yaw) from each relocation trial. Position values were calculated by averaging the roll pitch and yaw values for 1 second at the end of each subjective straight-ahead relocation movement (120 data points) just prior to the triggering of the tone used by participants to signal the next head movement. A global relocation error was calculated by combining roll, pitch and yaw data into a single displacement vector mathematically (single vector displacement = $\sqrt{[(\text{roll})^2 + (\text{pitch})^2 + (\text{yaw})^2]}$).

Changes in static subjective straight-ahead position (roll pitch and yaw) were determined by visualizing patterns in angular displacement over the course of the entire 6 minute collection and by calculating mean angular positions at specific time points to evaluate the impact of vibration onset and offset on subjective straight ahead static position. The time points used for this evaluation were; start, vibration onset, 30 seconds post vibration onset, vibration offset (start of recovery) and end of recovery. The means for each time point were calculated by averaging a 10 second (1200) data point block. Additionally, temporal characteristics regarding time to onset of head positional change following vibration onset and offset were calculated. This was done by setting a detection threshold of 3 standard deviations from a mean value collected pre-vibration (1000dp prior to vibration onset) and 3 standard deviations from mean value calculated for 1000dp immediately prior to the vibration offset.

Statistical analysis was performed using SAS 9.2 software. A significance value of alpha =.05 was used for all analysis in this study. Multiple repeated measures ANOVAs were performed to examine the main effect of vibration on head relocation error for relative and absolute relocation error (roll pitch and yaw) as well as global reposition error (single vector). Post hoc comparison analysis was used to determine relationship between no vibration, vibration and recovery conditions. Paired t-tests were used to determine significance between the selected time points (start-vibration onset, start-30seconds after vibration onset, start-vibration offset, start-end of recovery). A significance level of alpha = .05 was used to determine significance.

3.3 Results:

3.3.1 Unilateral neck vibration effects on head motion

During the presence of vibration and in the recovery phase, after vibration was turned off, there were measurable changes in head position, though the extent depended on the plane of motion and the specific task conditions. During the repositioning test with head rotation, joint position error during vibration and recovery periods of left dorsal neck muscles showed significant differences in head yaw ($p<.05$) and, to a lesser extent, pitch($p<.05$) compared to non-vibrated trials (Figure 3.3). Unilateral left sided dorsal neck vibration resulted in a significant increase in relative relocation error in pitch in the direction of neck extension when compared to no vibration or recovery trials (Figure 3.3). There was a significant increase in yaw (left rotation) during the recovery trials. Relocation errors in roll during vibration and recovery conditions failed to reach the level of significance compared to no vibration ($p=.09$). (Figure 3.3) Absolute relocation errors mirrored those of relative relocation error for rotation (Figure 3.4). Examining between subject relative relocation errors revealed substantial differences in both the accuracy and precision of subjective straight-ahead relocation between subjects across all conditions (Figure 3.4). In the non-vibrated control condition, some subjects were able to relocate the subjective straight-ahead position with relatively small degrees of error in all planes of motion (roll pitch and yaw). For example, subjects 3, 5 and 12 demonstrated little joint position error in the control condition (Figure 3.5). Whereas subjects 3, 8 and 10 performed the control condition trials with much greater amounts of joint position error. The between subject differences continued into the vibration and recovery trials. Some subjects like subject 12, had very large changes in their joint position error between the no vibration, vibration and recovery trials, while others like subject 10 demonstrated little to no changes in joint position error during the vibrated and recovery trials when compared to the no vibration control. The direction of joint position error changes between vibration and recovery conditions when compared to control was also variable between participants. For example, in the recovery condition in yaw, subject 1 demonstrated a negative joint position error (displacement to the right of starting position) compared to the majority of other participants being displaced to the left (positive joint position error).

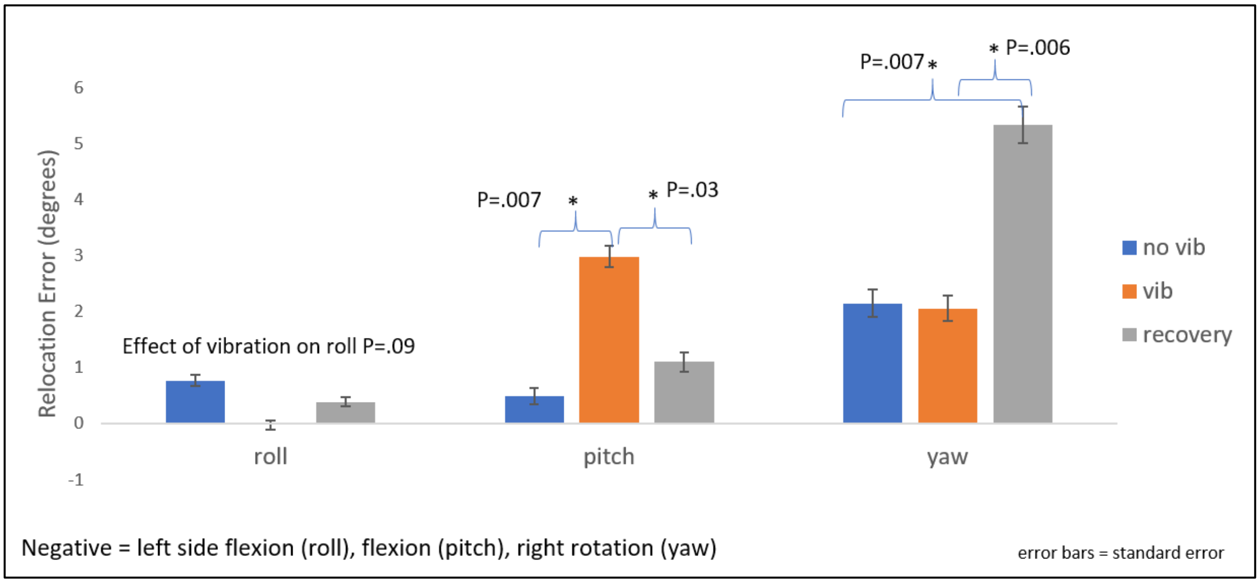

Figure 3.3: Mean relative relocation error across all participants (rotation). Error bars represent standard error.

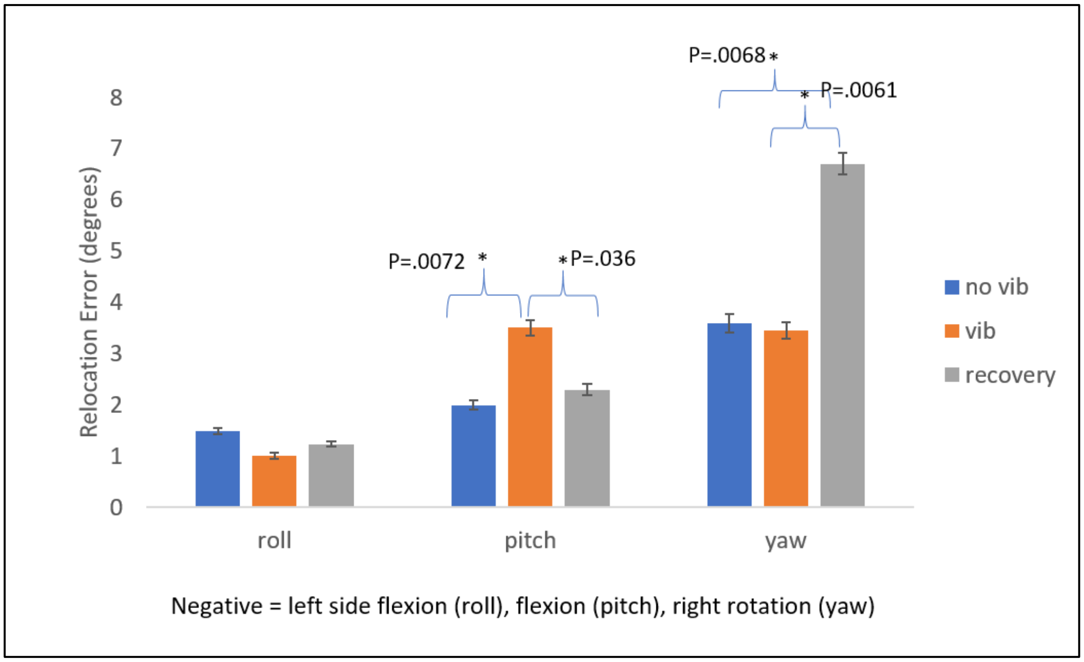

Figure 3.4. Mean absolute relocation error across all participants (rotation). Error bars represent standard error.

	Rotation Relocation Error (degrees)						Flexion relocation Error (degrees)					
	No vibration		Vibration		Recovery		No vibration		Vibration		Recovery	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Roll	1.50	1.07	1.01	0.91	1.24	0.83	0.972	0.88	1.41	1.12	1.22	1.12
Pitch	2.00	1.60	3.51	2.58	2.30	1.94	3.66	3.34	4.018	3.045	5.66	6.04
Yaw	3.59	3.05	3.45	2.73	6.71	3.72	4.56	4.24	3.482	3.24	6.98	5.09

Table 3.1: Mean relocation error and SD for subjective straight-ahead test following head rotation (transverse plane) and head flexion (sagittal plane) movements for roll, pitch and yaw.

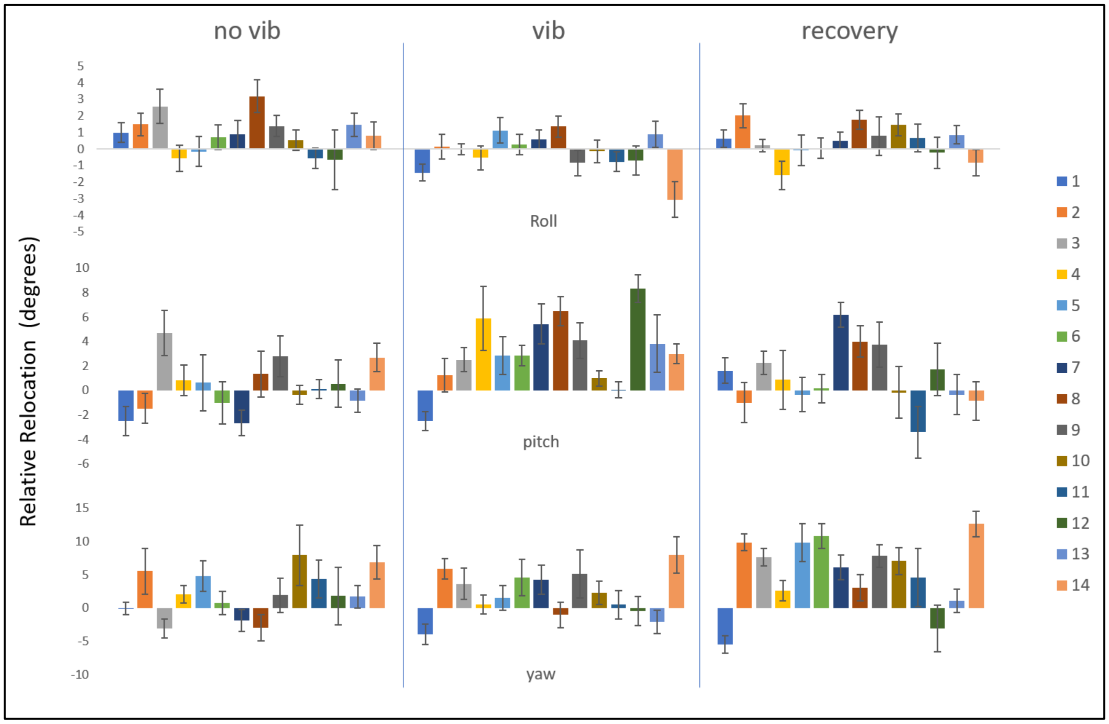

Figure 3.5. Relative relocation error for subjective straight-ahead test (rotation) averaged by participant. Error bars represent standard deviation.

3.3.2 Bilateral vibration effects on sagittal plane motion

Relocation error during the subjective straight-ahead test in the sagittal plane (head flexion) was not statistically significant between no vibration, vibration and recovery trials (Figure 3.6). It was hypothesized that relocation error in pitch would increase in the direction of neck extension during vibration, however the results showed that this error was identical during the no vibration and vibration trials (2.8 degrees) and decreased in the direction of flexion by 1.4 degrees during recovery trials though this change was not statistically significant. Relocation error in the yaw plane, although it was hypothesized would remain constant during bilateral neck vibration, increased during vibrated trials in the direction of left rotation and further into right rotation during recovery trials. However, these changes were also not statistically significant. There was substantially more baseline relocation error and variability during the sagittal (flexion) movements when compared to the lateral rotation task which may have contributed to the non-significant findings (Table 3.1). Even in the no vibration trials, participants had greater relocation error and standard deviation upon returning from flexion than during return from right head rotation for pitch (3.7 ± 3.3 degrees vs 2.0 ± 1.6 degrees) and yaw (4.6 ± 4.2 degrees vs 3.5± 3.0 degrees) (Table 3.1). The relocation error and SD across the three planes was more similar to the results of the rotation task during the vibrated trials however again there was increased error and standard deviation in relocation error following head flexion versus head rotation again in the recovery trials for both pitch (5.7 ± 6.0 degrees vs 2.3 ± 1.9 degrees) and yaw (7.0 ± 5.1degrees vs 6.7 ± 3.7 degrees). These findings were mirrored when absolute relocation error was examined (Figure 3.7).

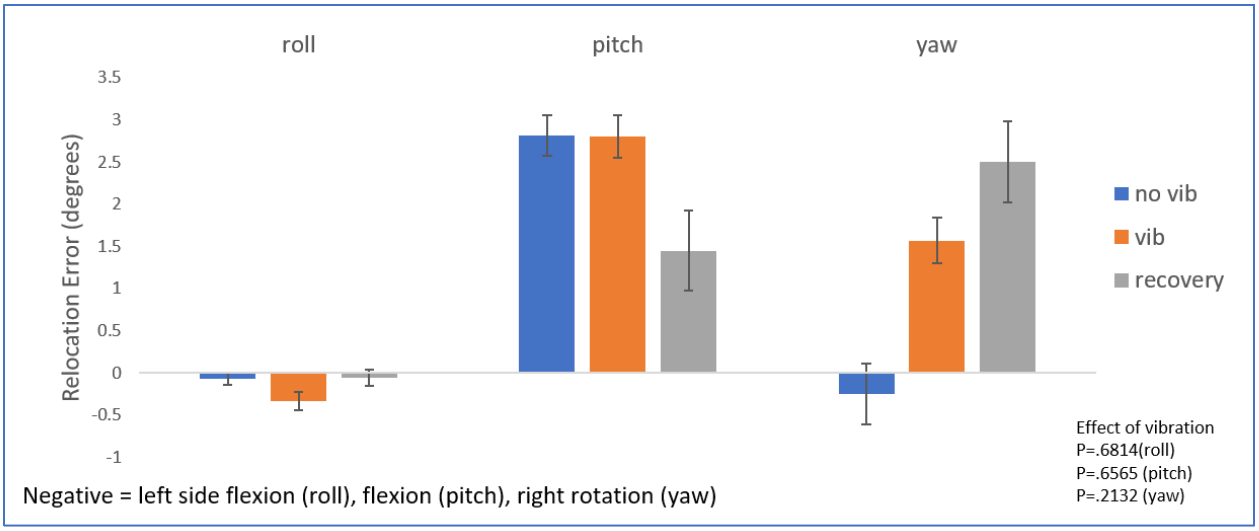

Figure 3.6: Mean relative relocation across all participants (flexion). Error bars represent standard error.

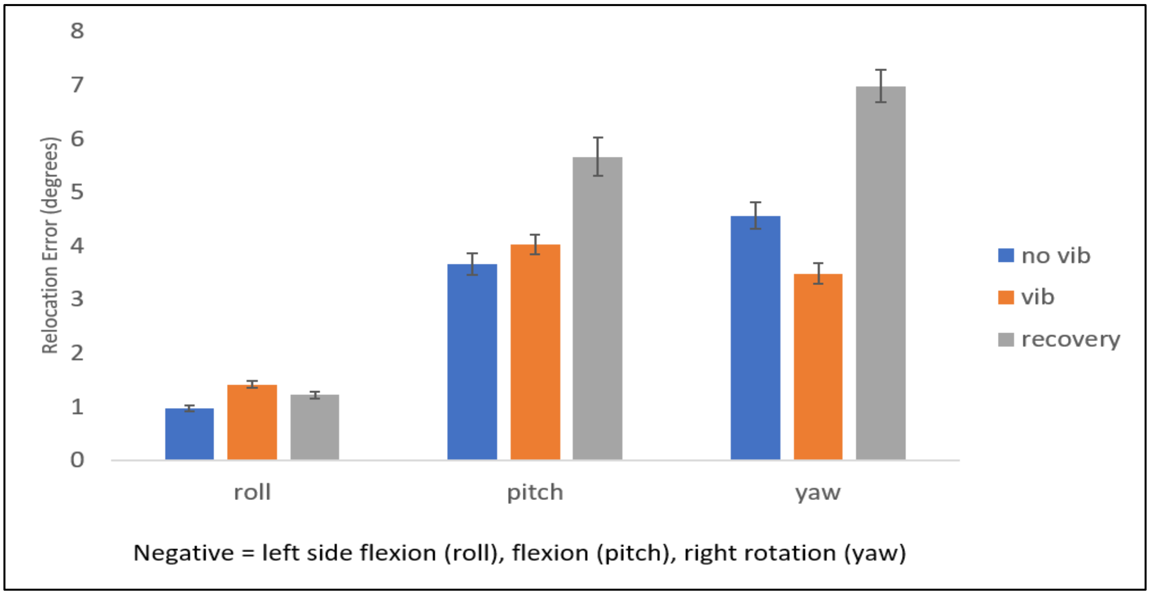

Figure 3.7: Mean absolute relocation error across all participants (flexion). Error pars represent standard error.

Examining individual differences in relocation error and standard deviation revealed substantial variation between participants similar to task 1(rotation) (Figure 3.8). Subjects varied in both direction and degree of relocation error across all conditions (no vibration, vibration and recovery) in all planes of movement. One subject, number 7 had substantial relocation error in yaw and pitch especially in the recovery condition when compared to the other subjects.

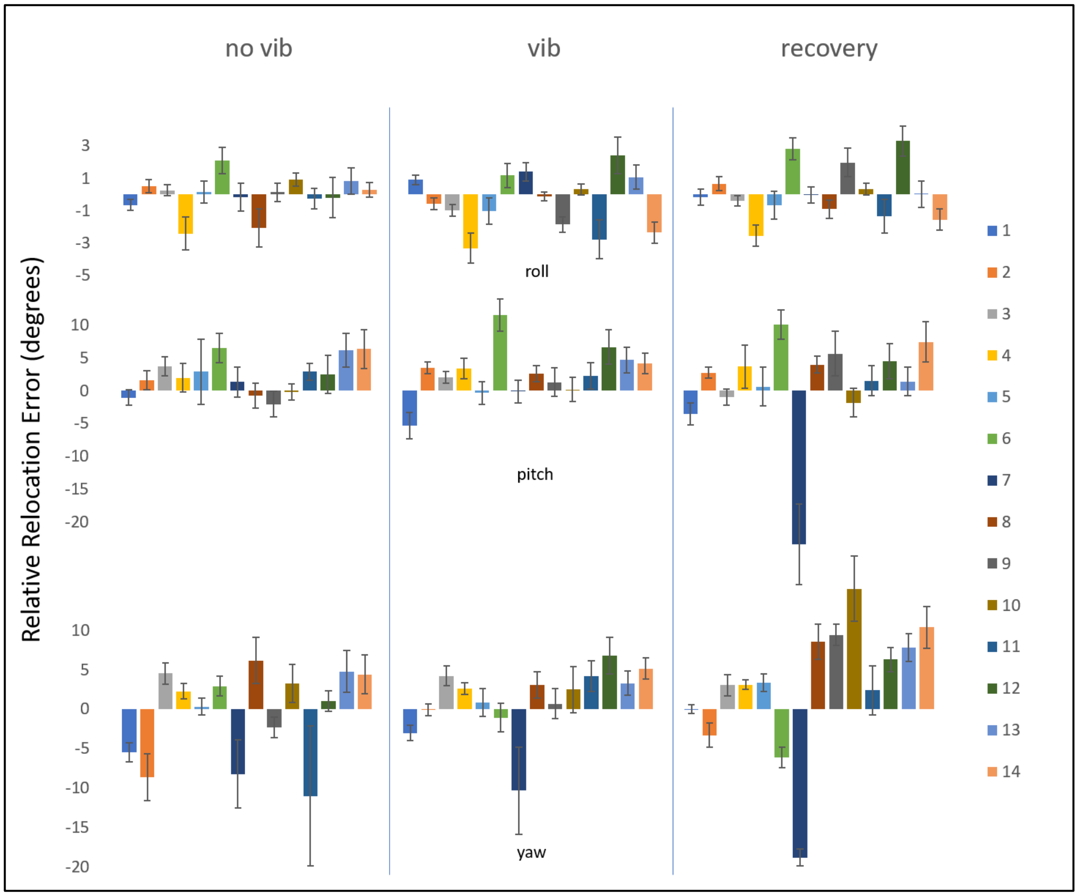

Figure 3.8. Relative relocation error averaged for each participant. Error bars represent standard deviation (flexion).

3.3.3 Temporal characteristics of head motion in response to unilateral neck muscle vibration.

The average time varying changes in head motion in response to application and removal of vibration is presented in Figure 3.9. For the purposes of this analysis roll, pitch and yaw data was collapsed into a single tri-planer grand average to represent head position change across all participants during the static subjective straight-ahead test. Overall subjects, angular positional change occurred rapidly after vibration onset with changes in pitch occurring 1.4 +/- .8 seconds after vibration onset. For yaw, and roll, angular positional change occurred at 2.0 +/- 2.3 seconds and 8.3 +/- 23.2 seconds respectively. Angular positional change following vibration offset for roll pitch and yaw, occurred at 4.0 ± 7.6, 5.2 ± 6.0 and 3.7 ± 3.1 seconds respectively across all participants.

Mean angular positions at specific time points were obtained (start, vibration onset, 30 seconds post vibration onset, vibration offset (start of recovery) and end of recovery) by averaging a 10 second (1200) data point segment at each of these time points (Figure 3.10). The results of the paired T-tests showed that the means of all time points were significantly different from the starting position. Additionally, significant differences were found between the mean at vibration onset and 30seconds into vibration but not between the end of vibration and vibration at 30seconds. The means at the end of vibration and end of recovery were not significantly different (Figure 3.10). In an additional attempt to quantify the magnitude of the impact of vibration during the static subjective straight ahead position the area under the single vector displacement curve was calculated during each condition (no vibration, vibration, recovery) (Figure 3.11). The results of this calculation revealed substantial differences in the magnitude of vibration induced changes in head position between subjects.

What is most noteworthy about the results of Part 3 was the significant between subject variability in their time varying response to the vibration. Such between subject differences, highlighted in Figure 11, likely account for some of the non-significant findings when evaluating the average time series across subjects. Subjects' response to vibration seemed to fall into one of 4 categories. 1. "responders" rapid initial response to vibration onset and offset. 2. "self-checkers" fluctuating response to vibration as if aware of head position change and attempting to correct for it. 3. "non responders" no or minimal effect of vibration on head position. 4. "delayed recovery" continued effects of vibration on head position following the offset of vibration.   An example head position tracing from a representative of each group is presented in Figure 3.13.

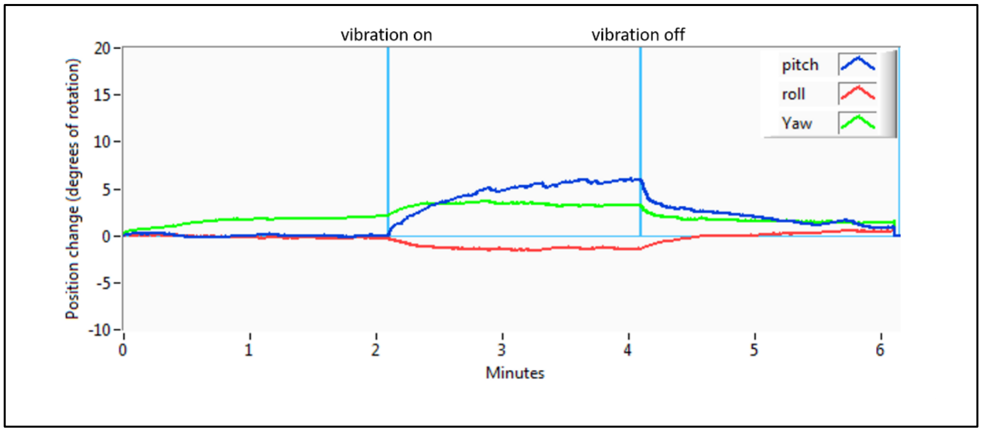

Figure 3.9. Static subjective straight-ahead position (roll, pitch, yaw) averaged across all participants.

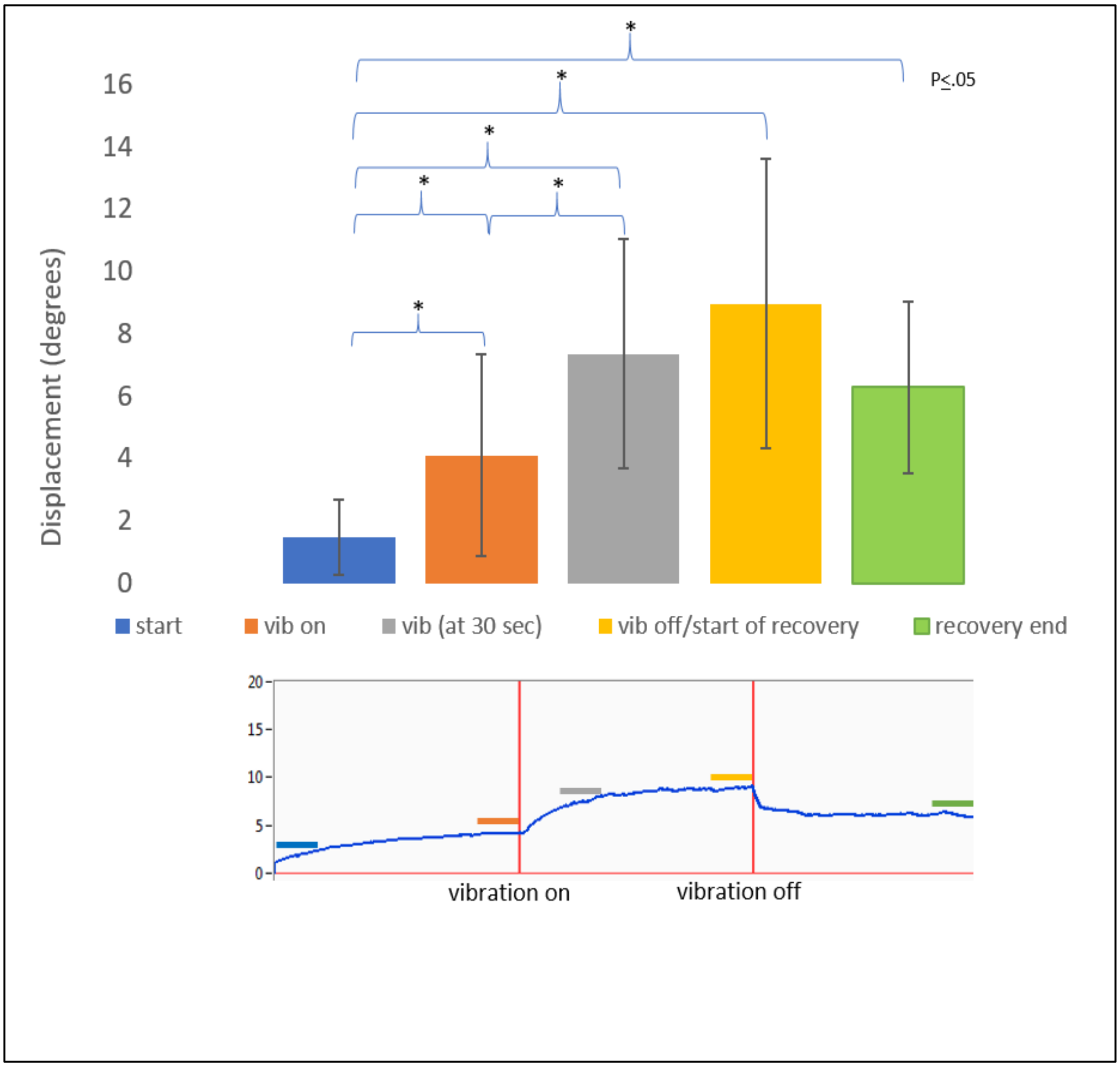

Figure 3.10. Mean head position change at start, vibration onset, 30 seconds into vibration, vibration offset/start of recovery and end of recovery during the static subjective straight-ahead. The * denotes statically significant differences (*p*<0.05) comparing between the different time points.

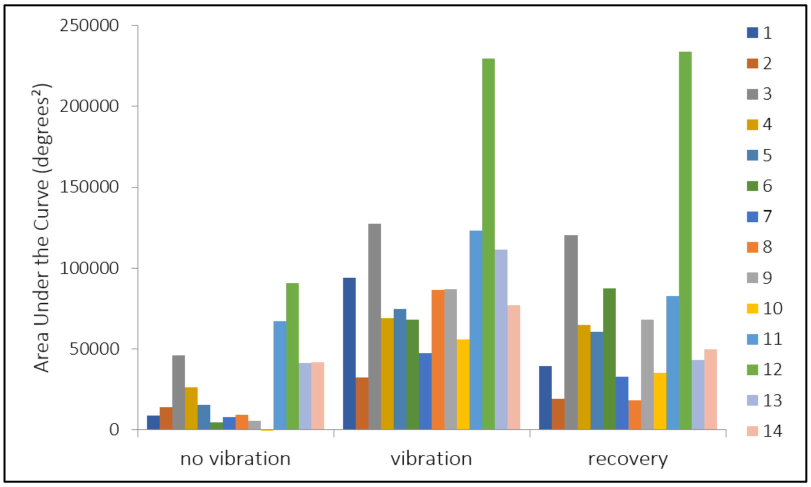

Figure 3.11. Area under single displacement vector curve for all participants during no vibration, vibration and recovery portion of the static subjective straight-ahead test

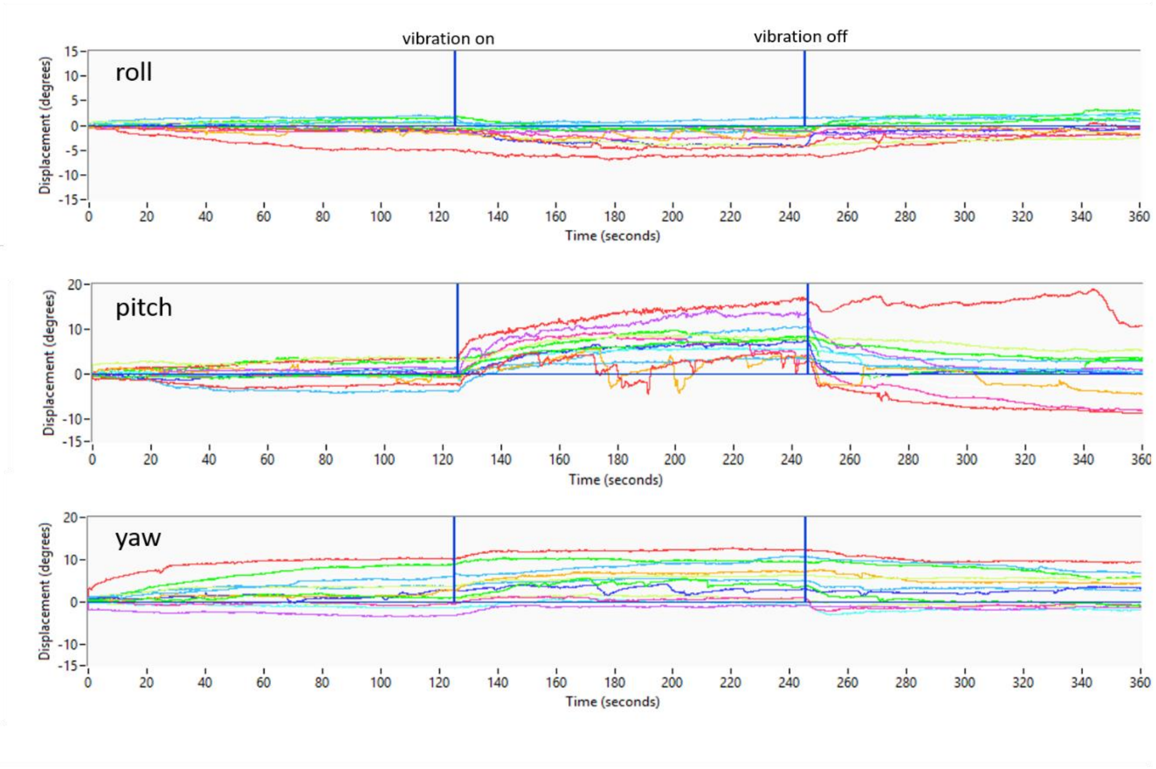

Figure 3.12. Static subjective straight-ahead position (roll, pitch, yaw) for all participants

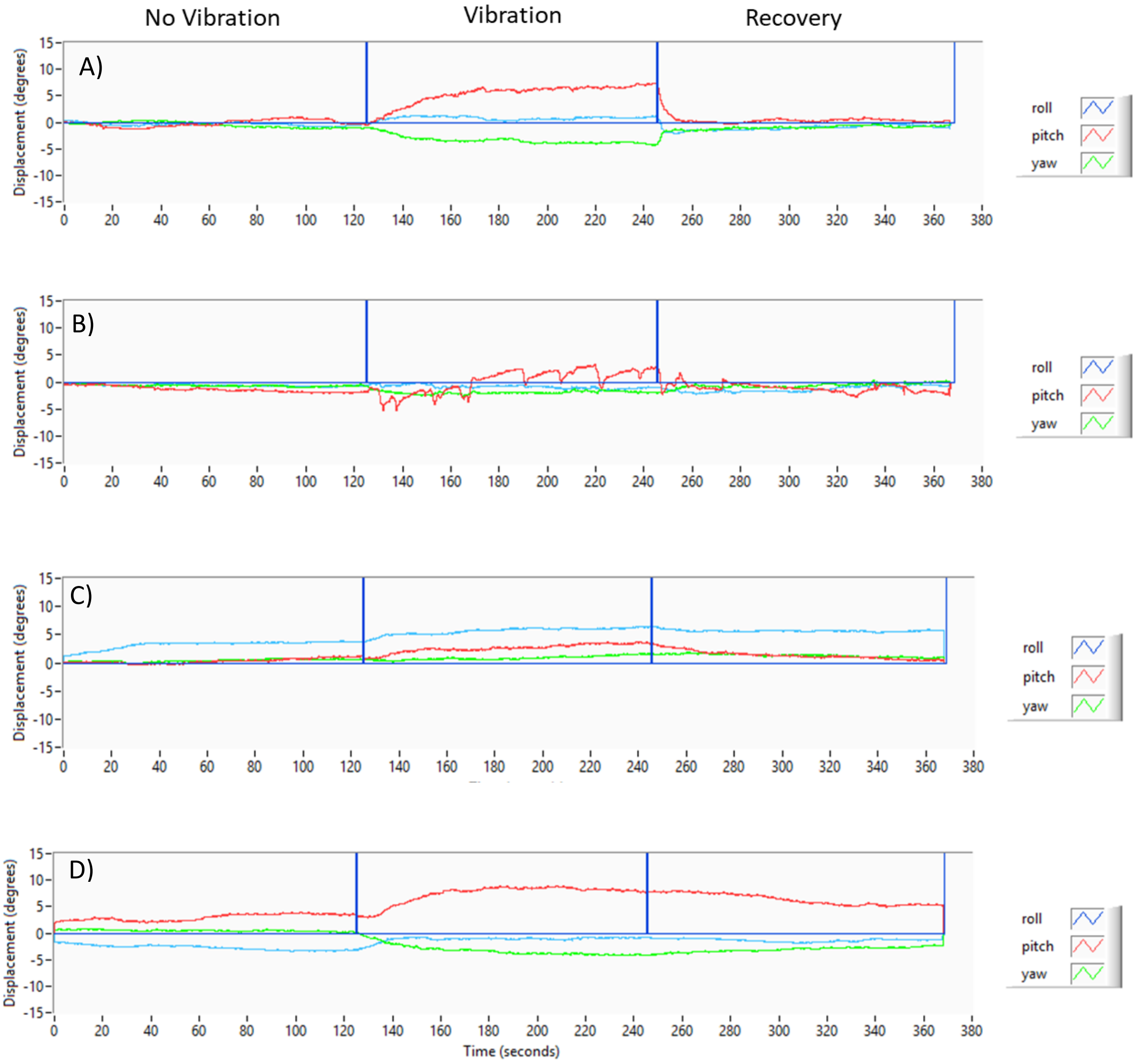

Figure 3.13: Representative sample from 4 different subjects to demonstrate the differing response of head position to the effects of unilateral dorsal neck vibration. A) “responder” rapid onset and offset of head position change in response to vibration. B) “self-checker” apparent conscious resistance to the effect of vibration on head position as indicated by attempts to relocate subjective straight-ahead during vibration. C) “non-responder” minimal effect of vibration D) “delayed recovery” effect of vibration on head position persists throughout the recovery period.

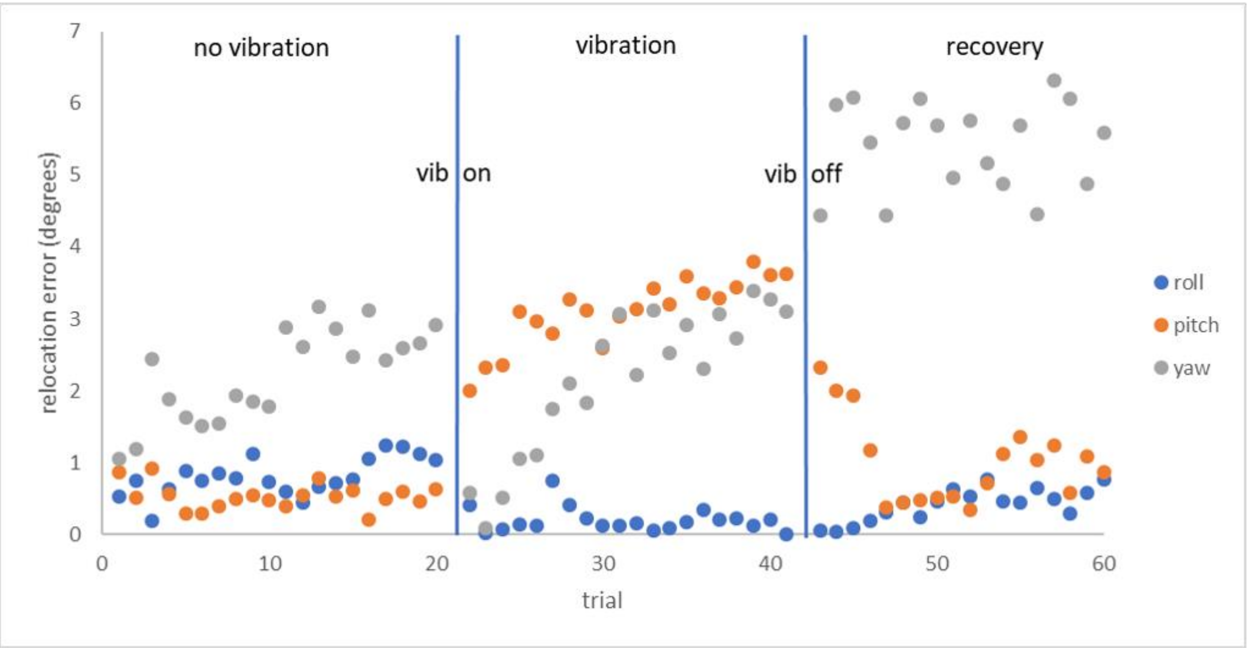

Figure 3.14: Mean trial by trial relative relocation error following head rotation (task 1) averaged across participants for roll, pitch and yaw during no vibration, vibration and recovery trials.

3.4 Discussion:

The first objective of this study was to examine the impact of dorsal neck muscle vibration on cervical joint position error upon returning to a subjective straight-ahead position following either head rotation, flexion or during maintenance of a subjective straight-ahead position without movement. The current study aimed to investigate both the effect during vibration but also the aftereffects of vibration during a recovery period after vibration was stopped, in order to inform on methodological use of neck vibration in future studies. It was hypothesized that unilateral dorsal neck muscle vibration (task I) and bilateral dorsal neck muscle vibration (task II) would result in relocation error during a subjective straight ahead test when compared to both non-vibrated and recovery (post vibrated) conditions and that the direction of this increased joint position error would be in the direction of left rotation in yaw (task I) and neck extension in pitch (task II). The findings for task 1 did not directly support the initial study hypothesis, in that significant differences in repositioning error were not seen in yaw during vibration but did significantly increase during the recovery period. There was, however, no significant change in pitch relocation error occurred during the vibrated trials upon returning to straight ahead following head turning. The significant increase in pitch relocation error during vibrated trials in part I of the study, would correspond to expected head position changes as a result of tonic vibration reflex from vibration of the splenius capitus and upper trapezius muscles vibrated in our study. The placement of the vibration unit between the level of C3 and C7, approximately 2 cm lateral to the midline, would have resulted in muscle contraction response of these muscles which in the case of left splenius capitus and upper trapezius would be expected to produce extension of the head, left head rotation and left side flexion. This was seen in the planes of pitch and to a lesser degree roll, although not reaching significance. Interestingly, however, contrary to the study hypothesis there was not a significant impact of vibration on yaw JPE during vibration, but significant increases in yaw error post vibration, during recovery trials.

In Part II of the study, contrary to the hypothesis, relocation errors in the direction of interest (pitch) during vibration were not statistically significant from non-vibrated trials. In this part of the study, although roll pitch and yaw mean values varied across conditions (non-vibrated, vibrated, recovery), none of these reached statistical significance. It is unclear why bilateral dorsal neck vibration did not result in significant relocation error across all participants in the current study. However as was described in the results section, the overall mean relocation error and standard deviation in the planes of pitch and yaw were generally larger during the flexion task versus the rotation task and hence this increased variability and baseline relocation error may have muted vibration induced effects. It is also unclear why during the recovery trials of this task relocation error in yaw was increased in the direction of left rotation. It was expected that the bilateral placement of the vibration unit would have stimulated both sides of dorsal neck musculature and therefore effects to roll and yaw would not occur. Although great care was taken in the placement of the vibration unit, one possibility is that the vibration unit was slightly asymmetrically stimulating the dorsal neck musculature resulting in a unilateral bias.

The significant increase in pitch relocation error during vibrated trials in part I of the study, would correspond to expected head position changes as a result of tonic vibration reflex from vibration of the splenius capitus and upper trapezius muscles vibrated in this study. The placement of the vibration unit between the level of C3 and C7 approximately 2 cm lateral to the midline would have resulted in muscle contraction response of these muscles which in the case of left splenius capitus and upper trapezius could be expected to produce extension of the head, left head rotation and left side flexion. This was seen in the planes of pitch and to a lesser degree roll although not reaching significance. Of interest however is the lack of impact to yaw joint position error during vibration, as was expected, but with increased error during recovery.

To our knowledge this is the first study to examine the effect of vibration to the cervical spine during an active dynamic subjective straight-ahead relocation test. However other authors have examined the post vibration impact on relocation error. The findings of task I of the study align with those of Beinert et al. (2015), who reported increased absolute reposition error in the horizontal plane post vibration. Beinert et al. (2015) examined subjective straight-ahead relocation error (cervicocephalic relocation test) post 30 seconds of neck vibration in both healthy subjects and those with neck pain. In their study, relocation error was examined with testing procedures outlined by Revel et al. (1991) using a cervical goniometer and laser pointer. An absolute joint position error was calculated in cm of displacement from a start position. In healthy subjects, post vibration resulted in increased absolute joint position error from 7.2cm (+/-3.1cm) to 12.0cm (+/-5.2). In task I of this study, participants as a whole also demonstrated increased relocation error in yaw (rotation) upon vibration offset from 2.05 degrees (+/-3.89degrees) to 5.33 degrees (+/- 5.5 degrees).

Cordo et al., (1995) examined the impact of tendon vibration on proprioception at the elbow during passive elbow movement. Their study examined the impact of various vibration frequencies and passive elbow movement velocities on the perception of elbow joint position. In addition, they explored the effect of vibration timing on altered joint position examining elbow proprioception with biceps tendon vibration before and during passive movement (Cordo et al., 1995). The results of their study demonstrated that tendon vibration effected elbow joint proprioception during passive movement with differing perceptual illusions (overshoot vs undershoot of target angle) at different vibration frequencies (20Hz overshoot, 40 and 60 hz undershoot). Additionally, their results demonstrated that the magnitude of error depended on the velocity of passive elbow movement with increased error (undershoot) at lower velocities. Lastly, they reported that vibration timing had an impact on proprioceptive error, demonstrating that if vibration stopped at the onset of movement, subjects were more likely to overshoot a perceptual target. In contrast, vibration termination during later stages of movement resulted in a tendency to underestimate a perceptual target. The results of task I of the current study shows some agreement in findings with respect to this perceptual overshoot following the termination of vibration prior to movement. In the current study, subjects' relocation error in yaw increased significantly in the recovery trials after the offset of vibration. However, in contrast to Cordo et al. (1995), vibration during active cervical rotation did not significantly impact relocation error in the direction of interest (yaw).

Is it possible that the lack of vibration impact on yaw following rotation, may be because active head rotation, in the current study, was performed to a familiar subjective straight ahead position. In the study by Cordo et al. (1995), passive elbow movement was to an unfamiliar position. Relocating the head to a neutral or subjective straight-ahead position is a common daily task and is therefore well practiced. The motor patterning for this movement is well established. It has been shown in primate studies that even in the absence of proprioceptive input, primates can accurately replicate a learned movement, however, accuracy declines if the task requirements are altered from the learned movement pattern (Sarlenga & Sainburg, 2009). Therefore, it is possible that the lack of impact on yaw JPE during vibration, may be in part because relocating the head to subjective straight ahead position is a well learned movement pattern and even though cervical proprioception was altered by vibration, participants were able to perform the task using previously learned motor patterns. Interestingly, there was an increased error in pitch during the vibrated trials. One might question if attention to the plane of movement could have contributed to the lack of relocation error in the testing plane and increased error in the movement plane not attended to. In the first task, (the relocation task to subjective straight-ahead following rotation), subjects may have given more attention to movements in yaw rather than to roll or pitch movements of the head because the task involved primarily yaw movement. Another explanation for the lack of impact on yaw relocation error during the vibrated trials is that the effect of vibration on yaw may not have been apparent until later in the vibration trials if the effect increased as vibration time continued. As was observed in Figure 8 the effect of vibration on head position in task III appeared to continue to increase a time continued and the effect was larger in the plane of pitch than yaw or roll. Therefore, it is possible that as vibration continued the relocation error in yaw increased. To examine this, relocation errors were plotted and compared across all participants by relocation trial number during the non-vibrated, vibrated and recovery conditions. (Figure 3.14). As is seen in this plot, across all participants yaw relocation error does seem to increase as trial number increases during vibration.

In task III of this study the aim was to explore the impact of unilateral dorsal neck muscle vibration on a static subjective straight-ahead position with the goal of exploring the timing onset and offset of vibration induced positional changes. During the vibration period of the task, subjects demonstrated head position changes that would also correspond to the tonic vibration reflex. Across participants, response to vibration occurred rapidly with changes in head position occurring on average at 8.3 (+/-23.2sec), 1.4(+/-.8sec), and 2.0 (+/- 2.3 sec) post vibration onset for roll, pitch and yaw respectively. Head position change after vibration offset occurred at 5.2 (+/- 7.6), 4.0 (+/-7.6sec) and 3.7 (3.1+/- 3.1 sec) for roll pitch and yaw respectively. It has been previously reported that onset of muscle contraction following vibration stimulation occurs rapidly (Goodwin et al., 1972). What was noted in this study was that as time continued the effect of vibration on head position continued to increase before reaching a plateau. Figure 3.9 shows the results of task III averaged across all participants for roll pitch and yaw head planes of movement. Although changes in pitch continued until vibration offset (3 minutes post vibration onset) changes in roll and yaw continued until an average peak at 47.5 secs ± 35.6 secs and 69.6 secs ± 26 secs respectively before reaching a plateau and remaining until vibration offset.

3.4.1 Between subject variability in response to vibration

Throughout all three tasks of this study there was significant variability between participants in both their inherent task performance abilities and response to vibration. In task I and II participants demonstrated large differences in their relocation error in both the absence of vibration and during vibration and recovery trials. This between subject variability was particularly apparent during maintenance of static subjective straight-ahead position in part III. During the non-vibration portion of this test some participants were able to maintain a consistent head straight ahead position with little drift, however a proportion of participants showed significant drift in one or more (roll pitch or yaw) planes. The head position drift during the no vibration period using a single displacement vector for all participants was 2.6 degrees (+/- 2.5 degrees) with a maximum up to 9.2 degrees. During the vibration period, the way in which participants responded to the vibration also varied. Some participants ("non-responders") responded minimally to vibration with only small head positional changes during vibration onset and offset (2/14 participants) while other participants seemed to respond to a greater degree to both vibration onset with more rapid head position changes and greater overall amplitude change "responders". Interestingly, during vibration 2 of the 14 participants appeared to constantly adjust their head position back to the starting position after positional changes ("self-checkers") almost as if they suddenly became aware of head positional changes and attempted to self-correct during the vibration. During the recovery period some participants demonstrated rapid return of head position change back towards the starting subjective straight ahead, while others (7 of 14 participants) continued to demonstrate altered subjective straight ahead even in the absence of vibration ("delayed recovery") similar to the active subjective straight ahead trials where post vibration resulted in increased relocation errors in yaw (Figure 3.13).

A few previous studies have reported a heterogeneous response to vibration and between subject variability and its impact on perceptual or illusory changes in visual and proprioceptive perception (Biguer et al., 1988; Goodwin et al., 1972; McIntyre & Seizova-Cajic, 2007; Taylor & McCloskey, 1991). In their study exploring visual perception of subjective straight ahead during neck muscle vibration Tylor and McCloskey (1991) reported that 4/13 participants failed to report any illusory visual target movement during posterior neck muscle vibration while 4 of the nine reported left moving visual illusions and 5 reported right moving visual illusions. Within the group of “responders” to neck vibration the degree to which vibration induced a perceptual shift in both visual dot location and head position perception (measured as pointing to the nose) varied significantly between subjects with some also reporting a feeling of dizziness or disorientation during neck vibration. The authors hypothesized that the differences in head position and visual perception illusion directions may have been due to positional error of the vibration stimulation affecting neck muscles with differing actions (splenius vs SCM). The authors also theorized that the differences in vibration effect may have been due to between subject differences in the way proprioceptive information is ignored or attended to during the task. They hypothesized that subjects with greater vibration response may have attended to the vibration stimulus, which elicited the illusion of head movement, versus the other somatosensory and proprioceptive cues (bite plate, chin rest, chair, other body segments) that would have provided non- movement cues. The authors hypothesized that their study provided evidence that neck proprioceptive information is used to aid in both the formulation of gaze direction and head position.

Karnath et al. (1994) also reported differences in the response of their participants to vibration stimulation. In this study, visual perception of straight ahead was again examined during neck vibration. Although overall, vibration resulted in a shift of visual straight-ahead perception, only 9 of 17 subjects reported a visual illusion of laser point motion to the right with left sided neck vibration. Four subjects had no reported illusion and 4 only had illusion reported to 1 side.

The between subject variability in task performance and response to neck vibration seen in the current study may be the result of several factors. Although great care was made to keep vibration unit placement consistent across all participants by carefully landmarking anatomical features and having only one researcher position the vibration unit for every participant, it is possible that the vibration unit may have been stimulating a slightly different area in each participant leading to more or less activation of muscle spindles from one participant to the next. Additionally, although participants were instructed to relocate their head position to subjective straight ahead as accurately as possible during Parts I and II of the study, it is possible that participants differed in their adherence to these instructions or fluctuated in attention to the task at hand over the course of the multiple trials.

However, it is also possible that the between subject variability in the way subjects responded to neck muscle vibration is representative of differences in the way these individuals use cervical afferent information for spatial orientation. It is known that sensory information from visual, vestibular or proprioceptive systems can be weighted differently depending on task and environmental conditions, or in the event that information from one sensory modality is unreliable (Horak, 2006; Peterka, 2002). Examples of this are seen in populations with vestibular loss, torticollis, or peripheral neuropathy (Borel, Lopez, Péruch, & Lacour, 2008; Bove et al., 2004; Horak & Hlavacka, 2001). It is possible that the between subject variability seen in the current study and other studies represents an innate difference in the way individual weight and use cervical proprioceptive information. Future studies should investigate whether between subject differences in the effect of neck muscle vibration are consistent across other sensory tasks in addition to joint position testing.

3.4.2 Portable wireless technology as a means to assess head position sense clinically

A secondary objective of this study was to examine the use of portable wireless technology (Xsens) in the assessment of joint position error during the subjective straight-ahead test. The use of this technology allowed for the examination of relocation error in roll, pitch and yaw planes of motion as well as the potential to explore head velocity and acceleration data (that was not examined in this study). The typical JPE test for cervical proprioception uses basic equipment including laser pointers and paper and requires the assessor to mark laser dot positions on a paper adhered to the wall (Revel et al., 1991). This method requires the practitioner to manually measure the distance from start to position relocation as indicated by the dot positions marked on the wall. Further algebraic calculation is then required to transform linear displacement into degrees of rotation. Although a custom LabVIEW program was used to analyze the results, the software provided with the Xsens system allowed for relatively straightforward visualization and analysis of the joint position error trials. Therefore, this type of technology may be of benefit as a clinical tool. Future studies should continue to investigate the feasibility of using such technology in a clinical setting.

3.4.3 Conclusion:

The current study demonstrated that unilateral left sided neck vibration resulted in significant relocation error upon returning to a subjective straight-ahead position during vibration but even greater error after the offset of vibration during a recovery period. Changes in head position during vibration occurred rapidly after vibration onset and continued to increase over time. Rapid changes also occurred immediately following vibration offset. Therefore, future studies should keep the timing of vibration effects and the post vibration effects in mind when using vibration to experimentally alter cervical proprioception. This study also provides evidence that the response to vibration, timing and effect size was quite variable between subjects and therefore future studies should aim to further characterize this between subject variability and whether the response to altered cervical proprioception persists in performance requiring integration of other sensory systems (vision, vestibular, balance and body proprioception). Lastly, the portable wireless technology such as Xsens, may be a means of measuring head position sense and head positional changes in a clinical setting.

Chapter 4: Study 3: Understanding the determinants of within and between subject variability in cervical JPE with and without neck vibration

4.1 Introduction

Cervical proprioceptive information is theorized to contextualize sensory information from visual, vestibular and body proprioceptive systems used for balance control (Pettorossi & Schieppati, 2014; Treleaven, 2008). Previous research from clinical populations and experimental manipulation of normal healthy subjects has identified the existence of between subject differences in the extent to which abnormal cervical proprioception impacts on spatial orientation, joint position error and vibration induced visual illusions (Biguer et al., 1988; McIntyre & Seizova-Cajic, 2007; Taylor & Mccloskey, 1991). Clinically, between subject differences have also been observed in the extent to which neck injury and pain result in the reporting of secondary symptoms including dizziness and unsteadiness, a condition termed cervicogenic dizziness (Brandt & Bronstein, 2001; Treleaven et al., 2003). Among these individuals with suspected cervicogenic dizziness sensorimotor performance on balance, joint position error and visual verticality tests are typically worse when compared to individuals with neck pain alone or healthy controls (Kristjansson & Treleaven, 2009; Treleaven, 2008; Treleaven & Takasaki, 2015). It is unclear why these between subject differences exist and what person specific characteristics may contribute to them. One possibility is that some individuals have innately better or worse cervical proprioceptive capabilities and that the extent to which this information is used for balance control purposes is tied to this ability. As a result, some individuals may rely more on cervical proprioceptive information than others and therefore may be more impacted by impairments to this sensory information. Currently, there are few studies that examine person specific factors related to cervicogenic dizziness and cervical JPE performance. Malmstrom et al. (2007) examined the musculoskeletal findings of individuals with simultaneous dizziness and neck pain from a non-traumatic source. Overall, these individuals had generalized tenderness in the zygapophyseal joints at all levels, suboccipital tightness, impaired postural control and decreased head dynamic stability when compared to healthy controls. Interestingly these individuals had normal or greater than normal cervical range of motion despite reduced cervico-thoracic mobility (Malmström et al., 2007). This is in contrast to traumatic sources of cervicogenic dizziness in which neck stiffness is often reported in addition to pain and muscle tension (Wrisley et al., 2000). More research is needed to characterize factors related to cervical proprioceptive capabilities and how they may factor into the development of cervicogenic dizziness with neck pain or injury.

As discussed, cervical joint repositioning tasks, such as the subjective straight-ahead test, are a way to objectively examine cervical proprioception function. Study 2 of this document used a version of the cervicocephalic relocation test described by Revel et al. (1994) to examine the impact of neck vibration on cervical JPE to subjective straight ahead (SSA). Main effects of neck vibration were observed on cervical JPE, but the results also revealed significant between subject differences in performance under both control and vibration conditions. Understanding the nature of this between subject variability in cervical JPE is important, since variability in cervical JPE between individuals may represent significant person specific differences that could help explain why some individuals seem more impacted than others following a neck injury. However, advancing understanding the sources of the variability are also critical to determine if such between subject differences may also be a product of methodological differences associated with the administration of the task or collection of testing data.

The cervicocephalic test or subjective straight ahead (SSA) test in its original form has been reported to have mixed psychometric properties linked to reproducibility. Interrater and intrarater reliability has been reported as poor to adequate for healthy controls with ICC values between 0.20 to 0.64 and 0.01 to 0.35 respectively (Strimpakos et al, 2006). In contrast, however, another study involving participants with whiplash injury reported interrater and intrarater reliability as excellent with ICC values (greater than 0.97) (Loudon et al, 1997). Test-retest reliability for the cervicocephalic test has been reported as adequate to excellent, with ICC values from 0.35 to 0.82 depending on rotation side and relocation target (neutral vs 30-degree rotation) (Kristjansson et al, 2001). As the cervical relocation task in study 2 of this thesis differed from the original test with the application of vibration during the task and the measurement of JPE using inertial sensors, and in light of the disagreement in test reliability presented in the literature it is necessary to examine our version of the test to a greater extent to assure that the within and between subject differences that were observed are not the result of methodological differences in the test's administration, but reflect both main effects from vibration and possibly the impact of person specific characteristics. Therefore, the first aim of this study was to examine the consistency of within subject differences in cervical JPE under control (no vibration) and experimental conditions (vibration applied to dorsolateral neck muscles). In this study, changes in cervical JPE was examined under control and experimental conditions across 4 variables. First, changes in JPE were examined across multiple successive trials, since the version of the task used in the current study had participants perform 10 consecutive trials under no vibration, vibration and recovery (post vibration) conditions for a total of 30 consecutive trials. Second, this study looked for changes in cervical JPE when vibration was applied to either the R or L dorsolateral neck muscles. Third, the current study examined changes in cervical JPE with and without neck vibration repeated on a second testing day 1 week later. Lastly this study looked for changes in cervical JPE across participants when a secondary cervical relocation target was employed (30 degrees to either the R or L) in addition to the SSA target, as a previous study had suggested that this might be more challenging to the cervical proprioceptive system than returning to SSA (Kristjannson et al 2001).

A secondary objective of this study was to examine the between subject variability in cervical JPE across different task conditions. It is possible that person specific characteristics may be a key determinant of cervical proprioceptive capabilities and in turn the magnitude of vibration induced impact on cervical JPE performance. Some of these potential person specific characteristics include cervical posture, flexibility, strength, circumference and body BMI. Previous research has indicated that poor posture, specifically forward head posture, is a risk factor for neck pain (Goodarzi, Rahnama, Karimi, Baghi, & Jaberzadeh, 2017; Kang et al., 2012; Lee, Chung, & Park, 2015). Forward head posture is defined as a head that is anterior to a vertical line through the center of gravity (Silva & Johnson, 2013). It is a relatively common postural issue that results in imbalances in the cervical musculature which is thought to cause neck pain due to a reduction in muscle length and function (Lee, Lee, & Yong, 2014). Only a handful of studies have explored the relationship between forward head posture and cervical proprioception. Sajjadi et al. (2014) assessed cervical JPE of 20 individuals with forward head posture following the cervicocephalic relocation test to neutral head position (Sajjadi et al., 2014). Although they found no significant differences in absolute or constant reposition errors in the experimental group compared to controls, they did report significantly greater variable error in the group with forward head posture, which is reflective of decreased precision in relocating neutral head position. Lee et al. (2014) also examined the cervical joint reposition error between normal healthy controls and individuals with forward head posture. In contrast to the previous work, they did find significant decreases in head repositioning accuracy and a correlation between the degree of forward head posture and cervical joint reposition errors following flexion, extension and rotation (Lee et al., 2014). These conflicting results illustrate the need for additional research.

In addition to posture, cervical flexibility is another factor with the potential to affect cervical proprioception ability. Although direct relationships between cervical range of motion and proprioceptive function have not been explored in great detail, limited evidence from specific groups, such as former rugby players and pilots, suggest a possible relationship between decreased cervical range of motion and decreased joint position sense (Pinsault et al., 2010). Additionally, it has been suggested that decreased cervical range of motion with age may also be implicated in decreasing cervical proprioception ability in older adults (Alahmari et al., 2017). On the other hand, evidence from investigations in other body joints suggests that the opposite relationship could also exist, more specifically, that too much cervical mobility could be related to decreased cervical proprioceptive function in certain individuals. It is known that joint hypermobility in the form of either benign hypermobility or more rarely congenital connective tissue diseases can effect up to 30% and 2% of the population respectively (Efremidou et al., 2009; Grahame, 1999; Murray, 2001). It is believed that joint hypermobility in the knees, hips and ankles may predispose individuals to joint pain, injury and degenerative changes (Golightly et al., 2018). Investigation of individuals with benign joint hypermobility has shown decreased joint proprioception in the hypermobile joints (Pacey et al., 2014). Therefore, it is possible that hypermobility or increased flexibility in the cervical spine may also impact on proprioceptive function in the neck and possibly increase the risk of neck pain and injury as is seen in hypermobile joints elsewhere in the body.

A third factor that has the potential to impact on proprioceptive function is muscle strength in the cervical spine. Previous research has demonstrated decreased cervical strength in individuals with neck pain from either a traumatic or non-traumatic source (Kim & Kwag, 2016; Prushansky et al., 2005). Imaging studies have revealed altered deep cervical muscle morphology, including changes in size and fatty infiltration in the deep neck flexors, extensor and stabilizers (Ghamkhar et al., 2018; Prushansky et al., 2005) . The deep flexors and extensor of the neck (longus colli, longus capitus, suboccipitals and multifidi) are believed to be vitally important stabilizers of the cervical spine (Boyd-Clark et al., 2002). They are comparatively rich with proprioceptive muscle spindles, and their deep, direct connections between the vertebral bodies of the cervical spine make them ideally placed to monitor movement of the cervical joints. Although it is, unknown whether the decreased cervical strength and altered deep cervical muscle morphology is the result of neck pain/trauma or a contributing factor to increased impairment it stands to reason that altered function and strength of cervical muscles may have a role to play in cervical proprioceptive function.

Advancing the clinical and biological meaning of a person’s ability to use cervical proprioception to position head and neck first requires more understanding of the factors that influence joint position sense and specifically joint position error.   The study is focused both on task related, within subject differences, as well as between subject differences such as BMI, cervical strength, cervical ROM, posture and cervical circumference. The current work is limited to a focus on normal healthy adults with no history of neck pain.

To examine within subject factors the study will examine the consistency of cervical JPE across different factors. It is hypothesized that both cervical JPE and the effect of vibration on JPE would be consistent across:

1) multiple successive trials
2) re-testing on a second day
3) R vs L sided vibration
4) cervical relocation to a different positional target (30 degrees vs SSA).

In relation to the second objective, to explore the relationship of between subject variability in cervical JPE and the impact of vibration on cervical JPE and person specific characteristics, it is hypothesized that:

1) Individual cervical JPE(30) and JPE(SSA) performance will be consistent across tasks when compared to other participants. Participants with increased JPE(SSA) will also demonstrate increased JPE to 30 degrees.
2) Increased JPE will be associated with increased variability in performance. Participants who are more accurate will also be more precise.
3) Better performance in JPE (less error) will be associated with greater impact from vibration.
4) Greater cervical proprioceptive ability as determined by decreased error in cervical joint position error testing will be associated with:
    a. Less cervical forward head posture

b. Cervical range of motion within normative values
c. Increased cervical isometric strength
d. Lower BMI

4.2 Methods:

4.2.1 Participants

Twelve young healthy adults (6 male) aged 20-34 (average = 23.33 yrs SD +/-4.22 yrs) participated in the study. Subjects completed a health status questionnaire, indicating that they were free from recent neck pain, injury or any neurological or musculoskeletal injury that could have impacted their ability to participant in the study.This study received ethical clearance from the Office of Research Ethics at the University of Waterloo.

Informed consent was obtained prior to participation in the study from all participants, indicating that the study purpose, procedures, potential risks and benefits, voluntary participation and ability to withdraw from the study at any time has been fully explained.

4.2.2 Instrumentation

Vibration Stimulation:

Vibration stimulation was delivered using a custom-made vibration unit that stimulated the left or right sided dorsal lateral neck muscles. This vibration unit consists of a small DC motor with an offset weight that creates oscillation of the motor and produces vibration. The vibration unit is 7.5cm x 2cm in size and will vibrate at approximately 80 hz when a 2.5-volt current is applied. The vibration unit was fastened to the neck using adhesive Velcro attached to a piece of adhesive athletic tape applied to the participant’s skin (protecting the skin from the

Velcro’s adhesive). The vibration unit was positioned over the left or right splenius capitus muscle approximately 2cm left of the midline between the cervical levels of C3 and C7 which was determined by palpation.

Motion Tracking:

Three-dimensional magnetic motion tracking system (Polhemus Liberty^{TM} Colchester, Vermont, U.S.A) was used to measure cervical orientation. The Polhemus sensor tracks orientation changes in roll, pitch and yaw planes of motion and sampled at 240hz. Orientation data was exported to and analyzed by a custom Labview program (National Instruments ^{TM} Austin Texas, U.S.A). All orientation data was low pass filtered at 1 hz. (Figure 4.1)

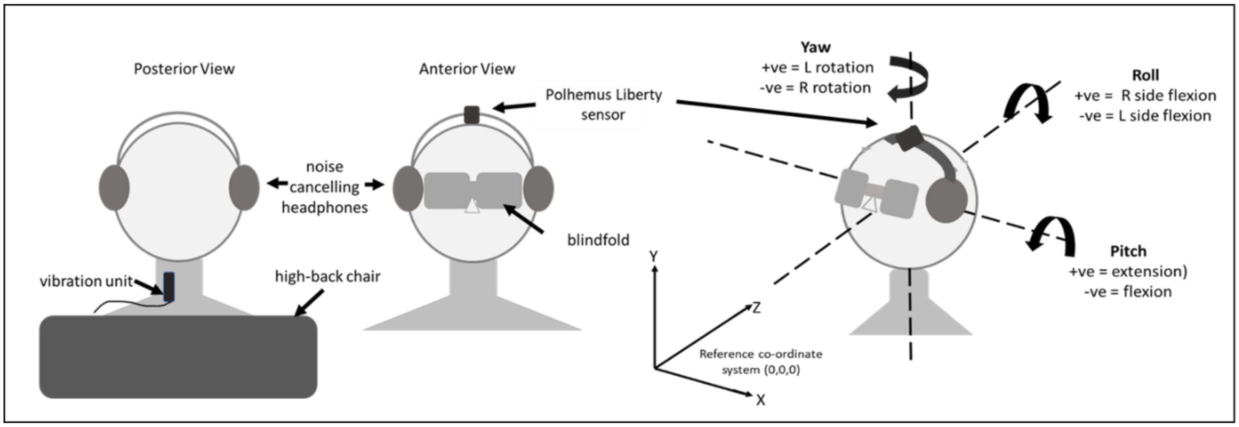

Figure 4.1 Experimental set up showing position of Polhemus Liberty^{TM} sensor atop noise cancelling headphones, vibration unit in experimental condition and planes of orientation

4.2.3 Measurements:

Cervical ROM testing:

Active cervical range of motion for each participant was measured using the three-dimensional magnetic motion tracking system described above (Polhemus Liberty^{TM} Colchester, Vermont, U.S.A). The tracking sensor was affixed atop the headband of noise cancelling headphones situated centrally atop the participant's head. Participants were seated comfortably in a high back chair that prevented trunk motion and were asked to move their head as far as they were comfortably able into flexion, extension, side flexion and lateral rotation to the right and left. Three measurements were recorded for each movement examined. ROM in each direction was recorded as the average of the three maximal excursions from head neutral position (starting position). A "Total ROM" variable was made which was the sum of the ROM averages for each direction with the following equations:

Total ROM = (flexion + extension + side flexion + right side flexion + left rotation + right rotation)

Cervical maximal isometric strength testing:

Cervical isometric strength was evaluated using a handheld dynamometer (ergoFET^{R} Hoggan Scientific, LLC, Salt Lake City, UT, U.S.A). Participants were seated comfortably in a high back chair. They were asked to exert maximal flexion, extension, and side flexion isometric contractions against the electrodynamometer which was held in a standardized position against the participants' head. For measuring isometric flexion, the dynamometer pad was placed under the participant's chin. The participant was instructed to imagine their chin rotating toward their neck as they exerted maximal pressure on the stationary dynamometer pad. For measuring isometric cervical extension, the dynamometer pad was positioned just below the occipital protuberance. Participants were instructed to imagine rotating their head to look upwards as they pressed into the stationary pad. For isometric side flexion, the dynamometer pad was positioned directly above the ear, against the temporal bone. Participants were instructed to imagine moving their ear towards their shoulder as they pressed against the stationary pad. All contractions were held for 5 seconds. Three contractions were repeated for each movement and the average strength for each direction calculated. A "Total Strength" variable was made which represented the summed averages of strength measurements in each direction with the equation:

Total Strength = (flexion +extension + right side flexion + left side flexion)

Cervical posture (forward head posture):

Forward head posture was measured in a method described by Raine et al. (1997) and replicated by Lee et al. (2014). Participants stood in front of a plain background looking ahead with hands at their side. A coloured marker was placed on the spinous process of C7 and a sagittal photograph was taken with a level tripod at the level of the participant's shoulder. A horizontal and vertical line were drawn on the plain background using a level to act as a true horizontal reference in the photograph. Participants were asked to stand comfortably and wore a blindfold to protect their identity. From the photograph, a saggital-C7-targus angle was calculated by measuring the angle between a line from the targus of the ear to C7 spinous process and a horizontal line through C7. Angle calculations were performed using AutoCAD software. It has been reported that normal healthy adults should have a C7-targus angle between

49 degrees and 59 degrees (Lee et al.,2014). Angles less than this indicate forward head posture (Lee et al., 2014).

Cervical Joint Position Error (JPE) measures:

Participants were seated comfortably in a high back chair that prevented trunk rotation. Cervical joint position error was examined using the Polhemus Liberty^{TM} system also used for cervical range of motion evaluation. The sensor was secured to the top of the head on the headband of the noise cancelling headphones used to deliver an auditory tone that cued the participant when to rotate their head. Participants were asked to orient their head to both a 30-degree rotation to the right and left as well as to a subjective straight-ahead position (neutral position where the participant feels their head is directly in line with their trunk facing forward). Participants practiced relocating these positions with and without vision until they felt comfortable performing the task. Participants were given the mental cue of imagining a clock face when relocating the 30-degree rotation orientations. In this cue they were instructed to visualize their nose representing a clock hand and 30 degrees to the right being the 1 o’clock position and 30 degrees to the left being an 11 o’clock position. During collection, participants performed 3 head rotations to the left and right before returning to subjective straight ahead. This position represented the starting position and the reference for SSA for each subsequent trial. At the sound of a tone participants were instructed to rotate their head as accurately as possible to a 30-degree position to the L, then return to subjective straight ahead at the sounding of the next tone as accurately as possible. Under the control condition, participants performed 30 relocations of each orientation (30 degrees to L, 30 degrees to R, SSA following left head rotation and SSA following R head rotation). Under the experimental condition, vibration was applied to either the R or L posterior-lateral neck muscles as described below immediately following 10 non vibrated trials. Immediately after the 10 vibration trials, 10 recovery trials were performed. The order of R vs L sided vibration was randomly determined.

<u>Impact of Vibration on Static SSA</u>

The impact of posterior lateral neck vibration on maintaining subjective straight ahead was examined under right and left sided vibration conditions. Participants assumed SSA position while seated comfortably in a high back chair following three head rotations. Participants were instructed to maintain this SSA position for 30 seconds without vibration, 30 seconds during vibration applied to either the right or left posterior lateral neck muscles and for 1 minute immediately following vibration offset. The order of right and left sided vibration was determined randomly. Impact of vibration was determined by visually examining the JPE wave form to look for the patterns of vibration impact observed and described in study 2 and also by calculating the area under the curve of SSA displacement to compare displacement differences between no vibration, vibration and recovery conditions.

Reproducibility of cervical JPE performance and vibration induced effects was evaluated by examining cervical JPE and the impact of vibration on a second testing day 1 week apart.

4.2.4. Protocol

At the start of test day 1 participants' weight (kg), height (cm), neck circumference (cm) and length (distance between occipital protuberance and C7 in cm) were measured. An adhesive marker was adhered to the spinous process of C7 (determined by palpation) and participants were then asked to stand comfortably beside a blank background and the sagittal photograph used to examine cervical posture was taken as described above. Following the postural photograph, participants were asked to sit comfortably in a chair and isometric strength testing was performed as described above. After this, participants were instructed on active ROM movements and the noise cancelling headphones with the attached motion tracking sensor and blindfold were applied. Participants completed the ROM movements in groupings of flexion, extension, side flexion and rotation always returning to subjective neutral after each movement. Participants were then instructed on the cervical JPE task to both neutral and 30 degrees of head rotation to the L and R. Participants always started with rotation to the L. After the control trials were performed without vibration, the vibration unit was applied to either the R or L dorsolateral neck muscles as described above. The order of this was randomized, as was the order of performance of either the active JPE task or the static JPE task. A 5-minute break was provided between any vibration trials to act as a washout period and ensure no vibration induced effects remained.

Testing on day one took approximately 1 hour and 30 minutes. On day 2 (1 week later) participants repeated the JPE tasks only and this took approximately 30-40 minutes.

4.2.5 Analysis:

Statistical analysis was performed using SAS 9.2 software. A significance value of alpha =.05 was used for all analysis in this study.

<u>Cervical JPE calculation</u>:

For the purposes of this study the roll, pitch and yaw orientation values provided by the motion tracking sensor were mathematically combined into a global JPE value. For JPE to SSA the equation was:

$$\text{JPE (SSA)} = \sqrt{[(\text{roll})^2 + (\text{pitch})^2 + (\text{yaw})^2]}$$

For JPE to 30 degrees the equation was:

$$\text{JPE (30)} = \sqrt{[(\text{roll})^2 + (\text{pitch})^2 + (30 - \text{ABS}(\text{yaw}))^2]}$$

In this equation the (30-ABS(yaw)) portion applies to the calculation of error based on the relocation target of 30 degrees of head rotation to either the R or L.

4.2.5.1 Examining within subject differences in cervical JPE across trials, test day, rotation side and vibration side:

Control Condition:

Two 3 factor repeated measures ANOVAs were performed to assess for differences in JPE(SSA) and JPE(30) in the control condition (no vibration applied across the 30 trials) related to the factors of rotation direction (side), multiple trials (group: first 10 trials, second 10 trials and third 10 trials) and day (day 1 vs day 2). The results are presented in Table 5.1.

Experimental Condition:

Two 4 factor repeated measures ANOVAs were performed to assess for differences in JPE(SSA) and JPE(30) in the experimental condition for factors of group (no vibration, vibration and recovery trials), testing day 1 vs day 2 (day), vibration side (task) or rotation direction (side). (Table 5.2) Post hoc comparisons were then performed to examine any significant findings.

4.2.5.2 Examining between subject differences in cervical JPE and response to vibration with person specific characteristics.

Relationship between JPE and person specific characteristics

For each participant, an impact of vibration and impact of recovery variable was calculated for JPE(SSA) and JPE(30) means and SDs by using the equations below:

Impact of Vibration on JPE(SSA) = [Vib JPE(SSA)]- [NoVib JPE(SSA)]
Impact of Vibration on JPE(SSA) SD = [Vib SD (SSA)]- [No Vib SD (SSA)]

Impact of Vibration on JPE(30) = [Vib JPE(30)]- [NoVib JPE(30)]
Impact of Vibration on JPE(30) SD = [Vib SD (30)]- [No Vib SD (30)]

Impact of Recovery on JPE(SSA) = [Rec JPE(SSA)]- [NoVib JPE(SSA)]
Impact of Recovery on JPE(SSA) SD = [Rec SD (SSA)]- [No Vib SD (SSA)]

Impact of Recovery on JPE(30) = [Rec JPE(30)]- [NoVib JPE(30)]
Impact of Recovery on JPE(30) SD = [Rec SD (30)]- [No Vib SD (30)]

The relationship between cervical JPE and person specific characteristics was examined by scatter plot and correlational analysis. Scatter plots were created, and Pearson correlation coefficients were calculated for JPE(SSA), SD and impact of vibration on JPE(SSA) and SD as they related to the factors of interest: cervical ROM, cervical strength, C7-targus angle, neck circumference and BMI.

Impact of vibration on static maintenance of SSA

Maintenance of static SSA with and without R of L posterior neck vibration was examined by visually inspecting JPE(SSA) performance under R and L vibration and between day 1 and day 2 across each participant to look for similarities in waveform performance. To quantify JPE displacement during the no vibration (first 30 seconds) vibration (second 30 seconds) and recovery (post vibration) period of the task the area under each single vector curve was calculated. Between subject differences in static and dynamic cervical JPE performance, and the impact of vibration on JPE were investigated using scatter plots. These plots compared static JPE(SSA) and dynamic JPE(SSA) by participant as well as the impact of vibration on JPE by participant. Impact of vibration during the static task was calculated as:

Impact of Vibration on static SSA = [(area under curve (Vib)]- [(area under curve (No Vib)]

4.3 Results:

4.3.1 Objective 1: Within subject consistency

In the control condition, (no vibration across all 30 trials) the results of the two 3 factor repeated measures ANOVAs showed that across participants there was no statistically significant difference in JPE(SSA) or JPE(30) across testing day, multiple trials (first 10, second 10 and third 10 trials), or rotation side to/from the R or L (side). (Table 4.1 and Figure 4.2) For JPE(30) in the control condition, the ANOVA did reveal a significant interaction between Group and Side (p=.0397). Subsequent investigation showed a slightly higher JPE(30) in the third 10 trials on day 2 vs day 1. Overall, participants demonstrated significantly larger JPE and greater variability (larger SD), when relocating a 30-degree rotation target (9.98 +/- 4.27 degrees) versus a SSA target (3.44 +/- 1.49 degrees).

In the experimental condition, in which R or L sided neck vibration was applied during the middle 10 trials, the 4-factor repeated measures showed no significant differences in JPE(SSA) or JPE(30) across testing day (Day) or rotation side (Side). For JPE(SSA) and JPE(30) there was a significant difference when comparing between Groups of trials (no vibration,

vibration and recovery) as expected. Post hoc single factor repeated measure ANOVAs were performed with comparisons to explore mean differences between no vibration, vibration and recovery trials. For JPE(SSA) there were statistically significant differences between all groups of trials (no vibration (3.30 +/- 1.68 degrees), vibration (5.23 +/- 2.55 degrees) and recovery trials (4.30 +/- 2.03 degrees). For JPE(30) there was a statically significant difference only between no vibration (10.45 +/-4.98 degrees) and recovery (9.59 +/- 5.42 degrees) trials, but not between either no vibration or recovery and vibration (10.6 +/-5.86) trials. (Table 4.2 and Figure 4.2). Due to the lack of significant differences in JPE across day, side and task in the control and experimental conditions, results were collapsed across these factors.

Control (No Vibration)			
JPE(SSA)		**JPE(30)**	
Factor	**p-value**	**Factor**	**p-value**
Group: First 10 Trials Second 10 Trials Third 10 Trials	.2706	Group: First 10 Trials Second 10 Trials Third 10 Trials	.4912
Side: Following L rotation following R rotation	.5682	Side: Rotation to L 30 degrees rotation to R 30 degrees	.3435
Day Day 1 Day 2	.8772	Day day 1 day 2	.8671
Group*Side	.0524	Group*Side	.5332
Group*Day	.4940	Group*Day	.0397*
Side*Day	.6332	Side*Day	.5488
Task*Side*Day	.4517	Task*Side*Day	.8136

Table 4.1: Results from the three factor ANOVAs comparing JPE(SSA) and JPE(30) in the control condition across factors (Day, Side and Group). *Shaded boxes represent statistical significance with *p*<.05.

Experimental (Vibration)			
Independent Variable: JPE(SSA)		**Independent Variable JPE(30)**	
Factor	**p-value**	**Factor**	**p-value**
Group: No vibration (First 10 trials) Vibration (Second 10 trials) Recovery (Third 10 trials)	<.0001*	Group: No vibration (First 10 trials) Vibration (Second 10 trials) Recovery (Third 10 trials)	.0114*
Task: control L vibration R vibration	.0783	Task: control L vibration R vibration	.0514
Side: following L rotation following R rotation	.6844	Side: rotation to L 30 degrees rotation to R 30 degrees	.9844
Day day 1 day 2	.8465	Day day 1 day 2	.4493
Task*Side	.1968	Task*Side	.0192*
Task*Day	.2077	Task*Day	.1527
Side*Day	.4274	Side*Day	.1237
Task*Side*Day	.1850	Task*Side*Day	.9091
Task*Group	.0021*	Task*Group	.5807
Side*Group	.7503	Side*Group	.7310
Day* Group	.1496	Day* Group	.9695
Side*Task*Group	.0250*	Side*Task*Group	.1089
Task*Day*Group	.3021	Task*Day*Group	.3745
Side*Day*Group	.5776	Side*Day*Group	.0683
Side*Day*Group*Task	.4363	Side*Day*Group*Task	.2093

Table 4.2: Results from the four factor ANOVAs comparing JPE(SSA) and JPE(30) in the experimental condition across factors. (Day, Side, Task and Group).

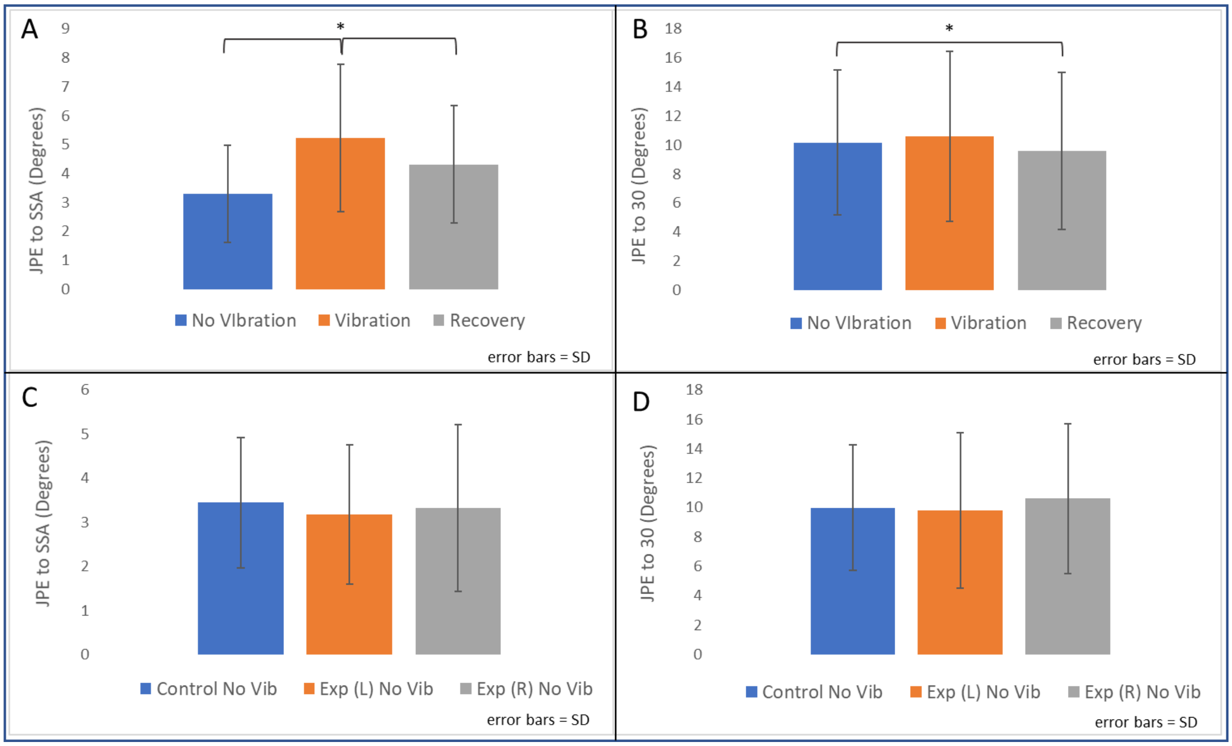

Figure 4.2: Overall cervical joint position error to subjective straight ahead **(A)** and cervical joint position error to 30 degrees **(B)** plotted by group (no vibration, vibration and recovery trials) collapsed across participant, day, and vibration side). Box **C** and **D** show the means of the first 10 trials in the control condition, and the no vibration trials (trials 1-10) in the experimental (R and L sided vibration) condition collapsed across participants, day, and side of rotation).

4.3.2 Objective 2: Between subject differences in cervical JPE(SSA) and JPE(30)

Participants varied significantly from one another in cervical relocation performance. (Figure 4.3 and Table 4.3). The maximum JPE mean/SD under no vibration conditions were 4.66 /2.57 degrees for SSA and 15.81/4.49 degrees for the 30-degree target. The minimum JPE mean/SD under the no vibration conditions were 2.35/.91 degrees for SSA and 5.28/2.49 degrees for the 30-degree target. The JPE(SSA) and JPE(30) means and standard deviations under the vibration and recovery conditions by participant are presented in Table 4.4 and Figure 4.4. Under vibration conditions, the maximum impact of vibration on JPE mean/SD was 4.20/2.60 degrees for SSA and 3.97/1.57 degrees for rotation to 30-degree target.

ID	**Control cervical JPE**			
	JPE(SSA)		**JPE(30)**	
	Mean	**SD**	**Mean**	**SD**
1	4.27	1.09	6.54	2.49
2	2.91	1.18	10.25	3.20
3	2.62	1.05	14.644	2.87
4	2.52	1.16	7.42	3.57
5	3.01	.91	15.81	3.23
6	4.66	2.57	11.20	4.49
7	4.56	1.91	7.18	3.94
8	2.57	1.40	9.47	4.12
9	2.90	1.26	5.28	3.87
10	3.85	1.47	14.94	3.56
11	4.44	1.56	6.70	4.28
12	2.35	1.15	11.56	2.71

Table 4.3. Between subject differences in cervical joint position error to subjective straight ahead and 30 degrees of head rotation. Means and standard deviations are presented for each participant under No Vibration conditions.

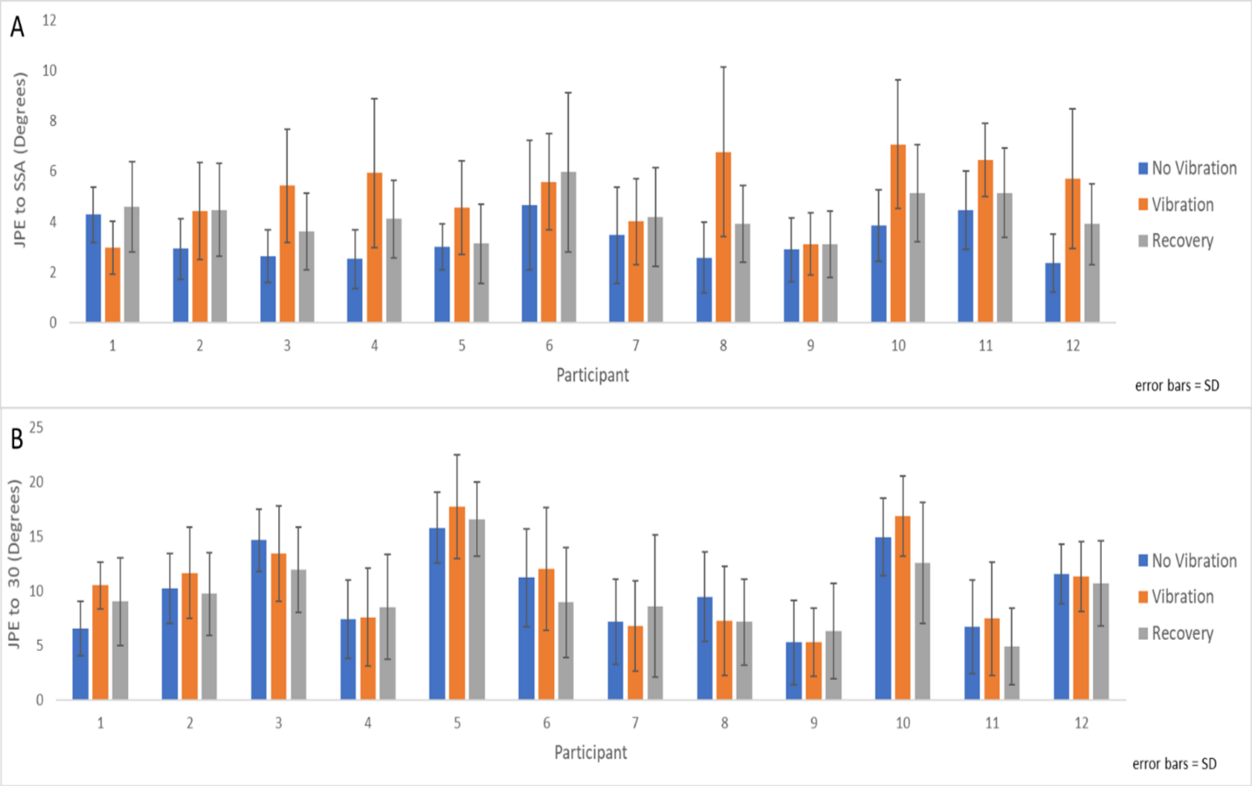

Figure 4.4 A. Between subject differences in cervical joint position error to subjective straight ahead and **B.** cervical joint position error to 30 degrees of head rotation under experimental conditions. Means are presented for JPE across no vibration, vibration and recovery trials. Error bars represent SD.

ID	Experimental cervical JPE by Participant								
	JPE(SSA)					JPE(30)			
	Group	**Mean**	**SD**	**Vibration Impact Mean**	**Vibration Impact SD**	**Mean**	**SD**	**Vibration Impact Mean**	**Vibration Impact SD**
1	No Vib	4.27	1.09	-1.31	-0.30	6.54	2.49	3.97	-0.31
	Vibration	2.96	1.04			10.50	2.17		
	Recovery	4.59	1.79			9.02	4.16		
2	No Vib	2.91	1.18	1.50	0.73	10.25	3.20	1.39	0.97
	Vibration	4.42	1.93			11.64	4.17		
	Recovery	4.46	1.85			9.74	3.79		
3	No Vib	2.62	1.05	2.79	1.29	14.64	3.20	-1.19	1.51
	Vibration	5.42	2.25			13.46	4.38		
	Recovery	3.61	1.53			11.94	3.93		
4	No Vib	2.52	1.16	3.41	1.06	7.42	3.57	0.18	0.89
	Vibration	5.92	2.95			7.60	4.46		
	Recovery	4.10	1.53			8.53	4.83		
5	No Vib	3.012	.911	1.53	1.22	15.81	3.23	1.92	1.57
	Vibration	4.45	1.86			17.73	4.80		
	Recovery	3.12	1.57			16.58	3.39		
6	No Vib	4.66	2.57	0.92	-0.86	11.20	4.49	0.80	1.12
	Vibration	5.58	1.92			12.00	4.49		
	Recovery	5.69	3.17			8.95	5.05		
7	No Vib	.346	1.91	0.54	-0.23	7.18	3.94	-0.38	0.20
	Vibration	4.00	1.76			6.80	4.15		
	Recovery	4.17	1.96			8.59	6.52		
8	No Vib	2.57	1.40	4.20	2.60	9.47	4.12	-2.23	0.90
	Vibration	6.77	3.36			7.24	5.02		
	Recovery	3.92	1.52			7.15	3.94		
9	No Vib	2.89	1.26	0.21	-0.12	5.28	3.87	-0.00	-0.72
	Vibration	3.10	1.23			5.28	3.14		
	Recovery	2.31	1.31			6.33	4.37		
10	No Vib	3.85	1.41	3.21	0.61	14.94	3.56	1.95	0.11
	Vibration	7.06	2.55			16.90	3.67		
	Recovery	5.12	1.92			12.57	5.52		
11	No Vib	4.44	1.56	2.01	-0.02	6.70	4.28	0.74	0.91
	Vibration	6.45	1.46			7.45	5.19		
	Recovery	5.13	1.77			4.92	3.51		
12	No Vib	2.35	1.15	3.35	1.14	11.56	2.71	-0.27	0.50
	Vibration	5.70	2.77			11.29	3.21		
	Recovery	3.90	1.61			10.70	3.89		

Table 4.4 Means, SD and impact of vibration on mean and SD for cervical joint position error to subjective straight ahead and 30 degrees of head rotation by participant.

4.3.3 Objective 2: Between subject Relationships between JPE means and SD and impact of vibration on JPE means and SD

Between subject relationships between JPE(SSA) mean and SD and the impact of vibration on these means and standard deviations was explored by plotting these variables for each participant, against each other in multiple scatter plots (Figure 4.5). The Pearson correlation coefficients for each comparison are presented in Table 4.6. For the purposes of this study, the strength of Pearson correlation coefficients has been quantified as per Table 4.5 (Akoglu, 2018). JPE(SSA) showed a moderate positive correlation with SD (r=.611) and a strong negative correlation with the impact of vibration on both recovery (r= -.781) and SD (r=-.754). There were strong positive correlations between the impact of vibration on JPE(SSA) and the impact of vibration on SD and recovery (r=.775, r=.828 respectively) and there was a very strong positive correlation between impact of vibration on recovery and the impact of vibration on SD (r=.920).

Correlation Coefficient		**Strength of Correlation**
+1	-1	Perfect
+.9 to 1	-.9 to -1	Very Strong
+.7 to .9	-.7 to -.9	Strong
+.4 to .7	-.4 to -.7	Moderate
+.1 to .4	-.1 to -.4	Weak

Table 4.5 Pearson Correlation Coefficient Interpretation

	JPE(SSA)	JPE(SSA)SD	Vib Impact	Rec Impact	SD vib impact
JPE(SSA)	**1**				
JPE(SSA)SD	.611	**1**			
Vib Impact	-.535	-.1685	**1**		
Rec Impact	-.781	-.595	**.828**	**1**	
SD Vib Impact	-.753	-.559	.775	.920	**1**

Table 4.6. Pearson correlation coefficients for comparisons between cervical joint position error to subjective straight ahead mean and standard deviation, impact of vibration on cervical joint position error mean and standard deviation and impact of vibration on cervical joint position error during recovery trials. Shaded boxes represent statistically significant coefficients ($p \leq .05$).

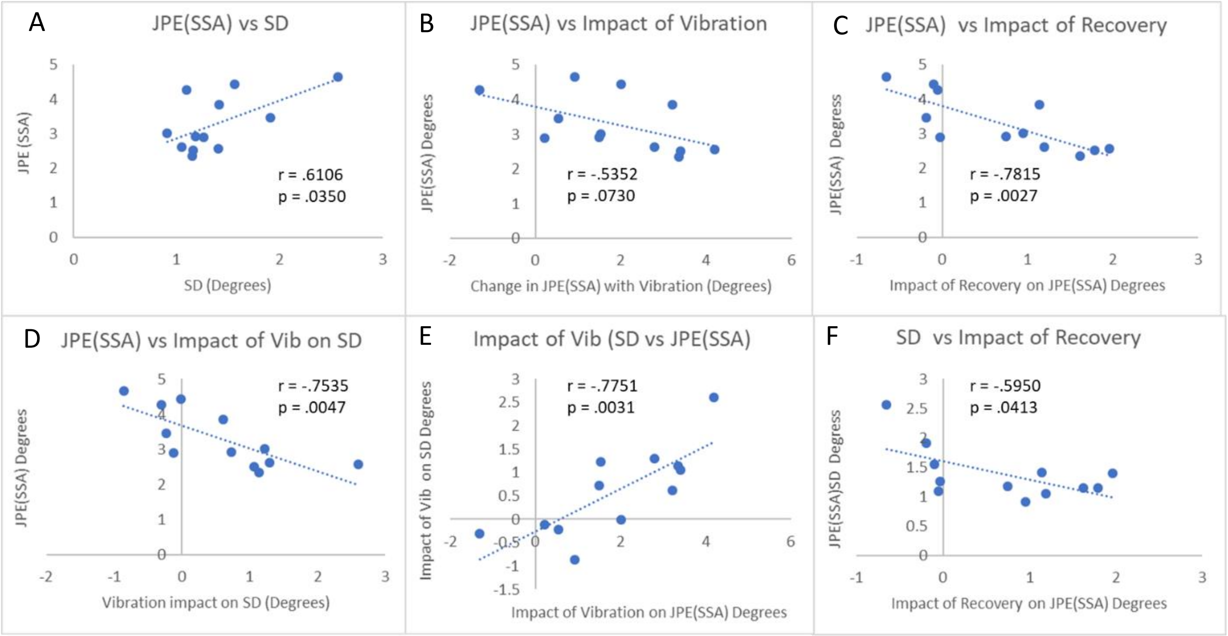

Figure 4.5 Scatter plots comparing cervical JPE(SSA) mean and SD to impact of vibration on JPE(SSA), recovery and SD. **A.** Comparison of JPE(SSA) and SD showing a moderate positive relationship. **B.** Comparison of JPE(SSA) and the impact of vibration on JPE(SSA) showing a

non-statistically significant negative relationship. **C.** Comparison of JPE(SSA) and the impact of vibration on recovery showing a strong negative relationship. **D.** Comparison of JPE(SSA) and the impact of vibration on SD showing a strong negative relationship. **E.** Comparison of the impact of vibration on JPE(SSA) mean vs impact of vibration on SD showing a strong positive relationship. **F.** Comparison of JPE(SSA)SD vs the impact of vibration on recovery showing a moderate negative relationship.

4.3.4 Objective 2: Between subject differences: Relationships between JPE(SSA) and JPE(30) performance

This study compared the participants' performance on relocating SSA to performance on relocating the 30-degree target using scatter plots and by calculating Pearson correlation coefficients for relationships between JPE means, SDs and the impact of vibration for the SSA and 30-degree target (Figure 4.6). There was no significant relationship between performance of JPE means towards SSA and 30-degree target (r=.164) or between the impact of vibration on SD towards SSA and 30-degree target (r=.425). There was a moderate negative relationship between the impact of vibration on JPE to SSA and the 30-degree target (r=-.615). There was a strong positive correlation between SD of JPE to SSA and 30-degrees (r=.738).

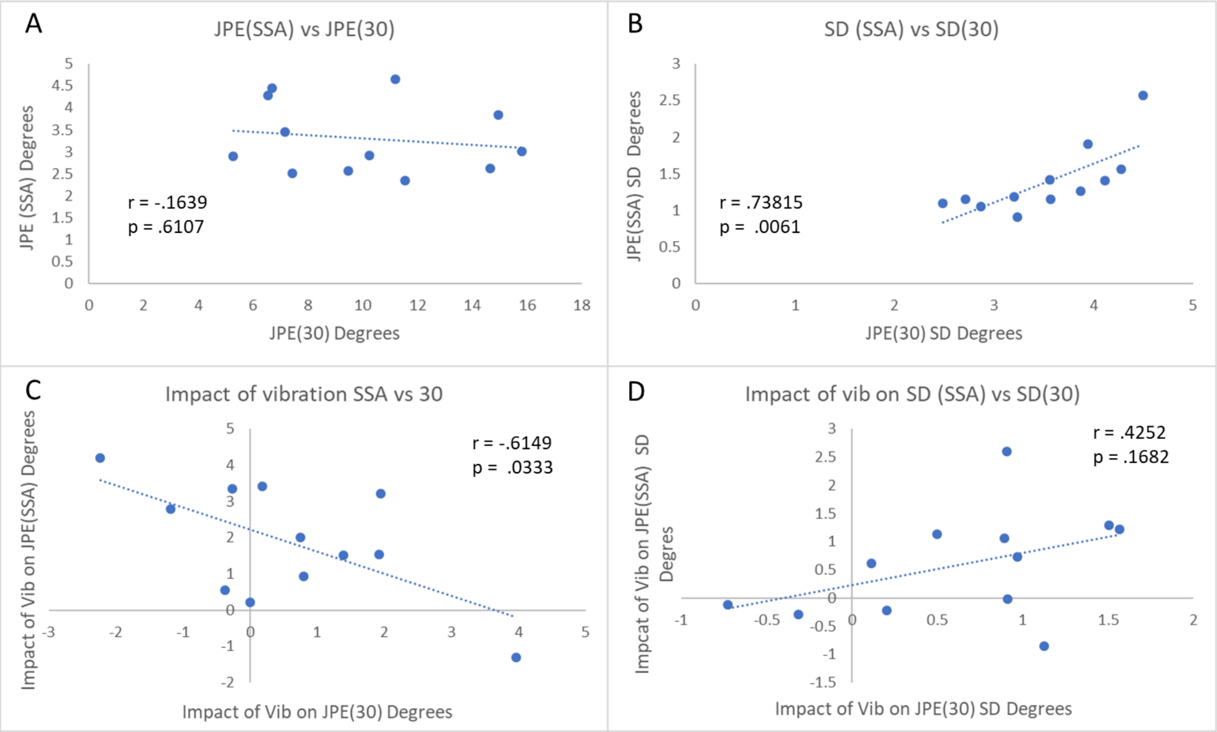

Figure 4.6 Relationships between JPE to SSA and JPE 30-degree target. **A**. Comparison between JPE(SSA) mean and JPE(30) mean showing now significant relationship. **B.** Comparison between JPE(SSA)SD and JPE(30)SD showing a string positive correlation. **C.** Comparison between impact of vibration on JPE mean between SSA and 30-degree target showing a moderate negative relationship. **D.** Impact of vibration on JPE SD between SSA and 30-degree target showing no significant relationship.

4.3.5 Objective 2: Relationship of JPE mean and variability to person specific characteristics

To examine the possibility of relationships between cervical JPE and person specific characteristics (posture, BMI, cervical flexibility, strength and circumference), JPE(SSA) means and SDs and the impact of vibration on JPE(SSA) mean, recovery mean and SD, were plotted against each person specific characteristic and Pearson correlation coefficients were calculated for each comparison (Table 4.8). Person specific characteristic measurements are presented in Table 4.7. Scatter plot comparison are presented in Figure 4.7. JPE(SSA) mean was moderately correlated with total cervical strength (r=.577) and showed strong correlation with neck circumference (r=.753). Interestingly, neck circumference was also negatively correlated with the impact of vibration on JPE(SSA) mean (r=-.690), SD (r=-.752) and recovery JPE(SSA) (r=-.759). A more detailed analysis of JPE(SSA) and cervical strength measures showed that JPE(SSA) was moderately positively correlated with both R and L side flexion strength (r=.675; *p*=.0160), r=.658 *p*=.0204) but not with cervical flexion (r=.332; p=.2917) or extension (r=.564; *p*=.0559) strength. JPE(SSA) SD was not significantly correlated with any of the variables, however it neared statistically significant relationship with total cervical strength (r=.560; *p*=.0583) and with total ROM (r=.554; *p*=.0615). BMI had a strong negative correlation with the impact of vibration on JPE(SSA) (r= -.778), and a moderate negative correlation with the impact of vibration on JPE(SSA) recovery (r=-.599). The measurement for FHP, targus angle, as well as neck length, did not have any significant relationships to JPE(SSA) mean, SD or the impact of vibration on these measures.

ID	BMI (kg/m2)	Targus Angle (degrees)	Total Strength (kgf)	Flexion Strength (kgf)	Extension Strength (kgf)	Right SF Strength (kgf)	Left SF Strength (kgf)	Neck Length (cm)
1	30.57	56.04	98.20	18.13	30.90	22.63	26.53	18.0
2	21.22	58.50	24.97	6.23	7.27	5.93	5.53	14.0
3	20.42	49.49	57.13	13.96	16.90	14.00	12.27	14.0
4	21.46	59.59	54.50	14.43	15.97	11.73	12.37	14.2
5	32.64	56.42	44.13	12.12	10.50	11.47	10.03	14.6
6	25.36	53.89	127.9	32.5	39.00	25.87	30.53	14.2
7	23.23	57.97	48.13	14.97	10.67	10.83	11.67	13.2
8	23.05	57.28	82.90	21.67	21.57	17.27	20.40	16.5
9	29.41	40.44	87.70	30.60	21.07	16.90	19.13	12.3
10	19.31	57.40	45.10	12.90	10.63	11.70	9.87	13.2
11	24.43	57.87	87.97	21.37	23.73	20.83	22.03	12.4
12	22.75	48.78	57.27	19.77	16.37	11.60	9.53	12.6

ID	Neck Circumference (cm)	Total AROM (degrees)	Flexion ROM (degrees)	Extension ROM (degrees)	Left Rot ROM (degrees)	Right Rot ROM (degrees)	Left SF ROM (degrees)	Right SF ROM (degrees)
1	41.2	286.04	31.97	45.12	64.93	68.19	53.02	40.81
2	30.5	348.05	52.53	48.73	77.15	72.82	47.55	49.27
3	32.4	319.53	43.77	36.26	81.30	69.41	41.21	47.59
4	31.8	318.311	32.10	52.10	65.54	80.43	45.39	42.75
5	33.3	351.25	47.57	58.13	71.51	84.48	48.23	41.34
6	37.5	450.19	72.73	68.93	99.70	93.96	53.94	60.95
7	35.5	330.77	48.96	64.63	66.13	96.77	45.67	35.61
8	31.5	445.74	77.96	102.83	68.40	80.36	58.66	57.53
9	39.5	328.21	40.64	65.23	61.32	72.89	42.13	45.81
10	36.7	334.99	49.53	58.41	78.93	71.16	46.18	31.79
11	39.0	415.54	77.56	61.47	78.46	87.30	50.15	59.61
12	33.0	395.45	70.82	70.03	73.20	79.33	46.84	55.22

Table 4.7: Person specific characteristic measurements by participant.

	BMI	Targus Angle	Total ROM	Total Strength	Flex Strength	Ext Strength	L SF Strength	R SF Strength	Neck Circ
JPE(SSA)	.3726	.2613	.1630	.5774	.33021	.5646	.6557	.6750	.7532
JPE(SSA)SD	.0803	.1158	.5543	.5600	.5610	.5264	.5404	.5036	.2972
Impact Vib	-.7783	.1803	.3957	-.3415	-.2173	-.3177	-.4142	-.3629	-.6900
Impact Rec	-.5989	.1369	.0009	-.5198	-.4478	-.4575	-.5588	-.5370	-.7517
SD Vib Impact	-.5186	.6774	.1522	-.4450	-.3946	-.4040	-.4595	-.4503	-.7589

Table 4.8: Pearson correlation coefficients for comparisons of JPE(SSA), SD and impact of vibration and recovery to person specific characteristics. Dark shaded boxes represent relationships reaching statistical significance (p≤ .05)

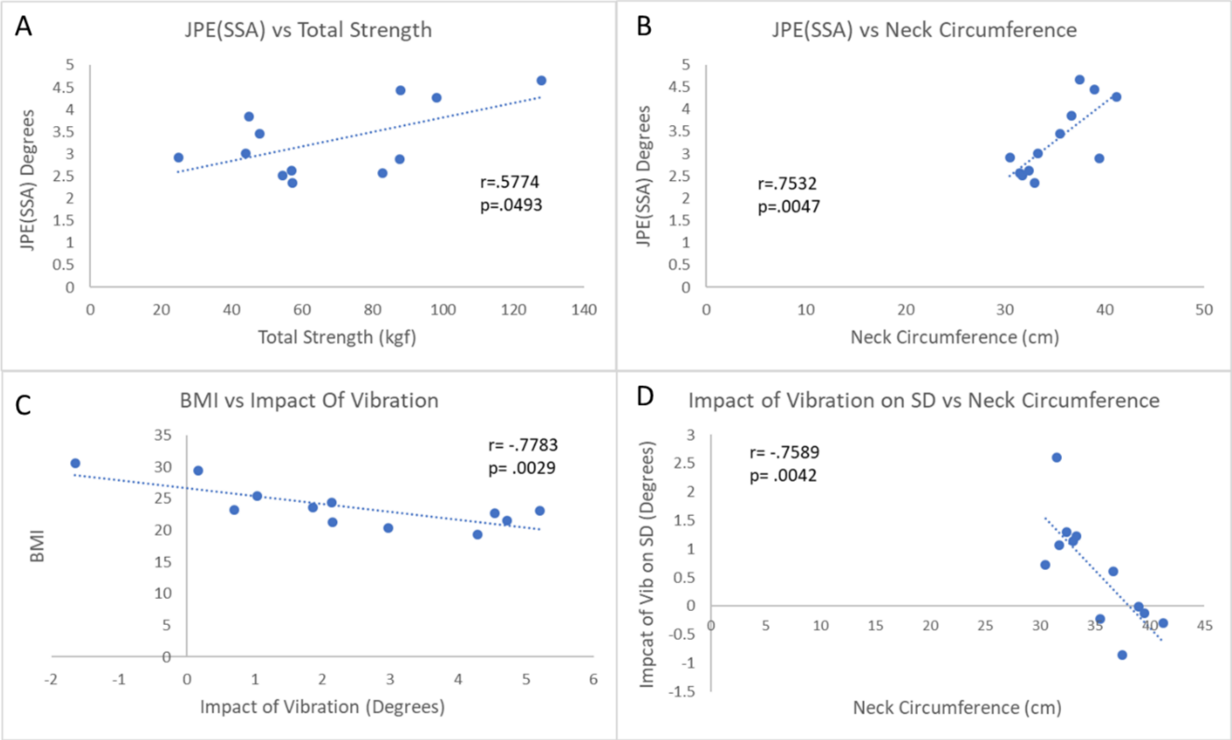

Figure 4.7: Selected scatterplots between JPE(SSA) mean, SD, impact of vibration on JPE(SSA)mean and SD and person specific characteristics. **A**. Comparison of JPE(SSA) and total cervical strength showing a moderate positive correlation. **B**. Comparison of JPE(SSA) and neck circumference showing a strong positive correlation. **C.** Comparison of BMI vs Impact of

vibration on JPE(SSA) showing a strong negative correlation. **D**. Comparison of neck circumference and impact of vibration on SD showing a strong negative correlation.

4.3.6 Objective 1 and 2: Within and between subject differences in Static JPE(SSA)

When participants were asked to maintain static SSA without, with and following R or L neck vibration, the JPE(SSA) tracings produced from the Polhemus data showed between and within subject differences in performance when compared across day and by side. Upon visual inspection, most participants demonstrated a similar pattern of response to vibration on the R when compared to the L and between Day 1 and Day 2 although some variability was seen in the amplitude of displacement within individual performance as is shown below (Figure 4.8). Some participants, however, did show additional variation in their visual pattern of response in which the pattern or response to vibration appeared to differ by vibration side but remained relatively consistent across testing day (Figure 4.9).

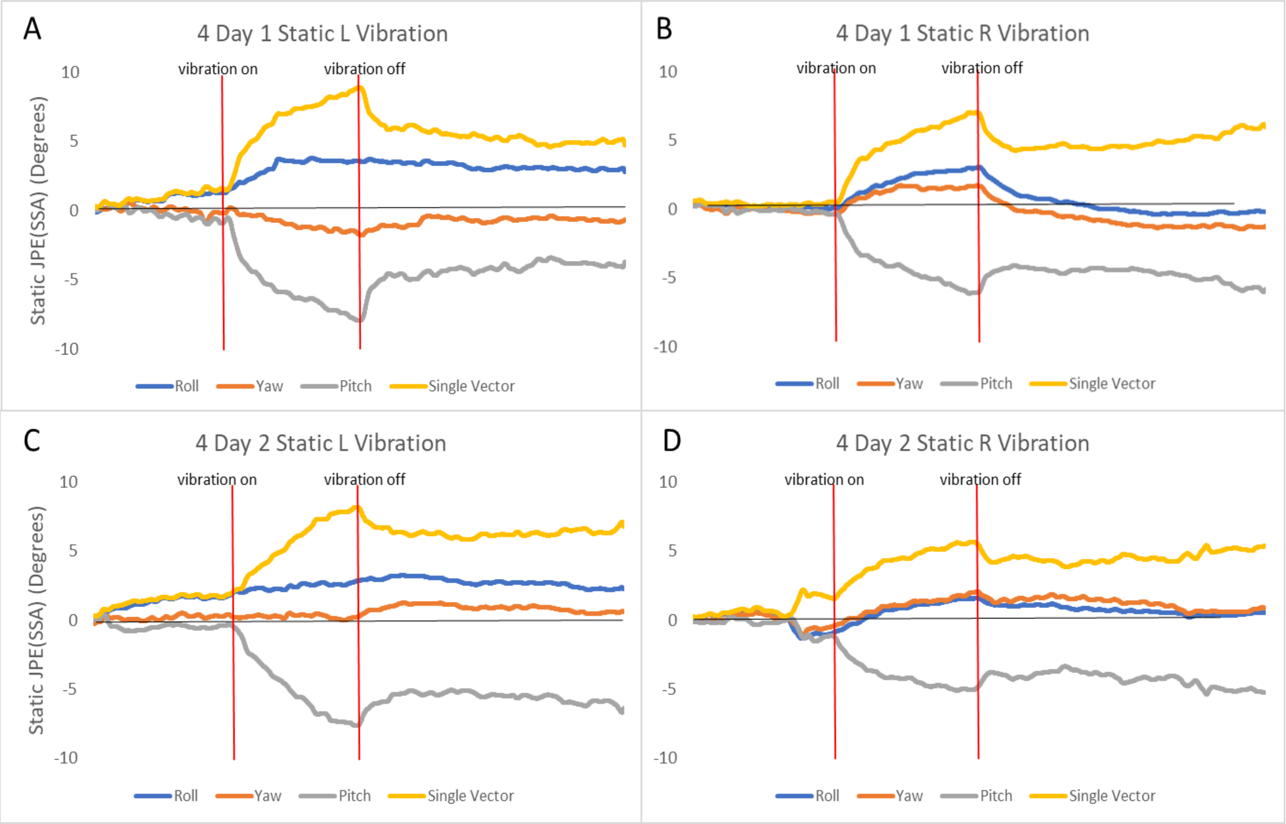

Figure 4.8: Example of Static JPE(SSA) for relatively consistent pattern of performance across vibration side and day for a single subject (Participant 4) **A.** Day 1 Left side vibration **B.** Day 1 Right side vibration **C.** Day 2 Left side vibration **D.** Day 2 R right side vibration.

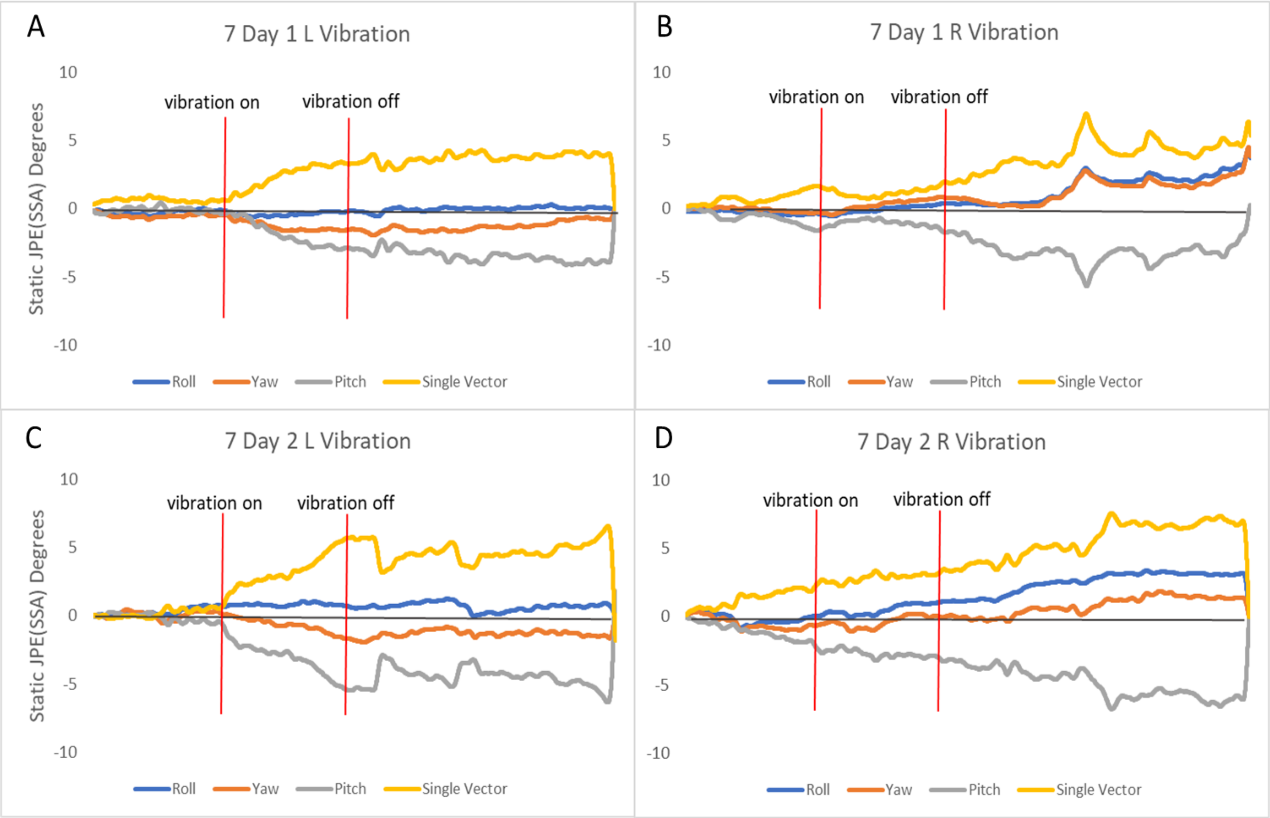

Figure 4.9: Example of Static JPE(SSA) comparing performance by Day and Side of vibration for a single subject (Participant 7), Demonstrates inconsistent performance by side, with the L side showing a response to vibration on both testing days but the R side showing little response to vibration. **A**) Day 1 Left side vibration, **B**) Day 1 Right side vibration **C**) Day 2 Left side vibration and **D**)Day 2 Right side vibration.

Quantifying the static JPE(SSA) by calculating the area under the curve of each trial also revealed differences in maintaining SSA without vibration, with vibration and following the offset of vibration. Averages were calculated by collapsing across day and vibration side by participant and are presented in Figure 4.10.

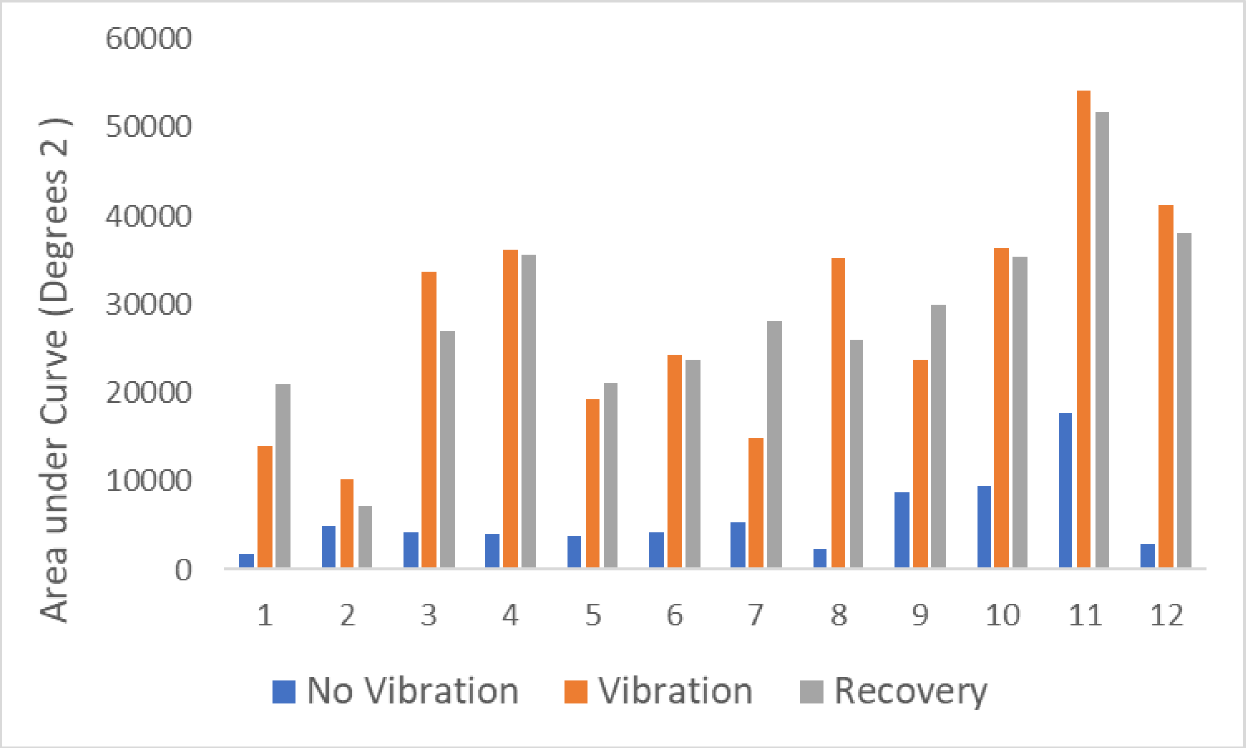

Figure 4.10. Between subject differences in static JPE(SSA) calculated as the area under curve for no vibration, vibration and recovery conditions. Averaged across day and side of vibration.

To further evaluate the relationship between JPE(SSA) performance during the dynamic and static task scatter plots were constructed to compare both JPE(SSA) and the impact of vibration and recovery. A Pearson correlation coefficient calculated between dynamic and static JPE(SSA) and impact of vibration on JPE(SSA) showed no statistically significant relationship between static and dynamic JPE(SSA) under no vibration condition (r= .427; p=.1167) and a strong positive relationship when comparing the impact of vibration on JPE(SSA) in the dynamic and static tasks (r=.755 p=.0046) (Figure 4.11).

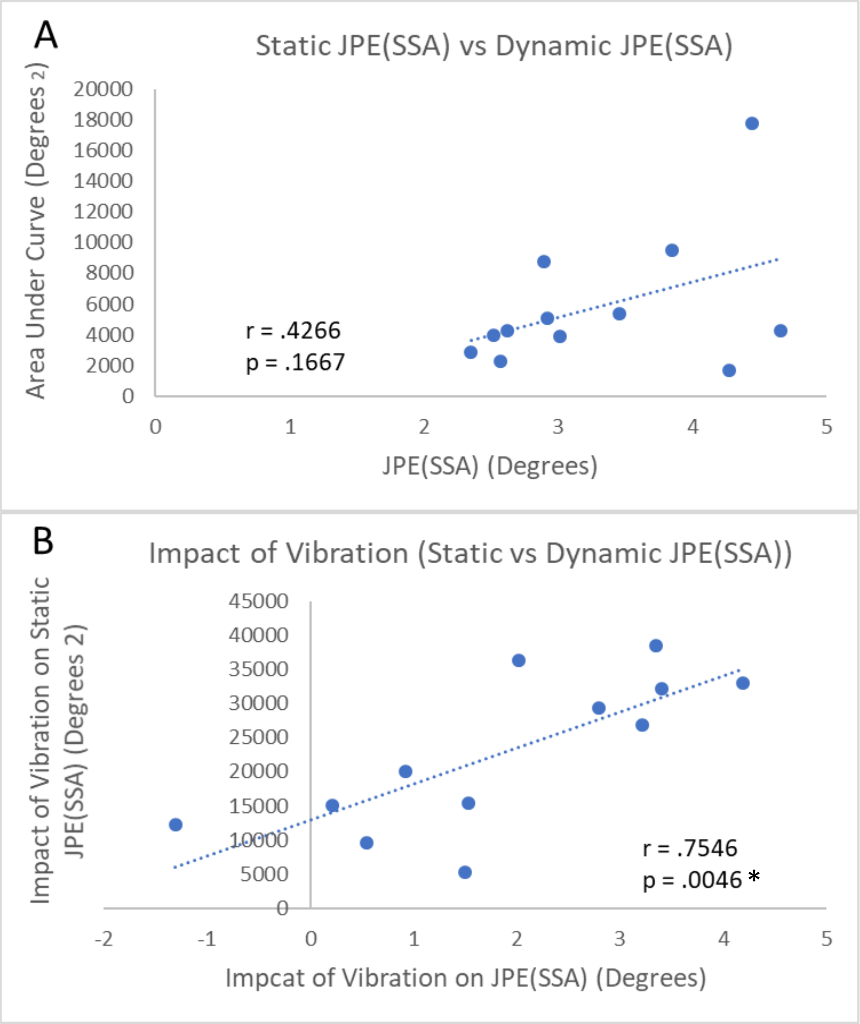

Figure 4.11: Comparisons between static and dynamic cervical JPE and Impact of vibration. A Scatter plot comparing JPE(SSA) between dynamic and static tasks. B Scatter plot comparing Impact of vibration on JPE(SSA) between dynamic and static tasks. Pearson correlation coefficient r values and significance p values indicated within each plot.

4.4 Discussion

The aim of this study was two-fold. The first objective was to explore the within subject consistency of cervical joint position error to a subjective straight ahead and a 30 degree target in a cervical relocation task under no vibration, vibration and recovery (post vibration) conditions when performed over multiple trials, following rotation to either the R or L side, under R or L posterior neck vibration conditions, and across two separate testing days. Secondly, this study aimed to explore whether between subject variability in performance of the cervical relocation task (JPE mean and SD) related to the extent to which vibration impacted performance of the task, or to person specific characteristic such as BMI, cervical ROM, cervical strength, circumference and posture.

4.4.1 Within subject consistency of cervical JPE

The results of the current study showed that across participants, joint position error (JPE) in relocating both a subject straight ahead (SSA) and 30-degree rotation target remained consistent regardless of trial grouping (first, second, or third group of 10 trials under the control condition), direction of head rotation (R vs L), test day (day 1 vs day 2) or during the experimental condition, vibration side (R vs L). These findings suggest that overall, repositioning performance is robust. The study findings of consistent JPE for relocating SSA following a R or L head rotation is supported by Pinsault et al. (2008) who reported no significant difference in JPE to SSA using the original version of the cervicocephalic relocation task by Revel et al. (1994). In the study by Pinsault et al. (2008) their paper, they also suggested the use of 8 to 10 trials to achieve optimal performance consistency. The mean and SD for JPE(SSA) in this study was 3.30 +/- 1.68 degrees which is similar to that reported by Pinsault et al. (2008) who reported absolute JPE of 2.7 and variable error of 1.5 degrees. Similarly, Revel et al. (1994) and Minguet et al. (1991) reported cervical JPE of 2.7 and 3.1 degrees respectively.

4.4.2 Consistency of cervical JPE when relocating SSA vs 30-degree rotation target

In comparing JPE to either SSA or 30-degree rotation target, participants demonstrated significantly better accuracy and precision in relocating SSA. Nearly every participant consistently undershot the 30-degree rotation target in every trial, despite practicing prior to collection. During practice, however, participants were not given any feedback about their performance, aside from the mental visualization cue of the clock face described above. The significantly larger JPE means and SDs observed for the 30-degree relocation target compared to relocating SSA may be due to the familiarity of the task. The task requirements of daily life require repeatedly assuming neutral head on trunk orientation for a great many things like eating, walking, driving or conversating. By comparison, assuming a 30-degree head rotated position is not a common task. Head rotations would more likely be directed to an auditory or visual stimulus of interest rather than towards a specified degree angle target. Given the high mean error and SD values in relocating the 30-degree target, as well as the lack of significant difference between no vibration and vibration conditions seen in our analysis, the relocation task to SSA was considered the more useful of the two tasks to quantifying and comparing cervical JPE in participants. Interestingly however, although there was no statistically significant correlation between JPE(SSA) and JPE(30) means, the strong positive correlation between JPE(SSA)SD and JPE(30) SD suggests their precision remained relatively consistent. This provides support in evaluating both the JPE mean and variability when employing a cervical relocation task.

4.4.3 Between subject comparisons: Relationship between JPE mean, SD and impact of vibration on the mean and SD

Overall, the results of this study revealed that individuals who were less accurate in relocating SSA were also less precise as was observed in the moderate positive correlation between JPE(SSA) mean and SD. Additionally, the negative relationship between JPE(SSA) mean and the impact of vibration on SD suggests that participants who were more accurate relocating SSA under no vibration conditions, experienced a larger decrease in precision when relocating SSA during neck vibration. In keeping with these findings, the strong negative correlation between JPE(SSA) and impact on recovery also suggests that participants with better accuracy in locating SSA under no vibration conditions, have poorer accuracy following the offset of vibration than those who are initially less accurate. Taken together, these findings would suggest that accuracy and precision performance in relocating to a straight-ahead position are linked and that individuals who are more accurate without vibration, may be more impacted during and following neck vibration. This finding may provide evidence to suggest that individuals with better neck proprioception (less JPE and variability during a cervical relocation task) may use this proprioceptive information to a larger extent than individuals with poorer proprioception and are therefore impacted to a greater extent when this information is impaired.

4.4.4 Between subject Relationship between JPE mean, SD, impact of vibration and person specific characteristics:

Contrary to the study hypotheses, cervical JPE was not related to forward head posture. Neither cervical JPE mean, SD or the impact of vibration on these variables, was related to cervical posture (targus angle). This result partially supports that of Sajjadi et al. (2014) who also reported no significant relationship between forward head posture and cervical JPE. However, in the current study JPE(SSA) SD was not related to FHP either. The results of the current study are in contrast those of Lee et al. (2014) who did report significant decreases in head repositioning accuracy and a correlation between the degree of forward head posture and cervical joint reposition errors. Our result may have been influenced in part because of our small sample size, but also because in our sample the majority of participants had targus angles within normal limits (49 to 59 degrees) with only 2 participants (# 9 and #12) with targus angles less than 49 degrees, indicating FHP.

Again, in contrast to the initial study hypothesis, lower cervical JPE was not related to increased cervical strength and range of motion. The opposite relationship was observed, with a significant positive relationship between JPE(SSA) mean and total cervical isometric strength, more specifically R and L side flexion strength, as well as with neck circumference. These findings suggest that participants with greater neck strength and circumference were less accurate in relocating subjective straight ahead. The reasons behind these relationships remain unclear. However, in this study there was also a moderate positive relationship between neck strength and BMI, a strong positive correlation between BMI and neck circumference and a moderate positive correlation between neck circumference and neck strength. These findings indicate that individuals with higher BMI tended to have larger, stronger necks. Therefore, it is possible that these factors may all correspond with differences related to fitness. Previous research has examined the relationship between BMI, muscle strength and endurance in children. Hasan et al. (2016) examined these variables in healthy children and found that although there was a positive relationship between BMI and muscle strength in various body muscles (quadriceps, triceps, abdominals) that it was negatively related to muscle endurance. A previous investigation of lumbar spine endurance has suggested a negative relationship between spinal proprioception JPE and endurance (Reddy et al., 2012). It is possible therefore that a more telling measure would be the endurance of stabilizing musculature in the neck such as deep neck flexors longus colli and longus capitus as well as suboccipital muscles, as they represent stabilizing muscles known to have increased proprioceptor density. Future work should compare cervical JPE with strength and endurance of cervical musculature.

The variable with the greatest relationship to JPE and the impact of vibration on JPE(SSA) mean, SD and recovery, was neck circumference. The positive correlation between JPE(SSA) and neck circumference and the nearly significant relationship between JPE(SSA)SD and neck circumference was surprising but may provide support for the idea of decreased physical fitness as a factor related to higher JPE. It is known that neck circumference is related to BMI and has been suggested as a proxy measure for upper body adipose tissue deposition. (Aswathappa et al., 2013). This finding and the relationship between JPE, BMI and strength discussed above, provides some indication that perhaps individuals who are less physically fit have increased cervical JPE precision and accuracy. One possibility to be considered is that the relationship between impact of vibration and neck circumference may also represent a difference in effective vibration dosage. It should be considered that larger impact of vibration may be associated with smaller neck circumference because these necks contain less adipose tissue and therefore greater impact on the muscles.

4.4.5 Between subject differences in static vs dynamic JPE(SSA) and patterns of response to vibration:

The results of investigating the impact of vibration on static cervical JPE showed that overall, the majority of participants showed a response to vibration and most had some consistency between performance regardless of vibration side and test day. This indicates that for the most part, the change in static cervical position acquired during vibration is reproducible and not due to methodological differences. Our results also suggested that some participants' pattern of response varied between side in either amplitude or the presence of a response and that this right vs left side difference remained consistent across test day. Although methodological differences can't be entirely ruled out, the consistency of R and L vibration side differences despite testing day and randomized order for vibration side suggests possible side specific differences in some participants either in anatomy, or in the extent to which vibration impacted proprioception.

In this study, the impact of vibration on maintaining static cervical JPE and relocating SSA were examined through correlational analysis and scatter plot. The strong positive correlation between the impact of vibration on static and dynamic JPE(SSA), suggests that the impact of vibration remains consistent within a person but varies between participants. Participants who were more impacted by vibration during the static task also had increased JPE when relocating SSA during neck vibration. This finding also supports the idea that response to vibration is impacted to an extent by person specific factors which would have important potential implications to any clinical testing/evaluation.

4.5 Conclusions

The findings of this study suggest that cervical JPE in relocating SSA is consistent across multiple trials, relocation direction and multiple testing days and that the impact of neck vibration is also consistent regardless of vibration side or testing day. Additionally, the findings support the use of a subjective straight-ahead relocation target rather than a 30-degree relocation target due to the overall better precision and lower variability in locating straight ahead. The findings of this study also highlight the existence of between subject differences in cervical JPE(SSA) performance and the extent to which vibration impacts this performance. The relationship between person specific characteristics such as neck circumference strength, ROM and BMI and cervical JPE mean, SD and the impact of vibration, may be important in understanding between subject differences observed in the response to altered cervical proprioception among clinical and experimental populations.

Chapter 5 Study 4: Exploring the between subject differences in the role of neck proprioception on contributions to balance control.

5.1 Introduction

Proprioception is an important contributor to postural and spatial orientation (Horak, 2006; Peterka, 2002). Given the role of the cervical spine in supporting and orienting the head, cervical spine proprioceptive information has an important role to play in these processes in part through reflex co-ordination and higher level multisensory integration with the visual and vestibular systems (Bove et al., 2009; Treleaven et al., 2006). Studies looking at clinical populations of individuals with traumatic and non-traumatic neck pain report seemingly associated symptoms of dizziness, unsteadiness, nausea and imbalance among a proportion of these populations (Hansson et al., 2006; Wrisley et al., 2000). The term cervicogenic dizziness is used to describe these symptoms in individuals in which altered cervical afferent information is believed to be responsible (Ryan & Cope, 1955, Treleaven et al., 2008, Kristjannesn et al., 2007). However, as discussed previously, cervicogenic dizziness remains a controversial diagnosis (Brandt & Bronstein, 2001). One of the arguments against cervicogenic dizziness as a plausible explanation is the apparent disconnect between neck pain/dysfunction severity and dizziness symptoms. Not all individuals with neck dysfunction and pain will report dizziness and imbalance and the severity of the neck pain does not necessarily correspond to the severity of the dizziness. To date it remains unclear why certain individuals will experience these symptoms while others will not.

Between subject variability in the performance of any task is a certainty, and to formulate generalizable conclusions it is necessary to combine results by collapsing across subjects and examining central tendencies such as the mean. However, central tendency both within and between groups can often be less useful when exploring foundational understanding of the determinants of task performance or control mechanisms. In addition, understanding the determinants of between subject variability is also critical to advance the development of clinical tools whose meaning needs to be relevant to a specific person. Unfortunately, examining and characterizing between subject variability is less commonly reported. Cervicogenic dizziness may be an example of a symptom that benefits from better understanding of the sources of between and within subject variability. Considering the argument that not all people with neck pain will report dizziness or imbalance, understanding why certain individuals may be more susceptible to experiencing these symptoms as a result of neck dysfunction seems a logical step. Unfortunately, disentangling between subject differences in a clinical population is complex. Therefore, exploring the variability of young healthy participants in a laboratory setting is a more feasible approach.

Even among laboratory investigations into the role of cervical afferent information for balance control and spatial orientation, not all subjects respond similarly. As has been described previously in this document, among neck vibration and perception studies, in which vibration is used to stimulate muscle spindles, signalling the illusion of muscle lengthening, multiple authors have described significant between subject variability in the response to this stimulus (Biguer et al., 1988; McIntyre & Seizova-Cajic, 2007; Taylor & McCloskey, 1991). Across the studies by Biguer et al. (1988), Taylor and McCloskey, (1991) and McIntyre and Seizova-Cajic (2007), a proportion of subjects within each of the studies were either not perceptually impacted by the neck vibration stimulous or reported visual motion perceptual illusions in a different direction than the majority of participants. These studies and others point to the existence of “responders” and “non-responders” when it comes to the production of perceptual illusions during cervical muscle vibration. In Studies 2 and 3 of this thesis, between subject differences both in cervical JPE performance (mean and SD), and in the way in which participants responded to the vibration stimulus, were also identified. Study 3 of this thesis found positive relationships between JPE(SSA) and SD as well as between JPE to different targets when looking at between subject variability, suggesting that individuals who had poorer accuracy in relocating SSA also had poorer precision or were generally more variable in their cervical JPE. Additionally, participants with higher variability relocating SSA were also more variable relocating a different orientation target. Furthermore, this study indicated that individuals with increased JPE were generally impacted to a lesser extent both during vibration and following the offset of vibration. Interestingly, this study also suggested that person specific factors including total neck strength, circumference and BMI were related to cervical JPE and the impact of vibration on cervical JPE. These findings lead to the question of whether individuals who are impacted to a greater extent by cervical muscle vibration during a cervical proprioceptive spatial orientation task (return to subjective straight ahead), would also be impacted to a greater extent by vibration while performing vestibular or visually guided orientation tasks or standing balance tasks.

Previous studies have explored the relationship between patient and experimental populations with cervical proprioceptive dysfunction and vestibular and visually guided spatial orientation ability and performance on standing balance tasks. Pettorosi et al. (2015) explored the impact of altering cervical proprioception using neck vibration and muscle contraction on the perception of body orientation during a vestibular orientation task involving asymmetric whole-body rotation and position tracking error. Their study showed significant changes in vestibular driven spatial orientation during neck vibration or muscle contraction, leading to the conclusion that cervical proprioceptive information integrates and informs vestibular information for the purposes of spatial orientation perception (Pettorossi et al., 2015).

Visual perception studies in both clinical and experimental populations have also explored the impact of altered cervical afferent information on spatial orientation perception. As has been previously discussed, studies have shown that visual illusions of target movement can be elicited by vibration stimulus applied to cervical muscles while a participant is fixating on a stationary target (Biguer et al., 1988; McIntyre & Seizova-Cajic, 2007; Taylor & Mccloskey, 1991). Pointing towards this illusory moving target has shown to result in systematic target relocation error in a majority of participants in theses studies. However, the magnitude of this relocation error is variable between subjects. Visual verticality testing using the analog Rod and Frame Test or updated digital versions of this task like the Box and Dot test have also been used as a method to examine the impact of altered cervical afferent information on visual orientation perception. The original Rod and Frame test involves the orientation of an illuminated rod within a rotated frame to perceived visual vertical (Bagust, 2005). Verticality error is calculated by comparing perceived verticality and true verticality. More recently, digital versions of the Rod and Frame test have been devised for use with a computer screen or virtual reality equipment. These updated forms have been shown to be as effective in gaging visual verticality perception as the analog form and now employ rotating dots within a tilted box rather than a line or rod (Docherty & Bagust, 2010; Kawase et al., 2011; Takasaki et al., 2012). A handful of studies have suggested that individuals with neck pain, WAD, or altered cervical proprioception in response to muscle vibration, demonstrate altered visual verticality perception during these tests and it has been suggested that this type of testing could be a useful clinical tool in evaluating cervical afferent involvement in sensorimotor dysfunction (Grod & Diakow, 2002; Kawase et al., 2011; Treleaven & Takasaki, 2015).

Lastly, standing balance COP measures in clinical populations with neck pain and dizziness or WAD or experimental populations in response to neck vibration or muscle fatigue have been used to examine the impact of cervical proprioception on postural control. As has been previously discussed in this document, bilateral cervical muscle vibration imparts a forward body lean in standing balance in the absence of vision (Verrel et al., 2011; Wierzbicka et al., 1998). Similarly to the visual illusions induced by vibration, it has been reported that substantial between subject variability exists in the postural responses to cervical muscle vibration (Wierzbicka et al., 1998). Clinical populations with neck pain and dizziness or WAD have shown altered standing balance control. A recent systematic review, examining standing balance measures in these populations, identified statistically significant changes in various measures of standing balance (normal, Romberg and tandem stance positions) including COP RMS ML and AP sway, sway area and average sway velocity in all but one of the twelve studies examined (Silva & Cruz, 2013).

In summary, these studies strongly suggest that cervical proprioceptive information is integrated with visual and vestibular information for the purpose of postural control. However, what remains to be determined is whether individuals who are impacted by disruption to cervical afferent information show similar perceptual orientation effects across various sensory modality tasks including visual, vestibular, body orientation perception and standing balance. The current study, as with other studies that make up this thesis, focussed on behaviour in young healthy adults to advance our understanding of the influence of altered neck proprioception on behaviours likely dependent on such sensory information. This work is necessary foundational work before advancing studies in clinical populations.

Therefore, the objectives of this study are to:

1) Evaluate the effect of altered cervical proprioception using unilateral dorsal neck vibration, across multiple sensory perception tasks (visual, vestibular and body orientation) and standing balance.
2) Examine between subject variability in cervical JPE(SSA) (mean and SD) and its relationship to performance across the sensory perception tasks (visual, vestibular and body orientation) and standing balance.

The first hypothesis is that unilateral neck vibration, compared to non-vibration trials would result in poorer performance in each of the sensory and standing balance tasks. More specifically it is hypothesized that neck vibration will result in:

a) Increased cervical JPE to SSA as observed in previous studies in this thesis
b) Decreased standing balance control as indicated by increased sway path, and ML and AP RMS COP sway.
c) Increased elbow joint position error when relocating a 90-degree elbow position following active flexion
d) Increased error in judging visual verticality during the Box and Dot test towards the vibrated side.
e) Increased error in indicating the start position during the vestibular orientation perception task.

The second hypothesis is that individuals would vary in their relative difference between vibration and non-vibration trials but that their relative performance across the various tasks would be similar. More specifically:

a) Individuals with lower JPE in both the neck proprioception and elbow proprioception tasks without vibration will show a greater effect from neck muscle vibration on all other tasks (balance, visual, vestibular)

b) Individuals with a history involving activities and training requiring a high level of body proprioceptive skill (dance, skating, gymnastics, athletics) will demonstrated lower JPE during neck and elbow proprioception tasks.

5.2 Methods

5.2.1 Participants:

Fourteen young healthy adults were recruited for the study (5 male). The average age of participants was 24.2 years +/- 6 years. Participants were free from recent head and neck, injuries within the past year, visual problems not amenable by corrective lenses and neurological or musculoskeletal injuries that could affect balance control or inhibit the ability to rotate the head or flex the elbow at 90 degrees of shoulder abduction. This study received ethical approval by the Office of Research Ethics at the University of Waterloo.

5.2.2 Experimental Set Up

There were five tasks in this study: 1) Cervical relocation to subjective straight ahead (JPE(SSA)) 2) Elbow proprioceptive task to 90 degrees (JPE(90)), 3) Standing balance with eyes open, closed or head rotated to 5 degrees to the left (EO, EC, Rot), 4) Visual verticality task

(Box and Dot Test) and 5) Vestibular orientation task (Chair and Steering wheel task). Each task was performed with and without unilateral dorsal cervical muscle vibration. The order of these tasks was randomly chosen for each participant. A 5-minute break was provided between each task and condition (vibration, no vibration).

Participants wore a headband containing the wireless accelerometer to track their head movements, noise cancelling headphones which provided participants with a tone to indicate when to begin movement of their head or arm and custom goggles that prevented peripheral vision during the study. The vibration unit was positioned over the left splenius capitus muscle approximately 2 cm left of the midline between the cervical levels of C3 and C7 and adhered firmly to the skin using double sided tape (Figure 5.1).

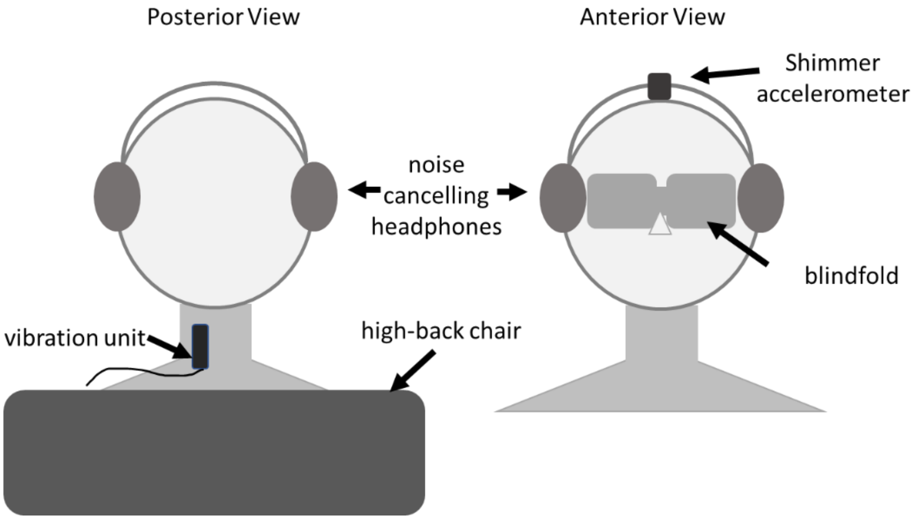

Figure 5.1: Experimental set up with vibration unit placement and accelerometer placement.

5.2.3 Protocol:

Cervical Proprioception Relocation to Subjective Straight-Ahead Task

Participants were seated comfortably in a high back chair with arms resting on their lap. In this part of the study participants were asked to adopt a neutral head position (subjective straight-ahead position) in the absence of vision. This position was the reference position and in each trial the participant was asked to try and return their head to this reference position as accurately as possible. At the sound of a tone the participant was asked to rotate their head to the right as far as was comfortable, hold for 3 seconds, before returning the reference position. 10 trials were performed with no cervical vibration, 10 trials were performed with cervical vibration applied continuously throughout the entire 10 trials and this was followed immediately by 10 trials of recovery when the vibration was turned off.

After a 5-minute rest, participants were asked to maintain a static subjective straight-ahead position for 3 minutes (1 minute no vibration, 1 minute with vibration turned on and 1 minute of recovery with vibration turned off).

Elbow Proprioception Relocation Task To 90 Degrees of Elbow Flexion:

Participants were seated comfortably in a high back chair with their right arm resting in a custom-made apparatus consisting of a low friction rotating metal arm covered in comfortable foam, pivoting on a stable tripod and outfitted with a potentiometer that provides a voltage that changes with rotation of the device arm. The participants shoulder was abducted to 90 degrees and sat comfortably on the foam pad and secured with a fabric strap. Participants were asked to assume an elbow angle of 90 degrees flexion (arm pointed subjectively straight ahead). This position was the reference position and in each trial the participant was asked to try and return their elbow to this reference position as accurately as possible. At the sound of a tone the participant was be asked flex their elbow (rotate arm towards midline) as far as was comfortable, hold for 3 seconds before returning to the reference position. 10 trials were performed with no stimulation applied, 10 trials were performed with the stimulation applied continuously throughout the entire 10 trials and 10 trials of recovery were performed immediately after the vibration was turned off (Figure 5.2).

Standing Balance Task:

In this task participants stood quietly with a standardized foot position as described by McIlroy and Maki (1997), on two force plates (Bertec Inc, Columbus, Ohio U.S.A) (McIlroy & Maki, 1997). Participants were still wearing the vibration unit, noise cancelling headphones and headband with the accelerometer attached.

There were three trials of each of the following conditions:

a. Quiet standing eyes open with no vibration
b. Quiet standing eyes open with vibration
c. Quiet standing eyes closed no vibration
d. Quiet standing eyes open with vibration
e. Quiet standing eyes open no vibration with head rotated 5 degrees to the left
f. Quiet standing eyes closed no vibration with head rotated 5 degrees to the left.

The head rotated position was used to explore whether individuals impacted by neck vibration would also be impacted by the added task of adjusting standing balance to a head rotation and therefore incorporating a change in cervical position information. The order of standing balance trials was a randomized block design based on vibration or no vibration. Within those two groupings trials were randomized.

Each trial was 30 seconds in length. A “washout” period of 5 minutes was observed between each block of the study to allow for the dissipation of any effects of muscle vibration. Previous studies have indicated the use of rest periods of between 1 minute and 10 minutes post vibration (Pettorossi et al., 2015; Strupp et al., 1999).

Postural Orientation: Visual Verticality Task:

In this task participants sat comfortably in a high back chair. Participants wore noise cancelling headphones, dorsal unilateral neck vibration unit and specialized goggles limiting peripheral vision. Participants were positioned 90 cm from a large screen displaying the Box and Dot visual verticality test. A computer keyboard on their lap with their index and ring finger of their right hand on the right and left keyboard arrows and the middle finger of the left hand on the Enter button. The Box and Dot Task consisted of a white square outline on a black background. The square was rotated either 18 degrees clockwise or counterclockwise. Within the box were 2 illuminated green colored dots. The angle of an imaginary line drawn between these dots could be rotated clockwise or counterclockwise by 0.05-degree increments using the right or left arrow keys on an external keyboard. The object of the test was to align the dots vertically within the rotated box as accurately as possible. Three variations of the task condition were conducted, each comprised of 20 trials of the Box and Dot Test. The task variation included: 1) control (no vibration), 2) continuous unilateral dorsal neck muscle vibration and 3) continuous unilateral vibration of the dorsum of the right foot. The latter task variation was to control for the possible distracting effect of vibration on performance of the task. Figure 5.3 shows a sample of the Box and Dot Test screen and the modified goggles. All task variations were performed in a block of 20 trials and the order of the task condition blocks was randomized across participants. A 5-minute break was provided between sets to allow for a "washout" of vibration effects and allow the participant to rest.

Postural Orientation: Vestibular Guided Postural Orientation Perception Task:

In this task participants sat comfortably in a high back rotating chair instrumented with a potentiometer to monitor rotation. Participants wore the cervical muscle vibration unit, opaque goggles and the noise cancelling headphones that provided participants with a tone 1 sec ahead of a chair movement. The high back chair rotated in the yaw axis and was controlled by a customized stepper motor installed within the base of the chair. The movement of the chair was controlled by a custom computer program into which rotation angles and angular velocity speeds were specified. For this study, there were 2 sets of 20 chair rotation trials (1 set with neck muscle vibration and 1 set without). Rotation of the chair occurred at velocities of either 8 degrees/sec or 12 degrees/sec and rotation angles of either 25 degrees or 45 degrees in either a clockwise or counterclockwise direction. The combination of these settings was administered in a randomized order. Participants indicated the starting position of each trial using a customized steering wheel that was also instrumented with a potentiometer. As the chair rotated, participants were instructed to keep the steering wheel directed at the initial starting position or perform equal and opposite rotation changes to the steering wheel as were perceived by rotation of the chair. The change in output voltage from the steering wheel potentiometer was compared to the output voltage change from the chair to calculate a positional change perception error value. Vibration and non-vibration trials were compared to examine the impact of neck muscle vibration on vestibular based positional orientation perception. In the vibration trials, vibration simulation was applied continuously throughout the collection. A 15 second break occurred between trials to ensure fluid within the semicircular canals has stopped moving between the end of the previous trial and the start of the next. (Figure 5.4)

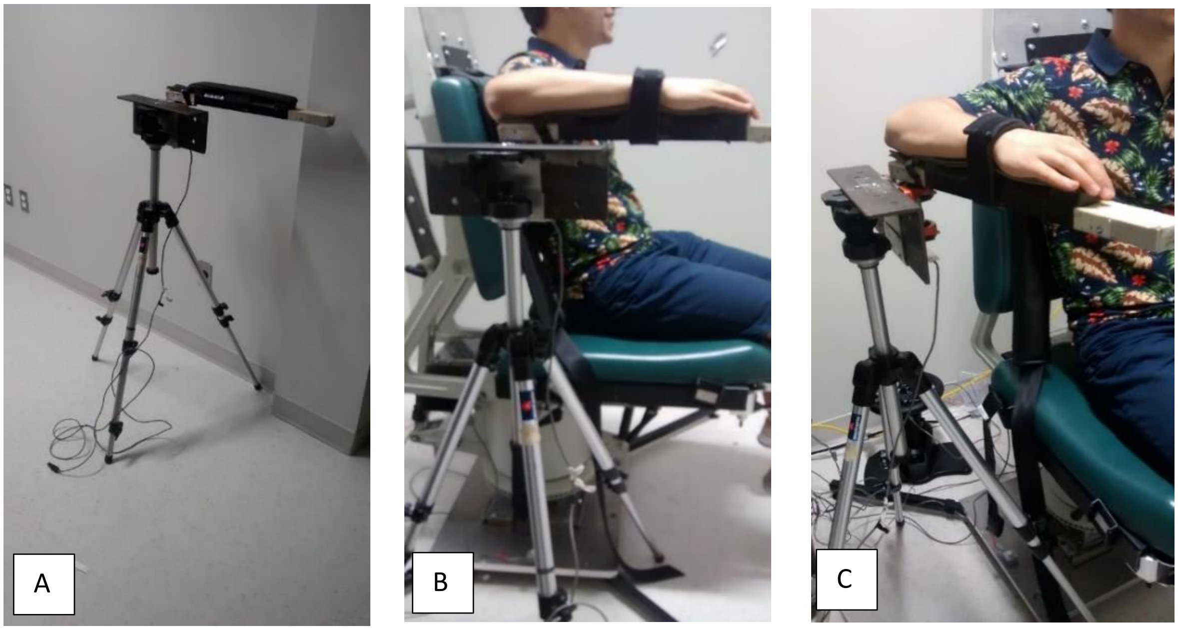

Figure 5.2: Set up for measuring elbow proprioception. A) Device used to measure elbow proprioception task. B) Experimental set up for elbow proprioception task. C) Example of elbow flexion prior to relocating 90 degree starting position.

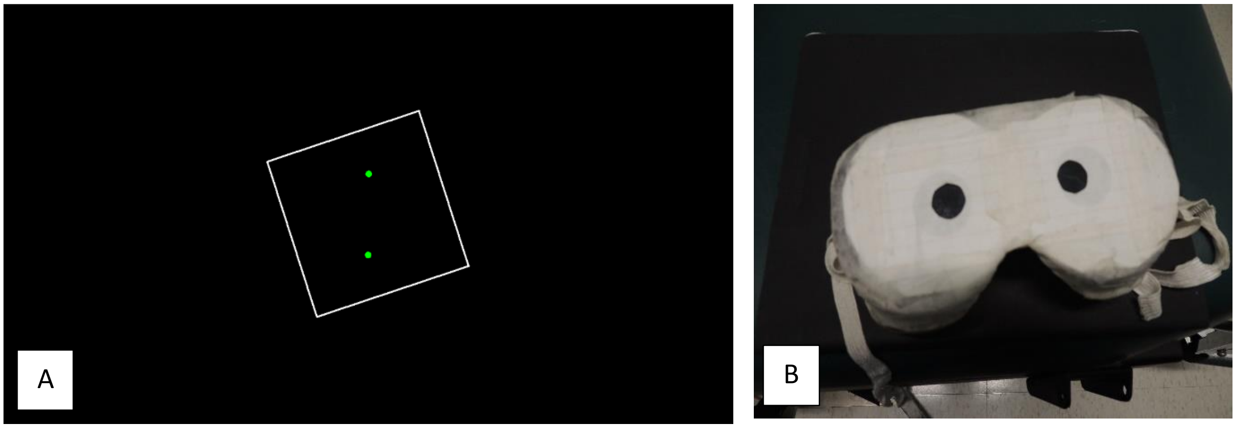

Figure 5.3. Box and Dot Test screen and goggles. A) Example of Box and Dot Test screen shot. B) Goggles worn by participants during Box and Dot Test to restrict visual field.

Figure 5.4: A) Experimental set up for Vestibular Orientation Task. B) Location and attachment of vibration unit to left sided dorsolateral neck muscles used throughout the study.

5.2.4 Instrumentation:

Stimulation: Vibration stimulation was administered via a custom-made vibration unit consisting of a small DC motor with an offset counterweight. The application of a 2-volt power supply resulted in vibration of the device at approximately 80hz. The vibration unit was 7.5cm x 2cm in size and was adhered to the left dorsal neck of each participant between C3 and C7 and 2cm lateral to the spinous processes at this level. Palpation was used to landmark this location for each participant.

Measurement: Accelerometers -with three-dimensional gyroscope (Shimmers) were used to provide information about head position. This was calculated by integrating the angular velocity data from the gyroscopes. The accelerometer was attached to the comfortable head band of noise cancelling headphones and positioned on the crown of the head.

Potentiometers: Changes in output voltage from potentiometers placed on the rotating chair, steering wheel device and elbow flexion and extension apparatus was used to monitor and compare position change perception and elbow joint position error. The voltages from the potentiometers were sent through an A/ D board and recorded by a custom LabVIEW program.

Force platform

Two force plates were used to collect standing balance postural sway data during quiet standing with and without vision and with and without the application of unilateral dorsal neck muscle vibration. These devices provided information about the displacement of forces in the vertical and horizontal axis associated with static postural sway. The summation of forces and changes in their position were used to calculate center of pressure (COP). The metrics used for comparison in this study was RMS COP (AP and ML) sway, average COP (ML and AP) sway, and path length (m).

Visual Vertical Perception Error (Box and Dot Test)

Perception of visual verticality was examined by asking participants to perform a digital form of the Rod and Frame test called the Box and Dot Test. As described above, this test involved aligning two illuminated dots to a perceived vertical orientation using the right and left arrow buttons on an external keyboard. The dots were presented within a box rotated 18 degrees to the right or left on a screen using a custom LabVIEW program. The angle error between true vertical and the perceived vertical (dot position) was calculated by the program and was used to determine participant’s visual verticality perception with and without unilateral neck muscle vibration.

5.2.5 Data Analysis:

5.2.5.1 Within subject differences: Impact of neck vibration across multiple sensory tasks

Cervical Joint Position Error to Subjective Straight Ahead

A custom Labview program was used to visualize and analyze the gyroscope data from the Shimmer IMU sensor. All gyroscope data was first low pass filtered with a 5Hz cut off. An integration calculation was then performed on the gyroscope data to formulate head displacement in degrees (roll, pitch and yaw). The displacement data was then de-drifted by subtracting by the slope of drift between the starting position and the return of the head to SSA at the end of the 30th trial or the final relocation. Initially, de-drifting was attempted by subtracting the integrated data by the slope between the starting position and the return of the 10th trial which would have represented the no vibration trials in both the control and experimental condition. However, when the post drift-corrected data was inspected, some participant's data showed continued drift, skewing displacement values increasingly as time continued (Figure 5.5). To overcome this issue, de-drifting to the final relocation position was done. This meant that the resulting displacement value for the final return to SSA (trial 30) was assumed to be 0 and was left out of the analysis. Subsequently, trial 1 to 10 represented no vibration trials under both the control and experimental conditions. Trial 11-20 represented vibration trials in the experimental condition and trials 21-29 represented recovery trials in the experimental condition. A single displacement vector was calculated mathematically using the equation below:

$$\text{Single displacement} = \sqrt{}[(\text{roll})^2 + (\text{pitch})^2 + (\text{yaw})^2)]$$

Joint position error to SSA, (JPE(SSA)) was calculated as the single vector difference between the relocated head position and the starting head position for each trial. A repeated measures ANOVA was calculated using SAS statistical software (9.2). Alpha was set at .05 for all statistical comparisons. Post hoc comparisons were made for any significant findings.

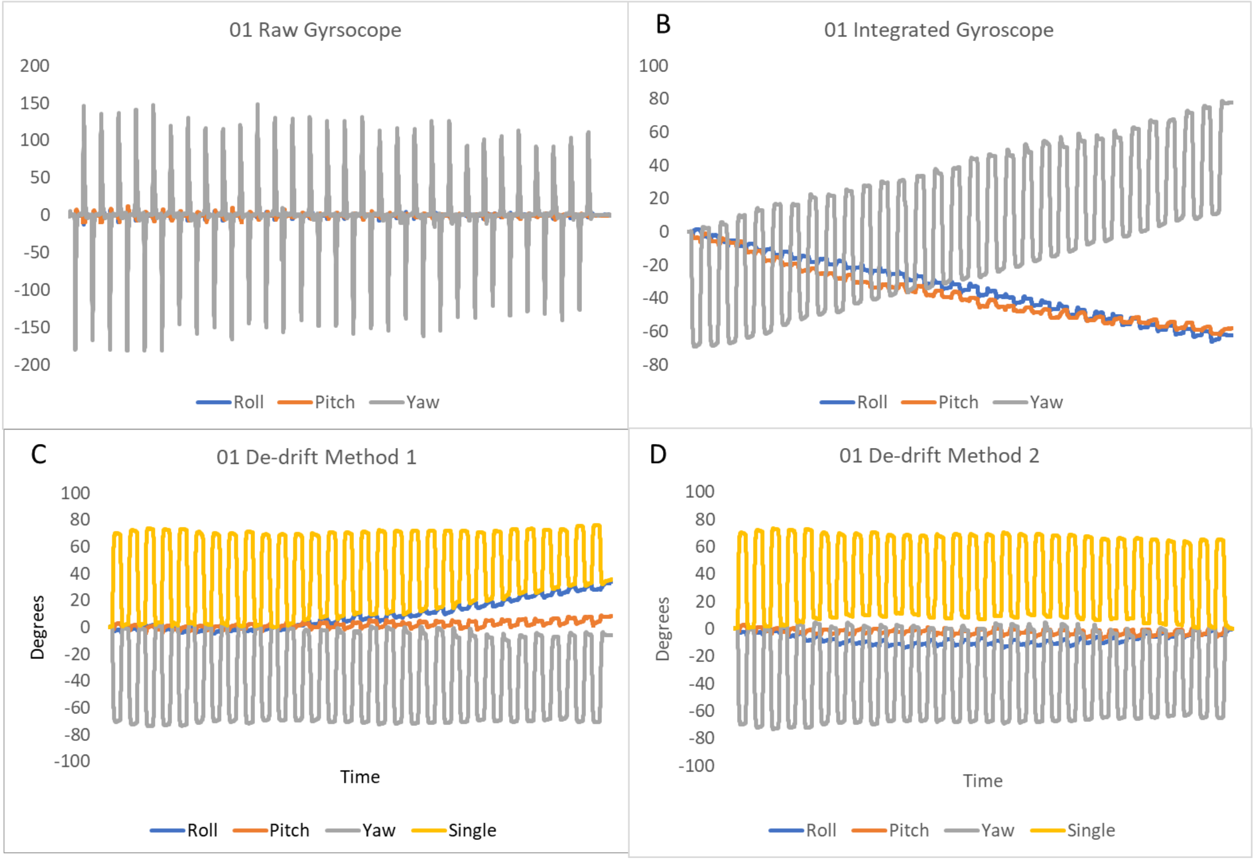

Figure 5.5: A) Raw gyroscope data from Participant 1 during control head relocation trials 1-30. **B)** Filtered and integrated gyroscope data from participant 1 control relocation trials. **C)** Participant 1 control head relocation trials de-drifted by method 1 (slope of first 10 trials). **D)** Participant 1 control head relocation trials de-drifted by method 2 (slope between first and 30th relocation trial).

<u>Elbow Joint Position Error:</u>

Elbow joint position error to 90 degrees of elbow flexion (elbow JPE (90)) was calculated from the potentiometer output from the elbow device. A custom LabView program was used to view and analyze the potentiometer data. Elbow JPE(90) was calculated as the relative and absolute differences between elbow relocation voltage and starting voltage for each trial. The resultant voltages were then converted to degrees. In the control and experimental condition trails 1to10 represented no vibration trials, trial 11 to 20 in the experimental condition represented vibration trials, and trial 21 to 30 in the experimental condition represented recovery trials. A repeated measures ANOVA was performed with alpha=.05 to test for statistical differences between no vibration, vibration and recovery trials within the experimental condition and test for differences in JPE(90) across the blocks of trials in the control condition. Post hoc comparisons were made for any significant findings.

Visual Vertical Perception Error:

Visual vertical perception error (VVPE) was calculated for each trial of the Box and Dot Test as the relative and absolute difference between the perception of visual vertical indicated by each subject's manipulation of the dot position and true vertical. Output from the custom Labview program that administered the Box and Dot test reported this value for each trial. A repeated measures ANOVA was performed to test for differences between the mean VVPE of the 20 trials in each of the no vibration, vibration and foot vibration conditions. Post hoc comparisons were made for any significant findings.

Vestibular Guided Orientation Perception:

Vestibular guided orientation perception error was examined by comparing the change in chair position (voltage change from the potentiometer on the chair) to the perceived change in position (voltage change from the potentiometer on the steering wheel) for each trial. Vestibular guided orientation perception error (OPE) was calculated as the absolute and relative difference between the voltage change from the steering wheel and the voltage change from the chair for each trial. This voltage change was subsequently converted into degrees. A repeated measures ANOVA was used to examine for statistically significant differences in OPE between the control and vibration conditions.

Standing Balance:

Standing balance performance data from the force plates was analyzed using a custom LabView program. Average center of pressure, RMS COP sway (ML and AP), and path length (PL) were calculated each of the standing balance trials. A repeated measures ANOVA was used to test for statistically significant differences in these variables during the no vibration EO and EC, neck vibration EO and EC and head rotated EO and EC conditions.

5.2.5.2 Between subject differences

To investigate between subject variability in JPE(SSA) and explore potential relationships between JPE(SSA), vibration induced changes in JPE(SSA) and performance on the other study tasks, two additional variables were calculated for each error measurement in the study (JPE(SSA), JPE(90), VVPE, OPE, PL). Impact of vibration on the error mean for each measurement was calculated using the following equation for each participant.

Impact of vibration on error mean = [(mean of vibrated trials)-(mean control trials)]

Scatter plots were constructed to explore for relationships between JPE(SSA), JPE(SSA)SD and the impact of vibration on these variables for each participant. Additional scatter plots were constructed to examine for possible relationships between JPE(SSA) and

JPE(90), VVPE, OPE and PL and RMS (AP and ML) sway. A Pearson correlation analysis was carried out to test for statistically significant relationships of interest between these variables.

5.3 Results:

5.3.1 Within subject impact of unilateral left sided neck vibration

The first hypothesis was that left sided unilateral neck vibration would impact performance across all tasks with an increase in cervical JPE(SSA) and elbow JPE(90), VVPE, OPE and standing balance COP sway and path length when compared to no vibration conditions.

Cervical Joint Position Error to Subjective Straight Ahead:

Unilateral left sided neck vibration resulted in significantly increased cervical JPE(SSA) when compared to the no vibration and recovery conditions in the experimental condition. Under control (no vibration) conditions, cervical JPE(SSA) remained consistent across the three trial groupings (1 to 10, 11 to 20, 21 to 29) and was not significantly different when the first, second and third block of relocation trials were compared. (Figure 5.6 and Table 5.1)

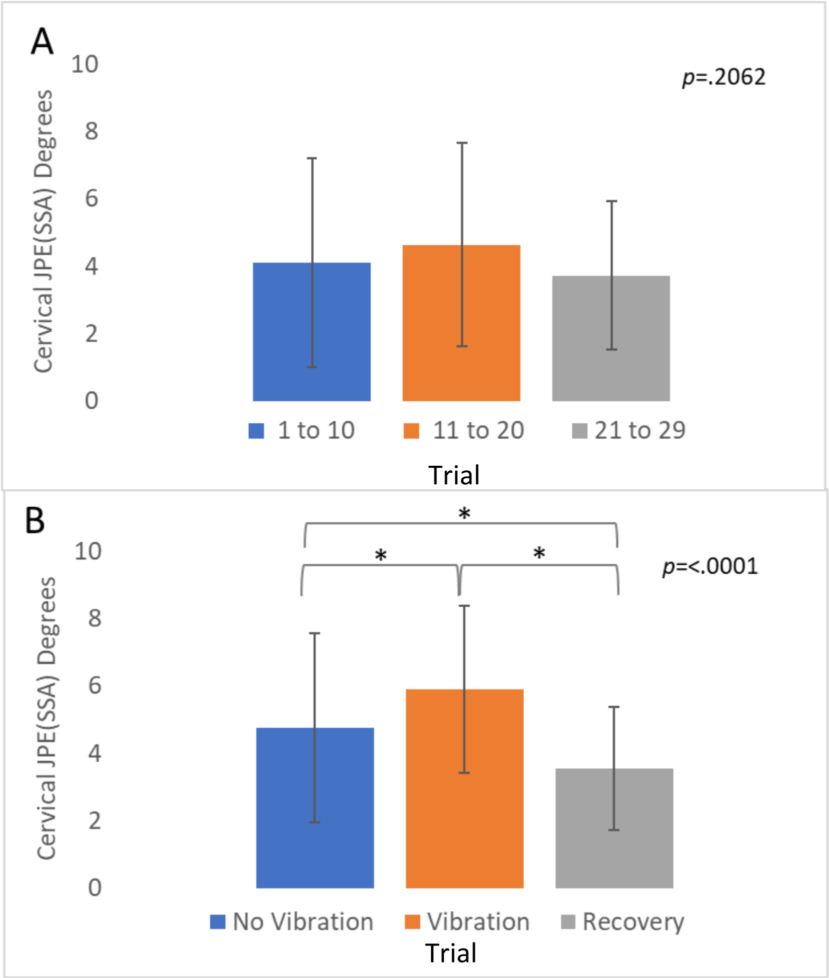

Figure 5.6 Overall cervical JPE(SSA) under control (A) and experimental (B) conditions across participants. Error bars represent SD. * represents statistically significant differences (*p*<0.05).

Trials	Control JPE(SSA) Degrees		Experimental JPE(SSA)Degrees	
	Mean	SD	Mean	SD
1 to 10	4.117	3.098	4.756	2.811
11 to 20	4.638	3.025	5.904	2.487
21 to 29	3.721	2.206	3.547	1.819

Table 5.1. Overall cervical JPE(SSA) means and standard deviations under control and experimental conditions across first second and third trial groupings.

<u>Elbow Joint Position Error to 90 Degrees of Elbow Flexion</u>:

Across participants unilateral left sided neck vibration resulted in a significant increase in elbow JPE(90) when compared to the non-vibrated trials and the recovery trials in the experimental condition (Figure 5.7). By comparison, there were no statistically significant differences in absolute elbow JPE(90) during the first, second and third group of 10 trials in the control condition, and between the first group of trials of both the control and experimental condition. Differences in relative elbow JPE(90) between no vibration, vibration and recovery trials were not statistically significant. Table 5.2 presents the means and SD for absolute and relative elbow JPE(90).

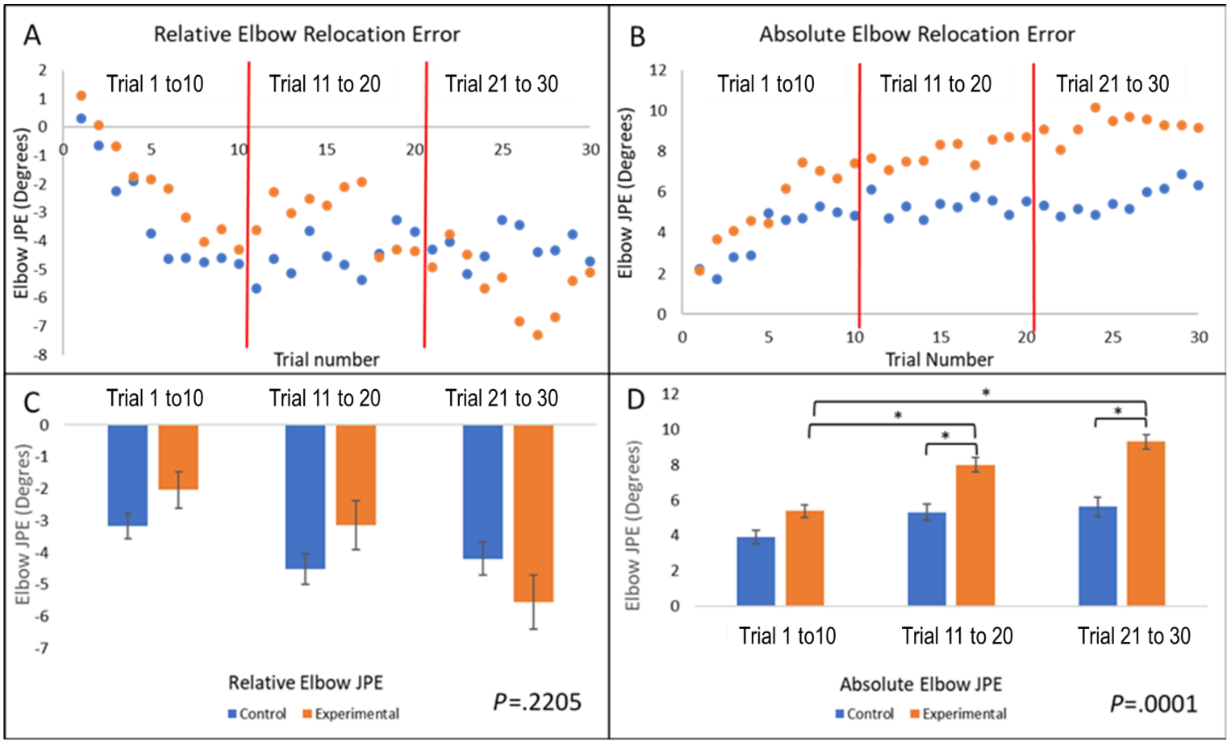

Figure 5.7: **A.** Relative elbow JPE(90) averaged across participants by trial. The red bars represent the onset and offset of vibration during the experimental condition (orange dots). **B.** Absolute Elbow JPE(90) averaged across participants by trial. Red bars represent onset and offset of vibration during experimental condition (orange dots). **C.** Means and SE (error bars) of relative elbow JPE(90) averaged across participants during first, second, and third block of 10 trials. **D.** Means and SE (error bars) of absolute elbow JPE(90) during first, second and third block of 10 trials. * Indicates statistically significant differences (*p*>.05).

	Relative Elbow JPE (SD)		Absolute Elbow JPE(SD)	
	Control	Experimental	Control	Experimental
No Vibration (Trials 1-10)	-3.16 (4.68)	-2.04 (6.81)	3.91 (4.07)	5.38 (4.63)
Vibration (Trials 11-20)	-4.52 (5.66)	-3.14 (9.13)	5.32 (4.91)	7.99 (5.34)
Recovery (Trials 21-30)	-4.19 (6.10)	-5.55 (9.98)	5.62 (4.81)	9.31 (6.58)

Table 5.2: Relative and Absolute JPE(90) means and SDs by trial grouping for the control and experimental conditions.

Visual Vertical Perception Error (Box and Dot Task):

Overall, across participants, VVPE mean and standard deviations were small during all conditions. During the control (no vibration) trials, VVPE mean (SD) with the box rotated clockwise (18 degrees) and counterclockwise (-18 degrees) were .55 (2.00) degrees and .74(2.25) degrees respectively. Across participants, unilateral left sided neck vibration resulted in a shift in relative VVPE toward the left (vibrated side) when compared to no vibration and foot vibration conditions. This shift in VVPE reached statistical significance when the box was rotated counterclockwise (-18 degrees), but not with the box in the clockwise orientation (18 degrees). There were no statistically significant differences in absolute VVPE between the no vibration, vibration and foot vibration conditions with the box rotated either clockwise or counterclockwise (Figure 5.8). The means and standard deviations for visual vertical perception error, showing the significant difference in VVPE between vibration trials and the no vibration and foot vibration trials, are presented in Table 5.3.

Condition	Relative Visual Vertical Error (degrees)				Absolute Visual Vertical Error (degrees)			
	Box Orientation				Box Orientation			
	CW		CCW		CW		CCW	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
No Vibration	0.5596	2.003	0.7412	2.248	1.6426	1.268	1.9121	1.388
Vibration	0.1237	2.036	-0.3040	2.503	1.6233	1.226	1.8249	1.735
Foot Vibration	0.3549	2.177	0.8901	2.261	1.7693	1.306	1.9671	1.420

Table 5.3: Means and standard deviations for relative and absolute visual vertical error across participants. CW represents clockwise box orientation (18 degrees) CCW represents counterclockwise box orientation (-18 degrees).

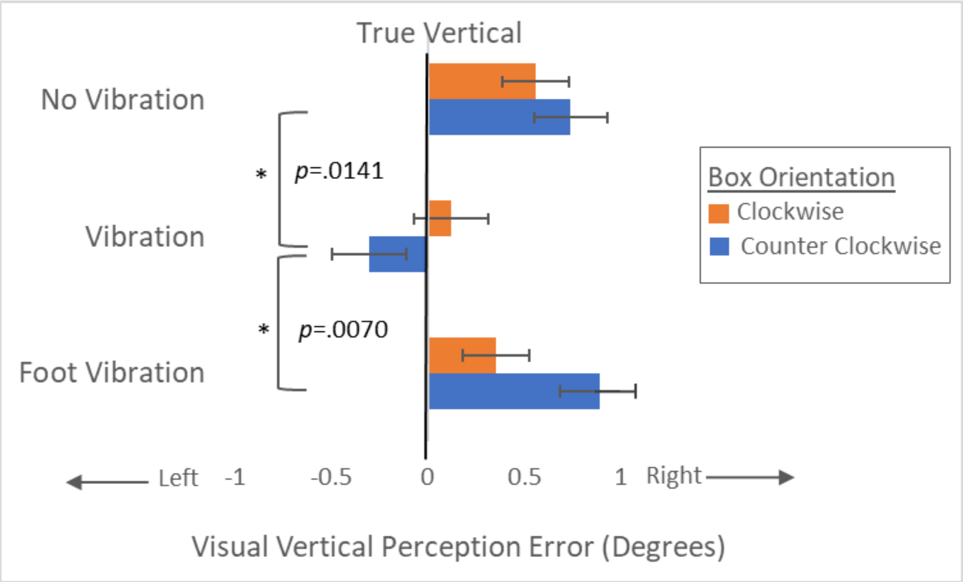

Figure 5.8: Mean relative visual vertical perception error across participants by condition showing a shift in error towards the vibrated side (left) during vibration trials. (Error bars represent SE). * Represents statistically significant differences p> 05.

Vestibular Guided Orientation Perception Error (OPE):

Overall, participants demonstrated large OPE error and variability during the rotating chair task. Relative and absolute mean error and standard deviations under the control condition were 31.37 degrees +/-32.03 degrees and 33.03 degrees +/- 30.31 degrees respectively. During the vibrated trials relative and absolute mean error and standard deviation increased to 35.78 degrees =/- 40.25 degrees and 37.00 degrees +/- 39.21 degrees, respectively. This increase however was not statistically significant (Figure 5.9).

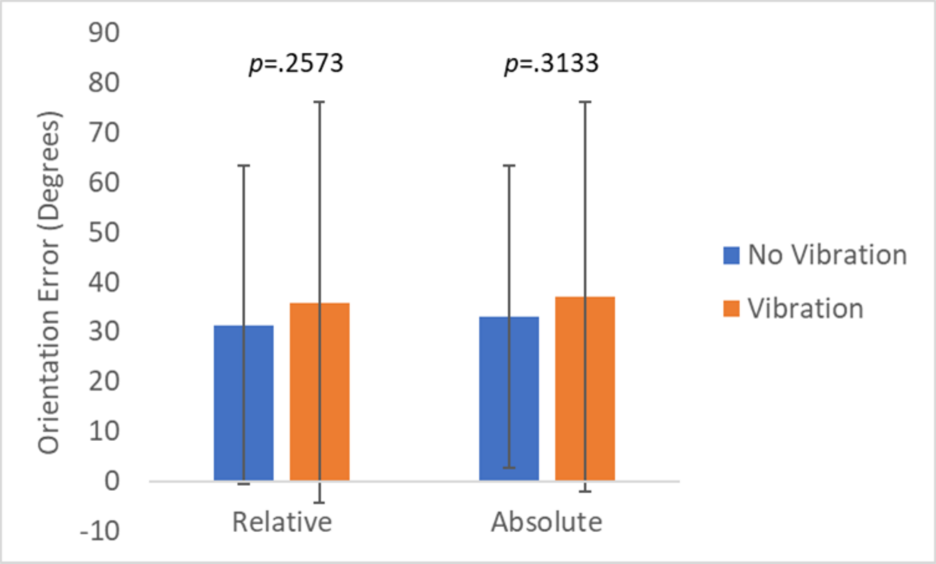

Figure 5.9: Relative and absolute mean orientation perception error across all participants. Error bars represent standard deviation.

There was significant variability in participant performance on the chair task. The maximum and minimum values for absolute OPE and standard deviations during the control condition were 89.60 degrees +/- 49.73 degrees and 7.32 degrees +/- 4.99 degrees respectively.

During the vibrated trials, the maximum and minimum absolute OPE and standard deviations were 132.53 degrees+/- 64.11 degrees and 8.57 degrees +/- 5.53 degrees respectively. Separate ANOVAs performed on each participants performance reveled that relative error was significantly different between no vibration and vibration conditions in 8 subjects, however in participants 2,4,7,8, and 9 , vibrated trials had increased error while in participants 5,6, and 12 error decreased (Figure 5.10).

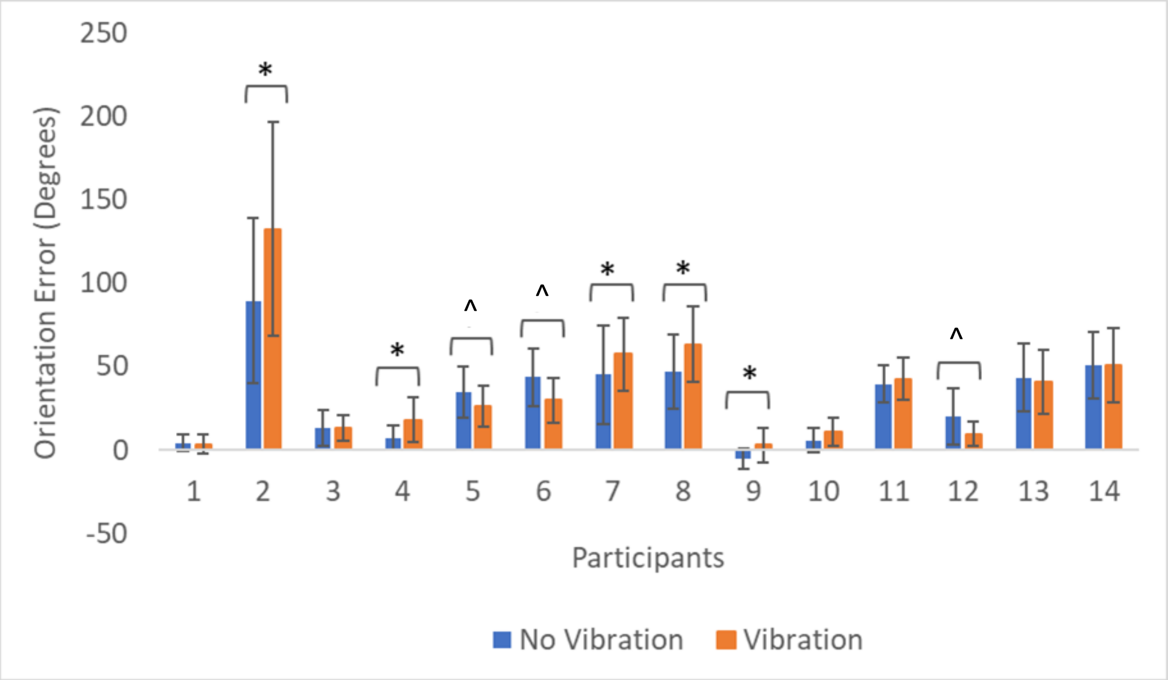

Figure 5.10. Relative OPE with and without neck vibration by participant, showing large variability in performance mean and SD between participants. Error bars represent SD. * denotes statistically significant increases in OPE means by participant ($p<0.05$). ^ denotes significant decreases in OPE means by participant (p<.05).

Standing Balance Center of Pressure, RMS sway and Path Length

Participants completed three trials of each of the three balance tasks, no vibration (EO, EC), neck vibration (EO, EC) and head rotated to the left (EO, EC). The average RMS ML and AP sway and PL with EO and EC was not significantly different when compared across task (no vibration, vibration and head rotated) conditions (Figure 5.11). Increases in PL and RMS AP sway in the EC condition compared to EO condition were statistically significant as expected (Figure 5.11). Average COP ML and AP across conditions were compared using a scatter plot and with a two factor repeated measures ANOVA. Only small differences were observed in average COP ML and AP across the no vibration, vibration and head rotated tasks (Figure 5.10). Compared to the no vibration condition average COP ML during vibrated trials with EO and EC shifted slightly to the left by -.47(+/-4.96) and -.31 (+/-4.61) mm respectively. There was a small AP shift anteriorly during vibrated trials with EO and EC by 2.49 (+/-6.73) mm and 1.42 (+/-7.33) mm respectively. The COP differences between no vibration and vibration trials did not reach statistical significance (*p*<.05.) The impact of rotating the head 10 degrees to the left did result in a shift of COP to the right and posteriorly. The COP AP shift with left head rotation was statistically significant in both the EO and EC trials (*p*=.0277) with an average posterior shift of 1.42 (+/- 6.33)mm and 2.87 (+/-3.69)mm respectively when compared to control conditions. The rightward (ML) COP shift during left head rotation with EO and EC was not statically significant, with the average shift of 2.08 (+/- 5.23) mm and 1.68 (+/- 4.99) mm respectively (Figure 5.12).

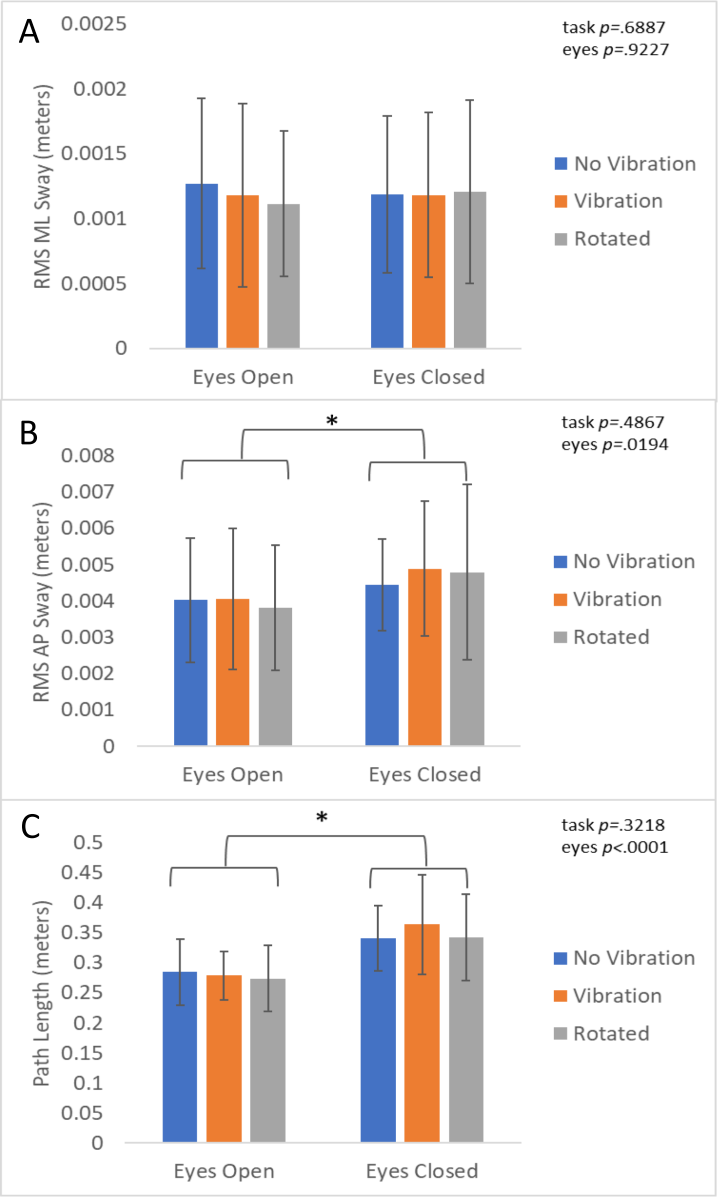

Figure 5.11: A) Average RMS ML sway (meters) across all participants by task (no vibration, vibration and head rotated conditions) with EO or EC. **B)** Average RMS AP sway (meters) across all participants by task (no vibration, vibration and head rotated conditions) with EO or EC. **C)** Averaged path length across all participants by condition and with eyes open or closed. Error bars represent standard deviation. * Denotes statistically significant differences *p*<.05.

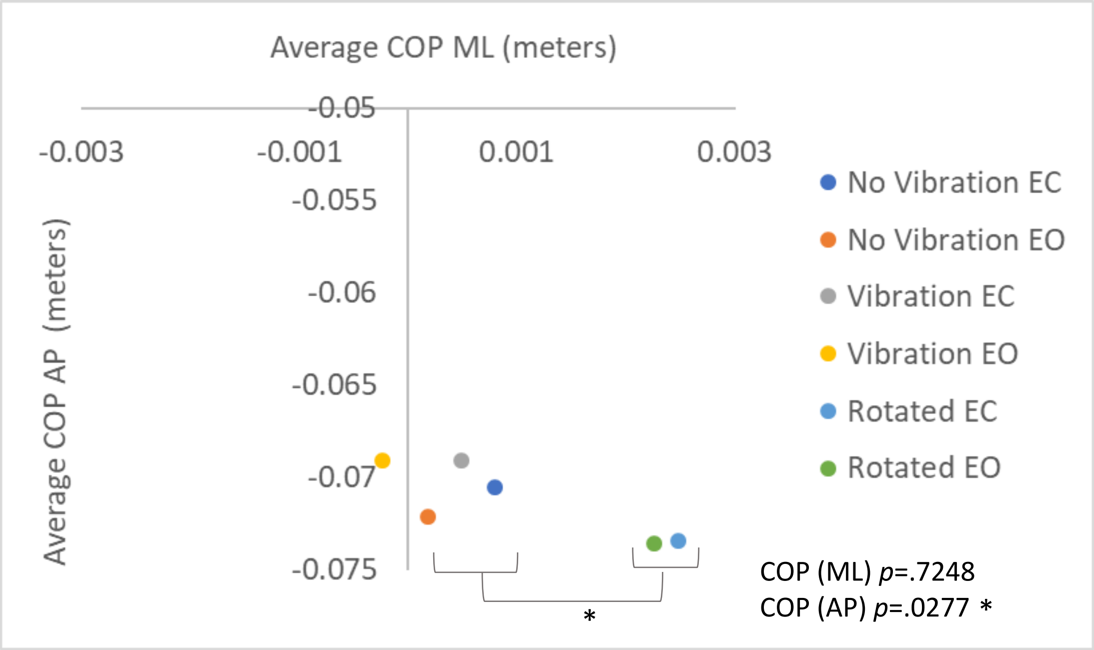

Figure 5.12: Average COP across conditions. This figure shows the small shifts in average COP (ML and AP) across participants by task condition and eyes open or eyes closed. In the figure during unilateral posterior neck vibration there is a small anterior shift in COP that is not statistically significant. During the head rotated trials there is a statistically significant posterior shift in COP compared to no vibration trials in both eyes open and eyes closed condition. * $p<.05$ denotes significant differences.

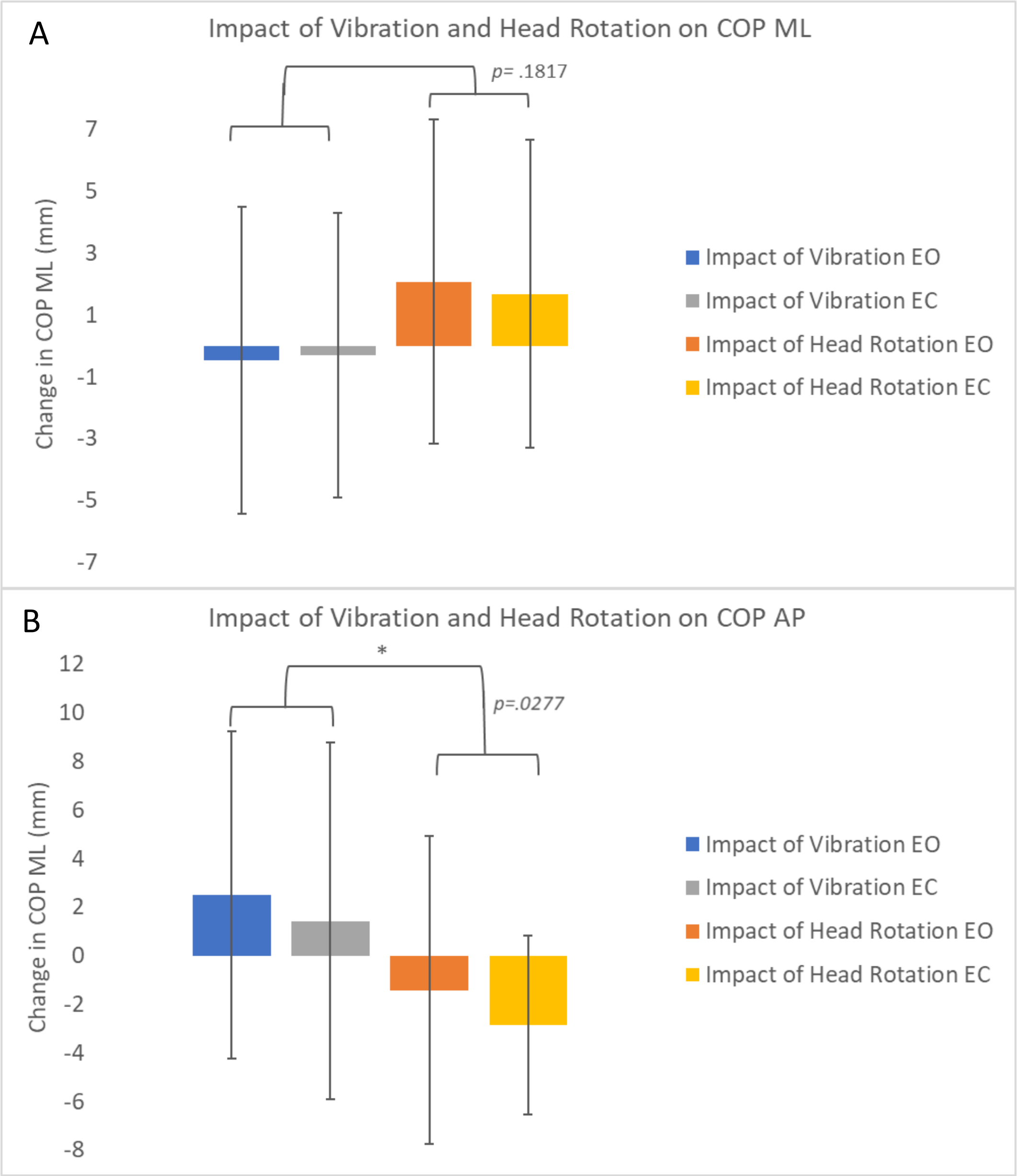

Figure 5.13. Means and SD (error bars) of COP during no vibration, unilateral neck vibration and left head rotation quiet standing balance with eyes open and closed. * $p<.05$ denotes significant differences between COP across participants. **A)** Shows differences in COP ML between task conditions and figure **B)** Shows differences in COP AP between task conditions.

5.3.2 Between subject variability and the relationship between JPE(SSA)mean and SD and the other error measurements (JPE(90), VPE, OPE, PL and RMS sway)

Cervical JPE(SSA), SD and Impact of vibration

JPE(SSA) mean, SD and impact of vibration were calculated for each participant and compared to one another using scatter plots. A Pearson correlation coefficient was calculated for each of the comparisons of interest. There was a statistically significant moderate positive relationship between JPE(SSA) mean and SD (r= .6253 and *p*=.0172). There was a statistically significant moderate negative relationship between JPE(SSA) and the impact of vibration on JPE(SSA) (r=-.5714 *p*=.0327). There was no significant relationship between JPE(SSA) SD and Impact of vibration (*r*= -.2817, *p*=.3291) (Figure 5.14).

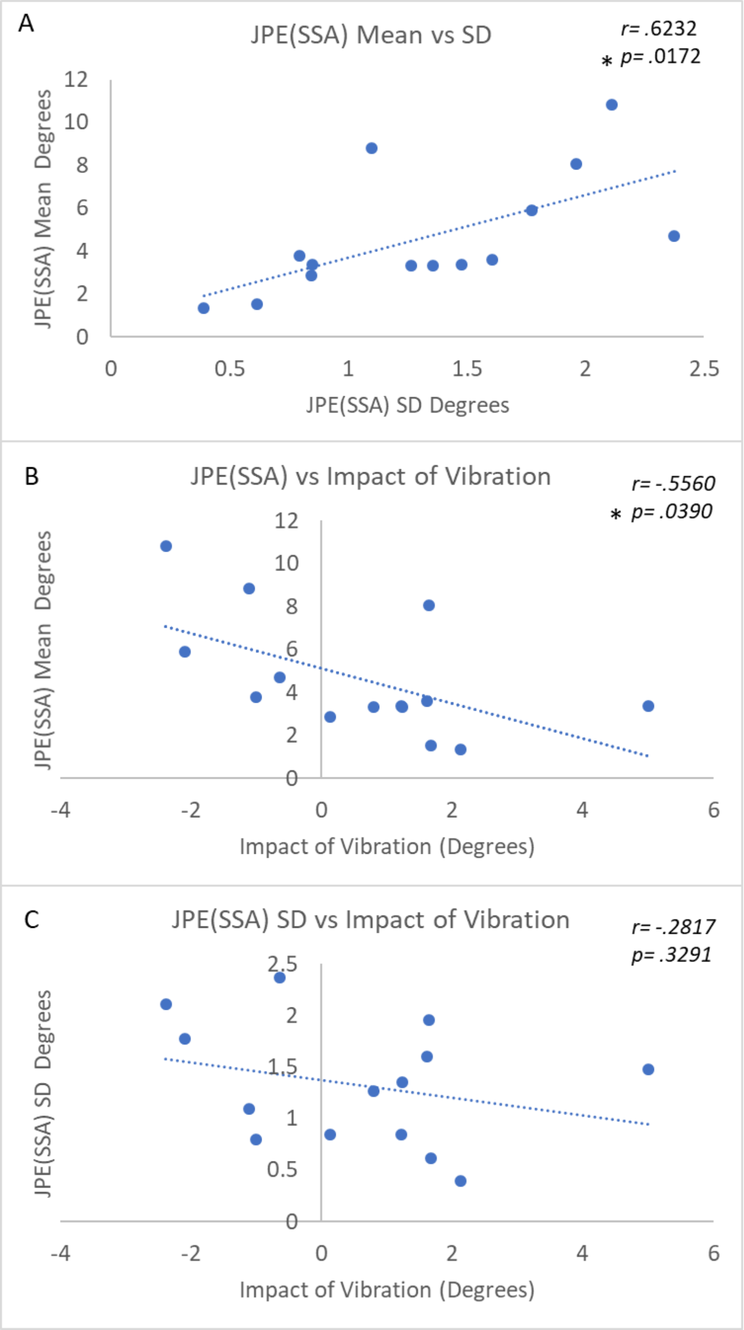

Figure 5.14: Scatter plot comparisons of JPE(SSA) mean, SD and impact of vibration by participant. Pearson correlation coefficient r values and statistical *p* values are presented in the top right corner of each comparison

Scatter plot comparisons between JPE(SSA) and the impact of vibration on the other error measurements failed to yield any significant relationships (Figure 5.15). When JPE(SSA) SD was compared to the impact of vibration on the other error measures, there was a strong positive statistically significant relationship between JPE(SSA)SD and the impact of vibration on VVPE (r .5560, *p*=.039) (Figure 5.16).

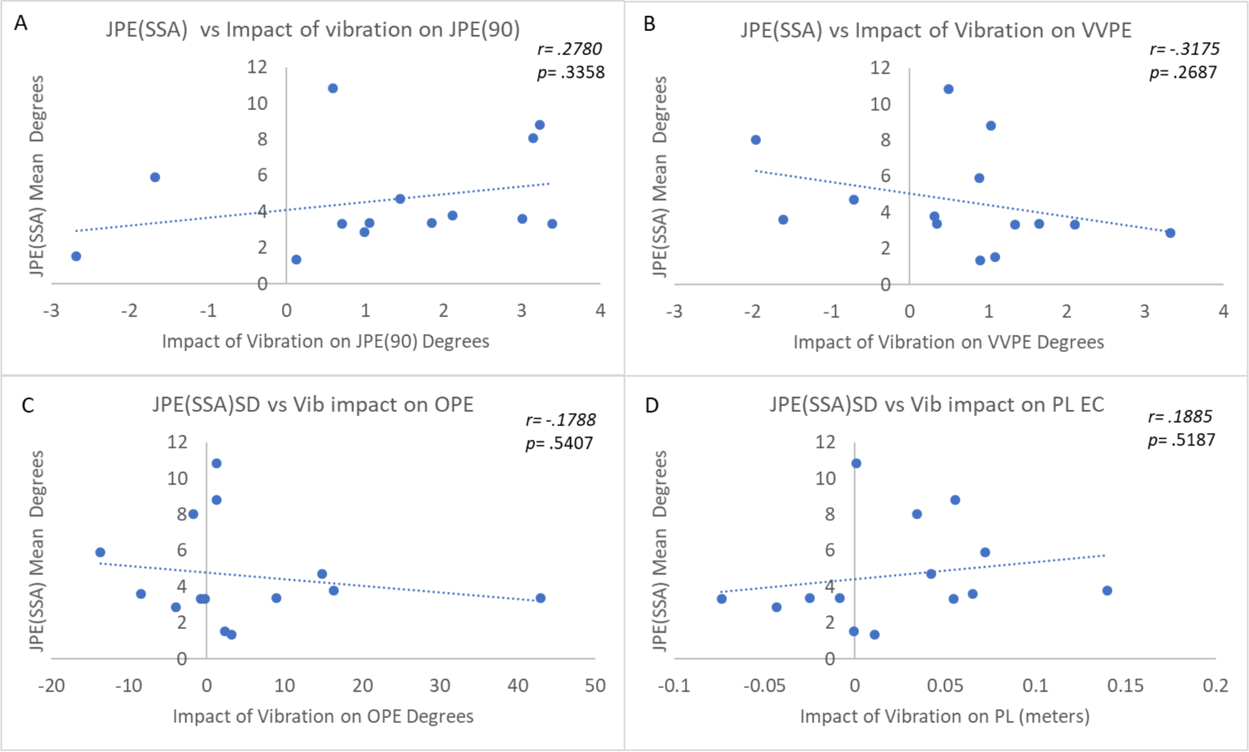

Figure 5.15. These scatter plots illustrate the relationships between cervical joint position error to subjective straight ahead and the impact of vibration on **A)** Elbow joint position error to 90 degrees **B)** Visual vertical perception error **C)** Orientation perception error **D)** Path length with eyes closed. Pearson correlation r values and *p* values for each comparison are provided in each box.

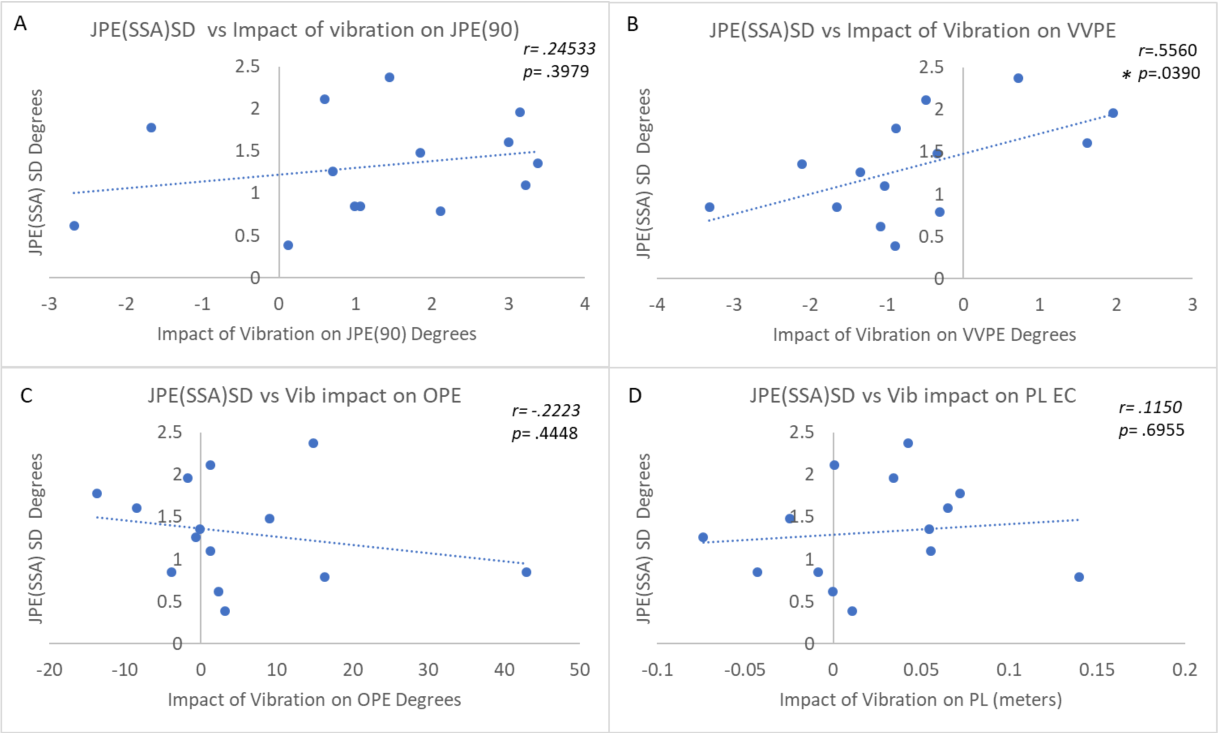

Figure 5.16: Scatter plot relationships between JPE(SSA) standard deviation and the impact of vibration on **A)** Elbow joint position error to 90 degrees **B)** Visual vertical perception error **C)** Orientation perception error **D)** Standing balance path length with eyes closed (* Denotes a statistically significant relationship *p*<.05).

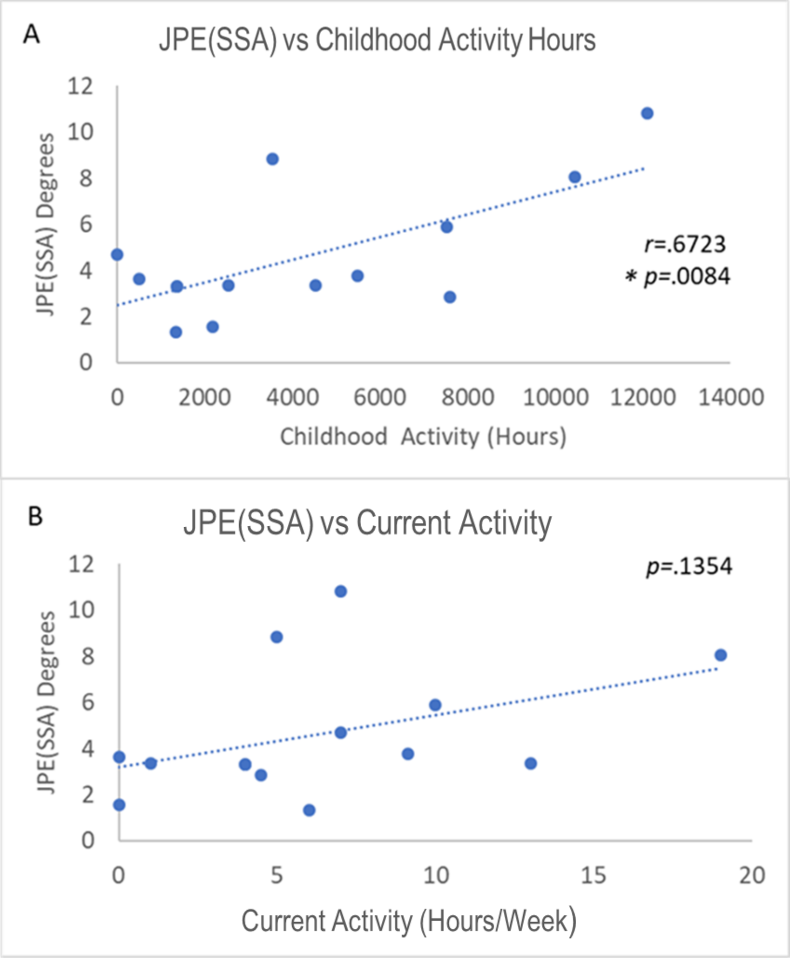

Figure 5.17. Relationship between JPE(SSA) and **A)** Self-reported childhood activity hours and **B)** Self-reported current activity level (hours/week). In figure A there is a statistically significant positive relationship between JPE(SSA) and self-reported number of childhood activity hours, denoted by * (p<.05). In Figure B the relationship between JPE(SSA) and Current Activity (hours/week) was not statistically significant.

<u>Between Subject Differences on the Impact of vibration and head rotation on standing balance</u>

Standing balance was assessed with and without vibration and with the heat rotated 10 degrees to the left. As presented earlier, no main effects of vibration or head rotation were found on RMS ML or AP sway although scatter plots comparing the impact of vibration with the impact of head rotation on RMS ML and AP sway with EO and EC revealed a positive significant relationship between RMS ML and AP sway in the EC but not the EO conditions indicating that individuals who showed greater impact on sway with vibration also had greater impact on sway during head rotation condition (Figure 5.18).

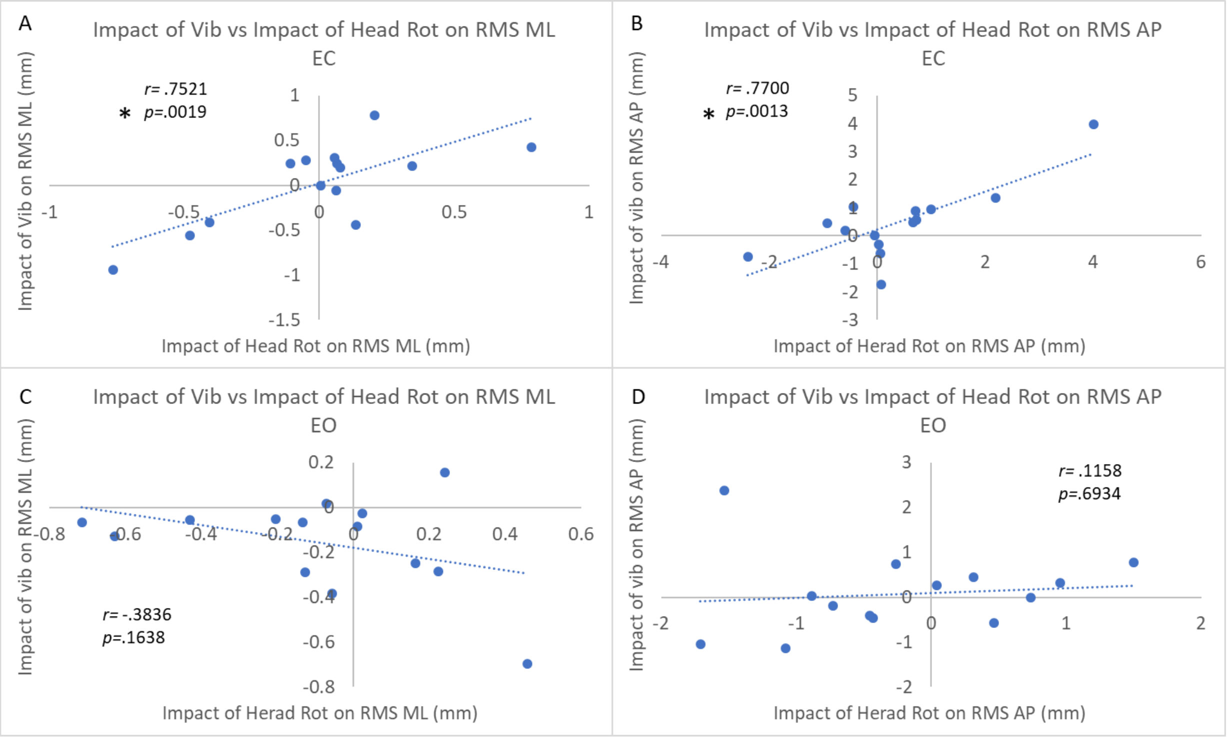

Figure 5.18. Comparison of impact of vibration and impact of head rotation by participant on **A)** RMS ML sway with eyes closed. **B)** RMS AP sway with eyes closed. **C)** RMS ML sway with eyes open. **D)** RMS AP sway with eyes open. Statistically significant relationships are denoted by * (*p*<.05).

When the impact of head rotation on average COP (ML and AP combined) was compared to JPE(SSA) performance, there was a statistically significant negative relationship between the size of COP shift during head rotation and JPE(SSA) SD (Figure 5.19). There was also a statistically significant negative relationship between the impact of head rotation on average COP and the impact of vibration on visual vertical perception error, indicating that participants who had the largest shift in vertical perception error with neck vibration also had the largest COP shift during head rotation during quiet standing (Figure 5.19).

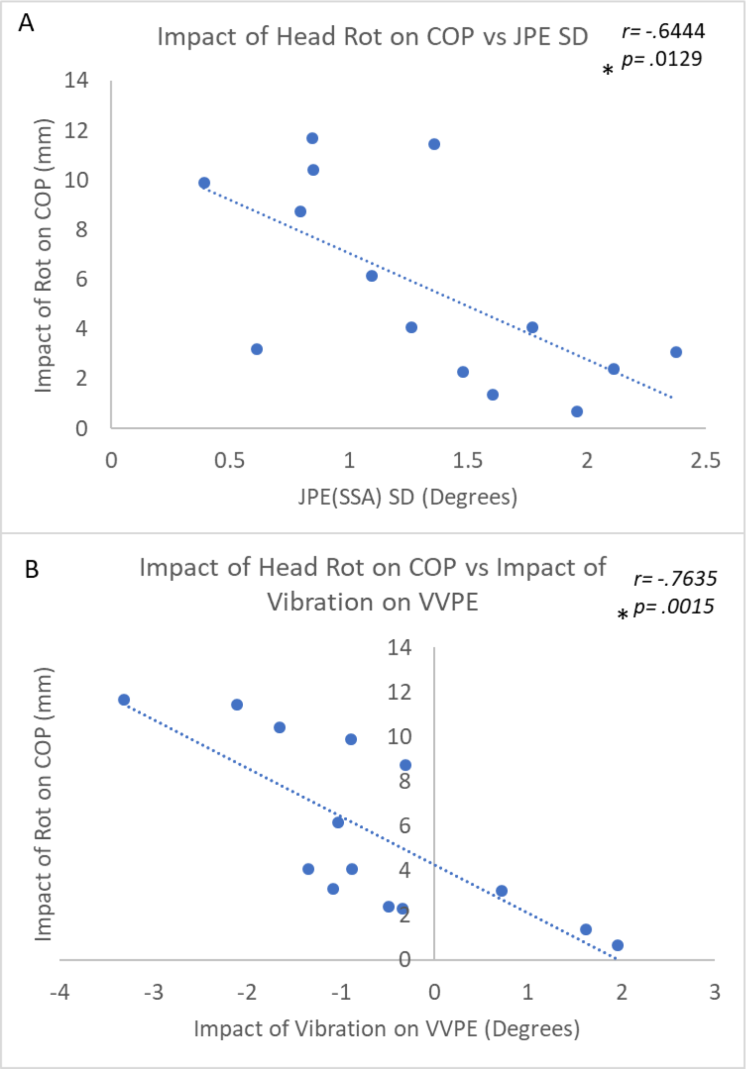

Figure 5.19. Comparing the impact of head rotation on average COP vs **A)** cervical joint position error SD **B)** Impact of vibration on visual vertical perception error. Statistically significant relationships are denoted by * (*p*<.05).

5.4 Discussion:

Overall, the findings of this study showed that altering cervical proprioception with unilateral neck vibration impacted not only the perception of head orientation, but also elbow orientation perception and visual vertical perception as well. Additionally, the study suggested that contrary to the study hypothesis, between subject differences in the impact of neck vibration was not consistent across multiple tasks.

The current study had two main objectives. The first objective was to explore the impact of unilateral neck vibration on cervical proprioception and spatial orientation perception error across multiple sensory tasks and quiet standing balance. The second objective was to examine between subject differences in cervical JPE(SSA) mean, SD and impact of vibration and their relationship to performance across the other sensory and standing balance tasks. The first hypothesis was that across participants, unilateral left sided dorsal neck vibration would result in increased relocation and perception error across each of the sensory and standing balance tasks.

This hypothesis was supported by the results of this study for three of the sensory tasks. There was a significant main effect of vibration on cervical JPE(SSA), absolute elbow JPE(90) and relative VVPE when compared to control conditions. However, there were no statistically significant main effects of neck vibration on vestibular guided postural orientation error or standing balance COP, RMS sway and path length.

5.4.1 Impact of Vibration on Cervical Joint Position Error

The increased absolute cervical JPE(SSA) during neck vibration seen in the current study is consistent with the findings of study 2 and 3 of this thesis in which unilateral posterior neck vibration also resulted in increased cervical JPE when relocating SSA. The impact of neck vibration on the perception of head orientation as discussed previously in this thesis has also been supported by other previous work. Karnath et al. (1994) and Cyete et al. (2006) both reported a shifting of midline perception and body orientation perception during neck vibration. Taken together, the results of this study and those of previous works suggests that cervical proprioception plays an important part in formulating a body schema and that manipulating cervical proprioceptive information with unilateral neck vibration, alters the perception of subjective straight ahead and the ability to accurately relocate it.

5.4.2 The Impact of Vibration on Elbow Joint Position Error

As hypothesized, left sided unilateral posterior neck muscle vibration increased absolute elbow JPE(90). When averaged across participants by trial, the shift in relative elbow relocation error across participants seen in Figure 5.7 during and after neck vibration did not reach statistical significance. The increase in absolute elbow JPE(90) however, during and after neck vibration was statistically significant and supports the idea that cervical proprioception is an important contributor not only to head orientation perception, but also contributes to limb positional perception as well. The results of this study are in line with a handful of previous studies that have explored the relationship between head orientation and elbow orientation perception. Knox and Hodges, (2005), investigated the impact of end range passive head movements on participants' ability to accurately relocate a desired elbow position. In their study, participants lay supine with their arm supported in a sling and an electro goniometer measuring elbow flexion angle. An elbow target angle was passively administered by the examiner after which participants actively relocated the angle in the absence of vision with the head in neutral or passively manipulated and held into full rotation, flexion or a combination of the two. The authors found that passively rotating, flexing or combining flexion and rotation to end range increased absolute elbow JPE sense. Similar to the current study, changes in relative elbow JPE sense were not statistically significant. A subsequent study by Knox et al. (2006a) using similar methodology, explored differences in elbow JPE in people with WAD compared to those without neck pain. This study also compared elbow JPE during head flexion and rotation, but only to 30 degrees. Contrary to their previous findings, elbow JPE with mid range passive head positions did not significantly increase elbow JPE. However, significant increases in elbow JPE did occur for individuals with WAD. The current study differs from previous works in the use of vibration stimulus to alter cervical proprioception inputs and the absence of passive or active head movement. Only one other study has examined the impact of neck vibration on elbow joint position sense in normal healthy participants. Knox et al. (2006b) simultaneously vibrated the contralateral SCM and SC muscles of participants and examined their ability to reproduce a passively assigned elbow target angle. Similar to the current study, the authors found that neck vibration resulted in increased absolute elbow joint position sense. This study adds to the work of Knox et al. (2006b) in that it also explores the post vibration impacts on elbow JPE(90) and in the relationship of elbow JPE(90) by participant to cervical JPE. In the current study, increased JPE(90) continued across the recovery trials and therefore suggests that the disruptive influence of neck vibration on elbow joint position sense persists even after the offset of vibration. This indicates that altered cervical proprioception may have lasting impacts of postural orientation possibly shifting the postural reference frame as has been discussed previously in this thesis.

5.4.3 The Impact of Vibration on Visual Vertical Perception Error

In the current study visual vertical perception error during the Box and Dot Test was impacted by neck vibration with a shift in perception error towards the vibrated (left) side. Although a noticeable shift occurred in the trials with the box rotated clockwise and counter clockwise, only the VVPE during counter clockwise trials was statistically different during vibration condition. These results support the idea that cervical proprioception interacts closely with visual inputs for the purpose of spatial orientation perception. The illusion of altered head position from the muscle vibration resulted in a corrective shift in the perception of visual vertical towards the side of vibration. The stimulation of muscle spindles from vibration, leads to the illusion of muscle lengthening. In the current study, vibration to the left splenius capitus muscle would induce the illusion of neck flexion, right side flexion and right rotation of the head. Therefore, under the influence of this illusion, a corrective shift in visual vertical perception in a counter clockwise direction (towards the vibrated left side) would be required to align the dots vertically as was seen in the results of this study. Although to our knowledge, this is the first study to explore the impact of neck vibration on VVPE in normal healthy participants using the Box and Dot Test, the results of the current study are in line with those of previous work examining the interactions between cervical proprioception and VVPE in clinical populations. Grod et al. (2002) employed the analogue Rod and Frame test to explore differences in verticality error between participants with and without neck pain. In their study, verticality perception error was significantly larger in participants with neck pain than those without. The authors theorized that their results support of the idea that cervical proprioception contributes to spatial orientation perception and can therefore impact on perception when it is impaired. More recently, Treleaven and Takasaki (2015), reported increased variable error and root mean squared error in participants with idiopathic neck pain, but not whiplash injury when compared to healthy controls. They theorized these results suggested differing strategies for individuals with neck pain in visual vertical perception. In the current study, the VVPE values in the no vibration condition were similar to those of previous studies. It has been shown that humans can discern true visual verticality to within 2-3 degrees (Dieterich & Brandt, 2019). Bagust et al. (2005) reported VVPE of 1.35 +/- .31(SEM) degrees with a box rotated 10 degrees clockwise and -.35 +/- .31(SEM)j degrees with a counter clockwise rotated box. Although the VVPE values in the current study were also small (0.56 degrees for the clockwise rotated box and 0.74 degrees for the counter clockwise rotated box), in the study by Bagust et al. (2005), the clockwise box drew the VVPE in a clockwise direction while the opposite was true for the counter clockwise box (negative) direction. In the current study, both directions of box rotation resulted in VVPE towards the right (clockwise). As the box orientation in the box and dot (Rod and Frame) test is meant to impart increased visual error towards the direction of the box rotation angle, it is unclear why in our study both the directions of rotation resulted in clockwise VVPE. Additionally, the variability in our study is in line with those reported in other studies. In the current study, SD for VVPE in the clockwise and counter clockwise box trials were 2.25 and 2.26 degrees respectively. This variability is in line with the results of previous work of Bagust et al. (2005), who reported an SEM of .31 degrees for both clockwise and counter clockwise box orientations. This value converted to SD equates to 2.48 degrees. Takasaki et al. (2012) reported slightly less variability with recorded SD in clockwise and counter clockwise box orientations of .95 and 1.02 degrees respectively which places the variability from the current study in the middle of those previously reported.

5.4.4 Impact of Vibration on Vestibular Guided Orientation Perception Error

Contrary to the study hypothesis, neck vibration did not significantly increase orientation perception error during the chair task. Although there was a small difference in OPE between the no vibration and vibration conditions, they were not statistically significant. The results of the current study differ from those of Panichi et al. (2011) who found that vibration of the contralateral SCM and spenius capitus resulted in altered orientation perception during asymmetric oscillation of a rotating chair. The current study design differed from that of Panichi et al. (2011) in that the orientation perception task did not involve asymmetric sinusoidal rotation. In this study, the chair moved in either a clockwise or counter clockwise direction and participants were to maintain the starting orientation by moving the wheel in an equal and opposite direction as the chair. One of the limitations in this task may have been the task difficulty. It is possible that the turning of the steering wheel was not as easily understood by participants as the use of a single rod as was used in other studies. Additionally, there was significant variability in the task performance between participants. As mentioned previously, some participants completed the task with relatively small OPE in both the no vibration and vibration conditions, while others have significantly larger OPE even during control conditions. These differences appeared despite the practice trials provided to participants in order to familiarize themselves with the task. Another possible explanation for the lack of significant impact from neck vibration in the current study compared to previous work was the differences in muscle vibration. In the study by Panichi et al. (2011), vibration was applied to two agonist muscle groups. It is possible that vibration of only the left splenius in this study did not impart enough of a disruption to overall orientation perception and participants were able to overcome the altered cervical proprioceptive information with other sensory inputs from non vibrated neck musculature and input.

5.4.5 Impact of Vibration on Standing Balance Measures

Contrary to the study hypothesis, across participants neck vibration did not significantly impact on quiet standing balance path length, average COP or RMS ML and AP sway. The significant impact of vision on RMS AP sway and path length was expected as lack of vision has previously been associated with increased PL and RMS sway (Popov et al., 1996). Previous work has reported that bilateral posterior neck vibration results in an anterior shift in COP (Ivanenko et al., 1999; Yagi et al., 1998). However, the current study failed to show this significant difference between no vibration and vibration balance trials. A possible explanation for these results may be the use of unilateral posterior neck vibration versus bilateral neck vibration. Most postural studies using neck vibration have implemented a bilateral neck muscle vibration stimulus. The subsequent anterior shift in COP has been explained as the counteraction to the illusion of a perceived posterior trunk lean induced by the illusion of lengthening neck muscles in the absence of perceived head motion. The current study used left sided unilateral neck vibration in order to maintain consistency in vibration stimulus across all of study tasks. In the current study during neck vibration trials, average COP did shift anteriorly slightly, but was not statistically significant. Of the few studies in which unilateral posterior neck muscle vibration has been employed, the impact on standing balance has been less consistent, with some studies reporting primarily ML COP shifts but others reporting AP shifts as well (Bove et al., 2007; Courtine et al., 2007). The lack of significant findings in the current study may also be due to variability in participant response to vibration. In the current study neck vibration resulted in a leftward ML COP shift in 8 participants, but a rightward ML shift in 6 participants. Similarly, in the AP direction COP shifted anteriorly in 10 participants and posteriorly in 4 participants. The mixed directional response to vibration may therefore have diminished significant statistical comparisons between the condition. It is also possible, as was discussed previously, that intact sensory input from body proprioception and the non vibrated cervical musculature may have compensated for the effects of unilateral neck vibration, thus limiting its impact on standing balance.

In addition to no vibration and vibration standing balance conditions, this study explored the impact of a 10-degree head rotation to the left on standing balance performance. Although the effects of neck vibration on quiet standing balance were not significant in the current study, the challenge of maintaining head rotation during quiet standing did significantly shift average COP (AP) when compared to control conditions. The change in COP observed in this study is in agreement with previous work showing that head rotation results in a shift in COP towards the side of the occiput (Lamontagne et al., 2003). The current study sought to examine whether the challenge of maintaining a head rotated position while maintaining quiet standing would result in increased postural COP sway or path length. Although neither of these variables differed significantly during head rotation compared to the control condition, interestingly, when the impact of head rotation and the impact of vibration on RMS ML and AP sway were compared by participant, the results showed a positive significant relationship in the eyes closed condition. These findings suggest that individuals whose balance was challenged to a greater extent by an orientation change in the head were also impacted to a greater extent by neck vibration.

Additionally, when the impact of head rotation on COP (ML and AP combined) was compared to cervical JPE(SSA) SD, the significant negative correlation between these variables suggests that individuals with greater variability relocating SSA shifted their COP less during quiet standing when challenged by a head turn. Furthermore, when the impact of head rotation on COP was plotted against the impact of vibration on visual vertical perception error, the strong significant negative correlation suggests that individuals with a larger shift in COP during head rotation also had a larger shift in visual vertical perception error during neck vibration.

Altered visual sensorimotor function, such as smooth pursuit tracking, has been reported in individuals with suspected cervicogenic dizziness (Treleaven, 2011; Treleaven et al., 2006). The Smooth Pursuit Neck Torsion Test (SPNTT) is an emerging test for sensorimotor impairment related to cervicogenic dizziness, with the potential to be used for diagnostic purposes in this population (Treleaven et al., 2005). In this test, visual smooth pursuit tracking gain is evaluated while participants visually track a moving target in a head rotated position. Initial studies have shown that individuals suspected of cervicogenic dizziness demonstrate altered gain in the head rotated position (Treleaven, 2011; Treleaven et al., 2006). Although continued investigation is warranted, the current study's finding of potential relationships between the degree of COP shift during standing balance with a head turn and the degree of visual vertical perception shift during neck vibration, may suggest that even in a young healthy population there are detectable between subject differences in the way that head position change (real or perceived) impacts on both postural orientation and visual perception. These between subject differences may help explain why certain individuals are more at risk of cervicogenic dizziness symptoms following a neck injury than others.

5.4.6 Between subject relationships between cervical joint position error, postural orientation perception error and standing balance

The second objective of this study was to examine between subject variability in cervical JPE(SSA) (mean and SD) and its relationship to performance across the sensory perception tasks (visual, vestibular and body orientation) and standing balance. It was hypothesized that the impact of vibration would remain relatively constant within a person across the study tasks so that participants with smaller cervical JPE and SD would be impacted to a greater extent by vibration across all other tasks then participants with larger cervical JPE. Although the results of this study support a relationship between cervical JPE mean, standard deviation and impact of vibration, the results of the current study largely failed to support the hypothesis of neck vibration having a person specific consistent impact on performance across the various sensory tasks and standing balance.

5.4.7 Relationship between cervical JPE(SSA) and impact of vibration

The positive correlation between cervical JPE(SSA) mean and standard deviation was also observed in study 3 of this document. As discussed previously this provides evidence suggesting that individuals who are less accurate in relocating SSA are also less precise. In the current study cervical JPE was significantly negatively related to the impact of vibration on JPE(SSA), suggesting that individuals with the greatest JPE are less impacted by disruption of cervical proprioception through unilateral dorsal neck vibration. This trend was observed in Study 3 of this document though it failed to reach statistical significance (p=.0730). However, in that study there was a statistically significant negative relationship between cervical JPE(SSA) and the impact of vibration on SD. This suggests that neck vibration resulted in greater variability in performance among participants who were more accurate during no vibration conditions. One explanation for these findings is the idea that individuals more impacted by vibration are those who weight cervical proprioception information to a greater extent than other sensory inputs for the purposes of postural orientation. As discussed previously in this document, there is clinical evidence to support a reweighting in cervical proprioceptive importance for balance control purposes. This support comes primarily from populations such as torticollis, neck pain and vestibular loss, in which there is evidence of an up weighting or de-weighting of cervical proprioceptive information when it, or other sensory information becomes un-reliable (Bove et al., 2004; Kristjansson & Treleaven, 2009; Wannaprom, Treleaven, Jull, & Uthaikhup, 2018; Yagi et al., 1998).

5.4.8 Between subject differences of impact of vibration across sensory tasks and standing balance

Overall, in contrast to the study hypothesis, there was no statistically significant relationship between cervical JPE(SSA) and the impact of vibration on elbow JPE(90), OPE, or standing balance. Although across participants, elbow JPE(90) increased during neck vibration and recovery trials, there was no significant relationship between the impact of vibration on elbow JPE(90) and cervical JPE(SSA) mean, SD and impact of vibration.

In examining the relationship between the impact of vibration on VVPE and cervical JPE the current study did find a statistically significant positive relationship between the impact of vibration on VVPE and cervical JPE(SSA) SD. This finding suggests that participants who were more precise relocating SSA (smaller SD) had a greater shift in relative VVPE towards the left (vibrated side). This finding is interesting in that it seems to support the idea that better performance in relocating SSA may be related to greater visual spatial orientation disruption when neck proprioception is disrupted. This finding has clinical significance it provides additional support to the idea that individuals who rely on cervical proprioception information to a greater extent for postural orientation, may be impacted to a greater extent when this sensory information is disrupted. It may also help to explain why previous work exploring the impact of neck vibration on visual and spatial perception have repeatedly described a sample of participants as “non responders” to vibration. It is possible that these individuals weighed cervical proprioceptive information differently for the purposes of spatial orientation or postural orientation than the “responders”. Is it also possible, that poor JPE performance (larger mean and SD) may be a predictor of individuals who will be less impacted by a neck injury then those with better JPE, also supports the need for rehabilitation to improve cervical JPE again after injury in individuals reporting cervicogenic symptoms following a neck injury.

As a secondary point of interest, participants in the study were asked to self report their childhood participation in activity. Participants filled out a questionnaire that had them list the involvement in recreational and competitive organized activities outside of normal daily activity. Participants recorded the activity type, number of years participated and number of hours per week of participation for each activity. A single childhood activity score was formulated to represent this involvement in activity. It was hypothesized that childhood involvement in activity might shape proprioceptive sense in the body and neck and therefore was predicted that individuals with greater self report childhood activity hours would demonstrate lower cervical JPE(SSA) mean and SD and lower elbow JPE(90) mean and SD. Contrary to the hypothesis, when compared using the scatter plot, and a Pearson correlation coefficient, there was a statistically significant positive relationship between self reported childhood activity level and cervical JPE(SSA), suggesting that individuals with higher reported participation in childhood activity had greater error in relocating SSA. This result was surprising, and it is unclear why increased activity might be associated with worse performance the cervical relocation task. One explanation is that the relationship is may be due to error and represents a false positive result. Self report measures are known for evoking bias (Sallis & Saelens, 2000). Participants may over or underestimate their responses because of recall bias or social desirability bias (Sallis & Saelens, 2000). It is possible that the relationship may represent participant error or bias in reporting. However, in these instances it might be more likely to result in a non-significant relationship between the factors of interest, rather than the significant positive relationship that was seen in the current study.

5.5 Conclusions:

Overall, the results of this study show that unilateral dorsal neck vibration is capable of impacting not only the accuracy and precision of relocating subjective straight ahead, but has further reaching impacts on postural orientation and spatial orientation perception as shown by its significant impact on elbow joint position error and visual vertical perception error. Although the current study failed to find significant neck vibration induced impacts on standing balance, this may be the result of using a unilateral dorsal vibration approach rather than evidence a lack of impact on upright balance or perhaps it represents participants' ability to disregard the disruptive cervical proprioceptive inputs in favour of other sensory inputs. The current study findings, therefore, provide additional evidence supporting the theory that cervical proprioception is an important contributor to postural and spatial orientation perception by helping to shape the perception of ourselves within the environment. The statistically significant relationships between cervical JPE mean , standard deviation and impact of vibration suggest that individual variability in the weighting of cervical proprioception information for postural orientation and may be an important factor in understanding why some individuals are more impacted by altered cervical proprioception than others in a clinical setting.

6.0 General Discussion

6.1.0 Summary of Findings:

The aim of this thesis was to explore the role of cervical proprioception in balance and movement control in order to better inform on the assessment and treatment of individuals with suspected cervicogenic dizziness in a clinical setting. This thesis set out to advance the understanding of the relationships between cervical spine proprioception and the control of upright balance and perception of body/limb posture, to explore between subject variability in cervical proprioception and the impact of vibration on cervical joint position error. The work is viewed as a necessary step towards eventual clinical studies that can advocate for improved clinical procedures for physiotherapists when assessing and treating patients with suspected cervicogenic dizziness. Although the research within this document focused on young healthy participants, the findings of these studies could inform on understanding of the impact of altered neck proprioception on balance control in a clinical setting as well.

There were three predominant findings from this thesis. The first is that altering cervical proprioception using unilateral dorsal neck vibration significantly impacts on postural and spatial orientation perception involving the perception of head and elbow orientation, and visual vertical perception. In a proportion of participants, vibration also induced perceptual errors when reaching error towards a remembered target and when discerning positional orientation using primarily vestibular information, although across participants the main effect of vibration was not statistically significant during these two tasks. The second finding is the existence of significant between subject differences in cervical proprioception performance, as measured by joint position error mean and SD, as well as between subject differences in the impact of vibration on JPE performance and performance across the other sensory perception tasks examined. The third main finding from this thesis is that person specific characteristics may impact on cervical proprioception, as seen in differences in cervical JPE as well as the extent to which neck vibration impacts on cervical JPE. Continuing to explore these person specific characteristics as they relate to cervical JPE and the extent to which it impacts on postural and spatial orientation perception when altered, may represent an important component to personalizing rehabilitation and assessment strategies for patients with suspected cervicogenic dizziness in a clinical setting.

6.1.1 Altered cervical proprioception impacts on postural and spatial orientation perception in young healthy participants

This thesis repeatedly observed, across multiple studies, that altering cervical proprioception using unilateral dorsal neck vibration, impacted on postural orientation and spatial orientation perception. In studies 2, 3 and 4, there was a significant main effect of vibration on the perception of head orientation perception with increased error in relocating subjective straight ahead. Increased perceptual error with neck vibration also resulted in significant changes in elbow orientation perception error and visual vertical perception error in study 4. These findings are in support of previous works, discussed throughout this thesis, that have also reported perceptual changes in head orientation when cervical proprioception is altered either experimentally with muscle fatigue, vibration or taping techniques, or in a clinical populations with neck pain or following a whiplash injury (Ceyte et al., 2006; Gosselin & Fagan, 2014; Lee, Lee, Kim, Lee, & Kim, 2015; Rix & Bagust, 2001; Taylor & McCloskey, 1991; Treleaven, 2011). Importantly, the findings of altered elbow orientation perception, and visual perception error in response to neck vibration, observed in this thesis, provide additional evidence to support cervical proprioception as an important contributor to postural orientation and body schema formation use in postural control.

Although in the current work, altering cervical proprioception using unilateral posterior neck vibration failed to significantly impact measures of standing balance control, (average COP, RMS sway and PL) there is enough evidence in the current literature to suggest that this lack of significant findings may be due in part to the use of a unilateral vibration approach rather than evidence that cervical proprioception has no impact on upright balance. In disentangling its role in balance control, it is important however, to make the distinction between the likely importance of cervical proprioception in postural orientation versus reactive control (postural equilibrium). Cervical proprioception likely has a greater influence on postural orientation rather than reactive standing balance control which has been shown to be largely governed by lower extremity somatosensory input. This is suggested by the lack of significant differences in COP RMS sway observed in the current and previous studies where cervical proprioception is altered. The shift in average COP observed in response to neck vibration in other studies is reflective of a change in postural orientation perception. In the current thesis the significant posterior shift in COP during slight head rotation and its relationship to both cervical JPE variability and vibration induced visual vertical error perception also suggests a role of head position sense in shaping and informing on postural orientation perception and its contributors.

6.1.2 The importance of between subject differences in cervical Joint Position Error and their relationship to person specific characteristics.

An important finding of this thesis, observed in every study, was the presence of significant between subject variability in cervical proprioception and the impact that neck vibration had on cervical JPE. In study 1 of this thesis, significant between subject differences were observed in the extent to which unilateral neck vibration impacted on reaching error to a remembered visual target, suggesting that not all participants were impacted to the same extent by altering neck proprioception by the vibration. In study 2, significant between subject differences were observed in orientation error while maintaining or relocating the head to subjective straight ahead without unilateral dorsal neck vibration, during vibration and post vibration. As was visualized in the head orientation tracings during static maintenance of subjective straight ahead, participants could be categorized as “responders”, “non-responders” or “self-checkers” to vibration. During neck vibration, responders displayed a rapid change in head orientation from the perception of subjective straight ahead during no vibration conditions. In contrast, “non-responders” failed to demonstrate significant head orientation change during neck stimulation. A small proportion of participants deemed “self-checkers”, seemed to be intermittently influenced by neck vibration with bouts of head orientation change followed by apparent attempts to recover to the initially perceived subjective straight-ahead position. Post vibration impacts on perceived subjective straight ahead were also variable with participants demonstrating either rapid recovery or more prolonged orientation perception impacts from the vibration during the recovery period. This visualization of vibration response suggested significant differences in the extent to which participants were impacted by altered proprioceptive input from the neck. In study 3, these between subject differences were again observed and their relationships to person specific characteristics was examined. The findings of study 3 suggested that participants with the largest cervical JPE, and by proxy, poorer proprioceptive performance, were also more variable in relocating subjective straight ahead and tended to have greater cervical total strength, larger neck circumferences and a trend towards greater total neck active range of motion. In this study, participants who had lower JPE and variability were impacted to a greater extent by neck vibration. Lastly, study 4 of this thesis explored possible relationships between cervical JPE performance with and without vibration and participant performance across other sensory perceptual tasks and standing balance. In support of the findings of study 3, participants with larger cervical JPE were again more variable but impacted to a lesser degree by neck vibration than participants with smaller, less variable cervical JPE. In addition, participants who were less variable (more precise) in relocating SSA had a greater shift in visual vertical perception towards the side of vibration. These findings again suggest that individuals with better performance in the cervical proprioceptive task were impacted to a greater degree by unilateral dorsal neck vibration than those with poorer performance on the task. Interestingly in examining the impact of neck vibration on standing balance, although there was no main effect of vibration on RMS sway or path length, when between subject differences in the impact of vibration was compared to the impact of a head rotation on standing balance RMS sway the findings suggested that participants whose balance was impacted the greatest degree by rotating the head slightly were also impacted to a greater extent by altering cervical proprioception with neck vibration.

Although it is not uncommon to observe between subject differences in any task performance, what makes the repeated observation of between subject differences in cervical proprioception and the impacts on joint position error when it is altered with neck vibration important, is that it may help address some of the controversy surrounding cervicogenic dizziness. One of the principal arguments against considering cervicogenic dizziness as a distinct clinical diagnosis is that not all individuals with neck pain or injury report the symptoms of dizziness, unsteadiness or vague altered postural control described by those with suspected cervicogenic dizziness (Brandt & Bronstein, 2001; Peng, 2018). Confirming the presence of significant between subject difference in the response to altered neck proprioception from neck vibration may provide some explanation as to the between subject differences observed clinically in the presentation of symptoms following a neck injury. The between subject differences in task performance observed throughout this thesis in response to neck vibration, suggest that perhaps altered cervical proprioception impacts are subject specific with increased impacts in some and relatively little impact in others. Furthermore, the significant relationships observed between cervical JPE mean, standard deviation and impact of vibration and person specific characteristics such as neck strength, neck circumference, BMI in study three and between cervical JPE and reported childhood activity hours in study four, suggests that multiple factors may influence cervical proprioception capabilities and its impact when disrupted, at a person specific level.

There are several possible explanations for why some individuals may be impacted to a greater extant than others by neck vibration or altered cervical proprioception. One explanation is that individuals' weight cervical proprioception information at varying levels for the purposes of balance control. Evidence for differential weighting exists in clinical populations. As discussed in the introduction of this thesis, studies examining individuals with torticollis, and vestibular loss have demonstrated a de-weighting of cervical proprioceptive information used in standing balance control (Bove et al., 2004; Cutfield et al., 2014, Lekhel el al., 1997) Therefore, it is possible that a cervical proprioceptive weighting differences also exist in a young healthy population. Although the reasons behind for this potential sensory weighting variability is unclear, it is possible that person specific characteristics, experiences and acquired skills may play a role. In study four of this thesis, the role of extracurricular childhood physical activity and current activity level in cervical JPE was probed as a possible contributing factor in shaping cervical proprioception ability and weighing. Contrary to the study hypothesis that increased activity level would correlate with reduced cervical and elbow JPE, the scatterplot results suggested that individuals with greater amounts of self reported extracurricular athletic participation in childhood had increased JPE.

Another possible explanation for the between subject differences in the impact of vibration that should be considered in this thesis, but also every other study using vibration to alter proprioception, is that person specific differences related to vibration impact may be related to stimulus dose. Although every attempt was made in this thesis to accurately landmark and affix the vibration unit in a consistent fashion across participants, it is possible that individual differences in body morphology and anatomy could result in differing doses of vibration. It is known that frequencies, amplitude and muscle tension can impact on vibration effects (Carlsöö, 1982). It is therefore possible that some of the differences between participants in response to vibration may relate to the amount of stimulus to the neck muscles and could therefore be influenced by factors such as adhesive quality to the skin, proportion adipose tissue versus muscle size in the neck or placement of the vibration unit. To address some of these concerns, study 3 of this study aimed to examine the consistency of vibration effects across vibration side, testing day and relocation target direction and found no significant differences in these variables. Additionally, even though there was a significant negative correlation between the impact of vibration and neck circumference and BMI, suggesting that larger necks in participants with potentially more adipose tissues were less impacted by vibration, in no vibration conditions, both neck circumference and total strength were significantly positively corelated to cervical JPE. These findings suggest that regardless of neck vibration, there are relationships between cervical proprioception and person specific characteristics. However, if neck vibration is to be used to alter cervical proprioception in future studies, it may be important to rule out the possibility of dosage related impacts by investigating methods of standardizing vibration dosage based on person specific factors such as BMI and muscle morphology.

6.2.0 Limitations

6.2.1 Vibration as a means to alter neck proprioception

There were some general limitations throughout the studies in this thesis. In all studies, unilateral dorsal neck vibration was used to alter cervical proprioception in an attempt to explore the impacts of disrupting sensory information from the neck. Although vibration has been utilized extensively in the literature to alter proprioceptive information from many parts of the body, the reality is that underlying mechanisms involved in clinical neck pain and injury as they relate to altered proprioception, are likely far more complex than the vibration induced changes in proprioception used throughout this thesis. The use of vibration stimulation, therefore, has the advantage of specifically impacting proprioceptive input from the muscles it is used on by way of muscle spindle activation and is therefore more of a targeted method to examine the impact of cervical proprioception. Unfortunately, as vibration stimulation essentially examines the repercussions of inducing irrelevant proprioceptive information, the results may inadvertently also be a measure of an individual's ability to inhibit or disregard this unreliable sensory input. In contrast, high velocity deceleration injuries have the potential to damage connective tissue, muscle and nervous tissue, mechanoreceptors and joint capsules. Tissue injury, inflammation, nociception mechanisms and muscle fatigue can all play a role in impaired proprioceptive function in clinical populations, but their impacts are not limited to proprioceptive function alone. Consequently, disentangling the role of a single sensory system in this clinical population is challenging. As a result, direct comparisons between the experimentally derived impacts on cervical proprioception observed in this thesis and clinically observed impacts from altered neck proprioception need to be done with caution.

6.2.2 Small sample sizes

An additional limitation across the studies in this thesis were the small sample sizes. The sample sizes in study 1 and 2 of this thesis were determined based on those of previous studies investigating the impact of neck vibration the body and spatial orientation perception using a within subject repeated measures study design (McIntyre & Seizova-Cajic, 2007; Taylor & Mccloskey, 1991). However, the high error variability during the reach to target task of study 1 may have diminished the expected effect size relative to task variability and could therefore have benefited from additional subjects. In studies 3 and 4 of this thesis, although the within subject analysis had enough statistical power to detect statistically significant main effects of vibration, the small sample sizes were likely under powered for the the purposes of the correlational analysis used to explore between subject differences in JPE and the impact of vibration related to person specific factors or performance across the various sensory perceptual tasks. A sample size closer to 20 in studies 3 and 4, may have provided a clearer understanding of the relationships that were explored. Additionally, statistical adjustments, such as a Bonferroni correction, were not made to the correlational analysis despite examining multiple comparisons. Given the exploratory nature of these correlation comparisons, it was feared that such conservative adjustments would have prevented the detection of relationships of interest.

6.2.3 The use of multiple systems to record test cervical JPE

Three different device systems were used in this thesis to evaluate cervical JPE. Two of the devices, Xsens, and Shimmer Sensing, are wireless inertial measurement units (IMU) and the third a magnetic field-based motion capture system. As one of the overall aims of this thesis was to provide clinical recommendations that might improve the assessment and treatment of patients with cervicogenic dizziness seen by physiotherapists, the two portable wireless systems (Shimmer and Xsens) were utilized to measures cervical JPE as they represented systems that could be accessible and affordable for clinicians. Although using the Polhemus system across all studies may have been desirable to allow for consistency across studies, the likelihood of implementing this type of device in a clinical setting is less likely, due to its higher cost and the necessity of a larger assessment space devoid of large metal objects, required for its proper use. The IMU sensor systems however do have some limitations when used to measure displacement or orientation change. The IMU systems use wireless inertial sensors to collect and record kinematic data such as acceleration and angular velocity. In the case of Xsens, real-time integration programing allows for the collection of orientation data as well, a feature now available in newer Shimmer sensors. However, using IMU sensor when calculating positional or orientation displacement can result in integration drift as was discussed in study 4 of this thesis. Although the real-time integration calculation software can reduce or minimize this drift, it is something to be aware of. Of benefit, however, is the collection of acceleration and velocity information by these devices. Although not explored in this thesis exploring these movement kinematics as they relate to the impact of proprioceptive dysfunction on the control of movement, may represent a future research direction in continuing to explore person specific differences in cervical proprioception. Although consistency in the devices used to measure cervical JPE across the thesis studies may have been more desirable, exploring the use of various assessment devices for measuring cervical JPE allowed us to explore their possible use clinically and the cervical JPE values, SD and impacts from vibration across studies measured using the different devices were relatively consistent and comparable to previously reported findings.

6.3.0 Importance of exploring between subject differences and going beyond the mean

Two important aspects of this thesis that may further the understanding of the role of cervical proprioception in balance control and its implications in cervicogenic dizziness are; 1. The exploration of between subject differences in cervical proprioceptive function and in response to neck vibration and 2. Looking beyond the mean by exploring individual variability of cervical JPE and how this variability relates to variables of interest.

Exploring between subject differences as they relate to cervical proprioception function and the extent to which it is impacted by neck vibration, is a unique aspect of this thesis that has the potential to aid in the understanding of why some individuals seem more impacted by a neck injury than others. Research often centers upon reporting overall outcome averages by collapsing across study participants. This grand averaging allows for a broader applicability of results to a population of interest. Although helpful in understanding overall effects, averaging across participants without regarding the variability between participant performance may result in a missed opportunity to better understand the findings. In this thesis, significant between subject differences in both cervical proprioceptive performance and the impacts of altering cervical proprioception, were observed in every study. Although previous works have reported differences in the presence and magnitude of vibration induced visual illusions among participants or have included participants based on their reporting of vibration induced illusions, the importance of these between subject differences has not been explored. In this thesis, the findings of significant relationships between cervical JPE and person specific characteristics such as neck circumference, strength and ROM provides insight into possible factors related to proprioceptive ability and the severity of impact when it is altered at an individual level. The real benefit to this additional information may be in its potential use in personalizing assessment, treatment and possibly preventative strategies for patients in a clinical setting.

Another important aspect of this thesis was the exploration of variability in proprioceptive performance in addition to the mean. This again provided additional insight into cervical JPE performance. In using JPE as a proxy for proprioceptive function, assessment of both performance accuracy (mean) and precision (SD) are required to get a better picture of proprioceptive function. For example, in Study 3 it was found that although participants varied in the cervical JPE mean when relocating SSA versus the 30-degree target, their variability was significantly positively correlated, indicating a consistency in precision across tasks despite varying accuracy. Additionally, in study 4, JPE precision (SD) was found to be significantly related to the impact of vibration on vertical perception error and average COP during head rotated standing balance. Examining both mean and variability in the variables of interest in this thesis provided insight into cervical proprioceptive functioning at an individual level, information that may have been missed if only and overall JPE mean had been examined.

6.4.0 Proposed next steps, future directions, and implications for clinical practice

Although the studies in this thesis focused on young healthy participants, the findings of altered visual vertical perception error and head and elbow orientation perception error suggest that to fully understand the impairments associated with cervicogenic dizziness, assessment strategies should expand to include body orientation perception and visual vertical perception as well. Additionally, future assessment and treatment strategies for cervicogenic dizziness might benefit from the use of portable technology and the analysis of not only performance means, but of variability in cervical and elbow JPE and visual vertical perception error as well.

6.4.1 Proposed next steps

The findings of this thesis prompt continued research in a number of areas. Future studies should focus on; 1. Continuing to explore how person specific characteristics/skills and training relate to cervical JPE and cervicogenic dizziness. 2. Evaluating the feasibility of using portable technology clinically, to assess cervical and JPE and visual vertical perception error in patients with neck pain. 3. Investigating the effectiveness of multimodal treatment approaches for cervicogenic dizziness.

6.4.2 Person specific characteristics and their impact on JPE and cervicogenic dizziness

As highlighted in the studies of this thesis, between subject differences exist in cervical JPE and the extent to which altering proprioception impacts on perception. Although the results of study 3 and 4 provide some insight into possible person specific characteristics that may impact on cervical JPE performance and by proxy, cervical proprioceptive performance, it still remains unclear which characteristics are of greatest importance and what other characteristics, expertise or acquired skillsets may also be important. Future research should continue to examine factors that impact on between subject differences in cervical JPE but also clinically, among individuals with suspected cervicogenic dizziness, in an attempt to discern whether certain factors predispose individuals to greater impact from neck injury.

6.4.3 Suggestions for clinical assessment and the use of portable technology

The findings of this thesis suggest the possibility of incorporating additional testing into a physiotherapy assessment for individuals with neck pain or neck trauma when cervicogenic dizziness is suspected. In any instance where symptoms of dizziness, light-headedness or imbalance are reported, especially following neck trauma, it is vitally important to first rule out vascular, central nervous system or vestibular sources. However, once additional sources of pathology are ruled out and a cervical source is suspected, incorporating postural orientation and spatial perception testing into a typical physiotherapy assessment may be beneficial. Although additional research is warranted, the results of this thesis provides some evidence that body orientation perception testing (elbow JPE) and visual vertical perception testing (box and dot test) could be used as assessment tools to help in evaluating cervicogenic dizziness related impairments, direct targeted rehabilitation strategies and monitor improvement. Although implementing cervical JPE testing using the traditional approach described by Revel et al. (1991) is slowly becoming more common, current clinical physiotherapy assessment practices do not regularly assess visual vertical perception or body orientation perception error in relation to neck pain. Luckily, with the continued improvements in portable technology, implementing these tests as well as using the digital type cervical JPE testing as was performed in this thesis has never been easier.

The work of this thesis highlights the possible use of portable technology in physiotherapy assessment and rehabilitation for cervicogenic dizziness. In order to fully address possible secondary impairments associated with cervical spine pain and injury, clinicians should incorporate the evaluation of body orientation perception and visual perception into clinical assessment. Although analogue methods have been used previously, wireless accelerometers have the potential to serve as a useful assessment tool. In study 2 and 4 of this thesis, two portable, wireless IMU sensor systems were used. The Xsens and Shimmer systems were used as they represented wireless, portable measurement systems with the capability of meeting the physical space limitations of clinical use. However, given the cost of the Xsens system, the Shimmer system is the more affordable, clinically feasible measurement option.

For a measurement system to be useful in a clinical setting it needs to meet several criteria. The first is that it must be valid and clinically meaningful. Second, measurement tools mut be affordable. Motion capture systems that cost tens of thousands of dollars are beyond the reach of most private practitioners. Third, given the time constraints for a typical clinical assessment and treatment appointment, any measurement tool must be easy to use with minimal time requirements for set up, assessment and data processing. The Shimmer system meets all of the above requirements. It is affordable, with a cost of a few thousand dollars for a multiple sensor kit, the sensors can be easily and comfortably applied to a range of joint segments and the newer systems come with software packages that provide real-time integration of gyroscope data into orientation changes with minimal drift. Additionally, though not examined in this thesis, the acceleration and velocity data from these sensors could also be examined to provide additional details about JPE movement. Taken together, portable wireless accelerometers represent a possible tool for measuring JPE in a clinical setting.

In addition to wireless accelerometers, study 4 of this thesis employed of a digitized version of the analog Rod and Frame Test (box and dot test) to examine visual vertical error. This format negates the use of large and cumbersome devices used in the original version and has been validated in a digitized format As visual spatial orientation was shown to be impacted by altered cervical proprioception, assessing for impairments in visual vertical error among patients with neck pain and injury should also be added to typical assessment strategies. Digital versions of the Box and Dot test could be produced in the future as an affordable, easily administered and time efficient standalone assessment program for clinical use.

6.4.4 Treatment approaches

The findings of this thesis support of the likelihood that a multi modal approach to rehabilitation for cervical proprioception may be required. To date, relatively few studies have investigated rehabilitation strategies for cervicogenic dizziness. The handful of studies that have, suggest some benefit in using manual therapy techniques to improve joint mobilization and soft tissue mobility alone or in combination with vestibular rehabilitation techniques may have some (Lystad et al., 2011; Reid, Callister, Snodgrass, Katekar, & Rivett, 2015; Reid et al., 2012; Yacovino & Hain, 2013). Additionally, some authors have also found improvement in cervical JPE and or dizziness symptoms following neck strengthening, cervical proprioceptive exercise protocols and the use of visual stability exercise such as smooth pursuit, cervicocollic reflex training in the treatment of cervicogenic dizziness (Treleaven, 2008; Wrisley et al., 2000). Although further research is required in a clinical setting, this thesis' findings of body orientation and spatial orientation perceptual impairments when neck proprioception is altered provide addition evidence to suggest that a multimodal approach to cervical proprioceptive rehabilitation training is required. Future studies should examine the impact of a multisensory cervical proprioceptive rehabilitation protocol using outcome measures to assess not only cervical JPE outcomes, but body orientation perception and visual vertical perception error as well.

6.5 Conclusions:

Overall, the findings of a main effect of neck vibration on cervical and elbow joint position error and visual vertical perception error support the theory that altered proprioceptive information from the cervical spine has an important role in postural orientation. Additionally this thesis provides evidence to support the importance of identifying and investigating between subject differences as they relate to cervical proprioception and the impacts of postural and spatial orientation perception when cervical proprioception is altered as these between subject differences may help explain differences in clinical presentation of symptoms after a neck injury. Furthermore, the methodology used in this study supports the incorporation of additional assessment techniques using portable technology for measuring head proprioception and visual vertical error in a clinical setting when cervicogenic dizziness is suspected.

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