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Article

Neck Muscle Vibration Alters Upper Limb Proprioception as Demonstrated by Changes in Accuracy and Precision During an Elbow Repositioning Task

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Abstract: Upper limb control depends on accurate internal models of limb position relative to the head and neck, accurate sensory inputs, and accurate cortical processing. Transient alterations in neck afferent feedback induced by muscle vibration may impact upper limb proprioception. This research aimed to determine the effects of neck muscle vibration on upper limb proprioception using a novel elbow repositioning task (ERT). 26 right-handed participants aged 22.21 ± 2.64 performed the ERT consisting of three target angles between 80°-90° (T1), 90°-100° (T2) and 100°-110° (T3). Controls (CONT) (n=13, 6F) received 10 minutes of rest and the vibration group (VIB) (n=13, 6F) received 10 minutes of 60Hz vibration over the right sternocleidomastoid and left cervical extensor muscles. Task performance was reassessed following experimental manipulation. Significant time by group interactions occurred for T1: ($F_{1,24}$ = 25.330, p < 0.001, η_p^2 = 0.513) where CONT improved by 26.08% and VIB worsened by 134.27%, T2: ($F_{1,24}$ = 16.157, p < 0.001, η_p^2 = 0.402) where CONT improved by 20.39% and VIB worsened by 109.54%, and T3: ($F_{1,24}$ = 21.923, p < 0.001, η_p^2 = 0.447) where CONT improved by 37.11% and VIB worsened by 54.39%. Improvements in repositioning accuracy indicates improved proprioceptive ability with practice in controls. Decreased accuracy following vibration suggests that vibration altered proprioceptive inputs used to construct body schema, leading to inaccurate joint position sense and the observed changes in elbow repositioning accuracy.

Keywords: Neck Muscle Vibration; Proprioception; Body Schema

1. Introduction

The cortical organization of sensory information from the upper limb is highly dependent on head and neck position [1]. Neck muscle proprioception plays a significant role in balance, movement organization and forming accurate body schema [2]. To compute the position of the upper limbs, the central nervous system (CNS) references incoming sensory information against the position of the head and neck. Proprioception is defined as the conscious and unconscious awareness of the body's position, mediated by proprioceptors in muscle tissue, joints and tendons [3]. Previous research demonstrates that muscle spindles are the major proprioceptors of the neck and that neck muscles have the highest density of proprioceptors in humans [4-6]. Body schema is the cortical perception of the location, orientation and functional integrity of the body and it's appendages in space [7]. It is cortically constructed through the integration of somatosensory and visual information involving a complex network of cortical areas that process information using the most appropriate reference frame [7, 8]. Body-centered reference frames provide a topographical representation of the body in reference to the position of the head and neck, and exist primarily in the primary and secondary somatosensory cortices [8, 9]. Eye-centered reference frames compute the location of body parts using information encoded in the visual cortices [7]. In the absence of visual information, proprioceptive information from muscle spindles becomes increasingly more important. Given this, alterations in

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

Previous research has demonstrated that chronic neck pain and subclinical recurrent neck pain (SCNP) alter afferent input from the neck and impact many cortical processes including proprioception [1, 10-12], sensorimotor integration (SMI) [13, 14], and multisensory integration [15, 16]. When comparing the effects of SCNP on head, shoulder, trunk and whole body positions during active and passive movement of the right shoulder, Paulus and Brumagne found significant differences in head movements between groups suggesting inconsistencies in reference frame selection [1]. This indicates altered cervical proprioception and suggests that individuals with SCNP demonstrate altered proprioceptive processing, possibly due to re-weighing of sensory information. Cervical extensor muscle fatigue leads to impairs upper limb proprioception [17], altered sensorimotor integration and reduced motor accuracy of the upper limb [18]. These effects were greater in the absence of visual information of the target [18]. Head orientation also influences upper limb proprioception, demonstrated by deviations in reproduced hand drawings while the head was tilted in either direction [19]. Head rotation in either direction has also been shown to generate increased joint position error of the upper limb, indicating an impact on upper limb proprioception [20]. Additionally, these studies provide strong evidence that proprioceptive dysfunction is exacerbated in the absence of visual feedback [20, 21].

High frequency, low amplitude vibration over a muscle belly excites muscle spindles and the associated afferent nerves (primary (Ia) afferents) [22]. The CNS perceives this as joint rotation and movement thereby generating illusions of movement if the vibration frequency exceeds 30Hz [23, 24]. This is supported by research done by Knox and Hodges, who found that vibration of the left sternocleidomastoid (SCM) and contralateral splenius at a rate between 59-64Hz was sufficient to induce illusions of head rotation [25]. Other research demonstrated that 10 minutes of SCM vibration at rates between 5-100Hz was sufficient to increased upper limb position tracking error above controls, with rates above 60Hz generating prolonged error persisting up to 22 hours following vibration [26].

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

2. Materials and Methods

2.1. Participants

26 healthy participants, 14 males and 12 females, were recruited for this study and randomly allocated to the vibration (n=13, 6 females) or control (n=13, 6 females) group. Inclusion criteria included right-hand dominant participants between 18 and 30 years old. Handedness was determined by scoring above 40 on the Edinburgh Handedness Inventory. The neck disability index (NDI) was used to screen for neck pain and a score of less than 5 was required for eligibility [27]. Exclusion criteria included left hand dominant individuals and neurological or neuromuscular disorders including recurrent neck pain multiple sclerosis (MS), epilepsy and seizure disorders, autism spectrum disorder (ASD) and attention deficit hyperactivity disorder (ADHD). This research was reviewed by the University of Ontario Institute of Technology (Ontario Tech University) Research Ethics Board and received ethical approval [REB #16520].

2.2. Elbow Repositioning Task (ERT)

The elbow proprioception device was composed of a mechanical goniometer containing a handle housing a small button. This device was fixed to an adjustable table so that the handle fit comfortably in the palm of each participant's right hand while standing in anatomical position with the elbow in extension. Prior to beginning the protocol, participants were given 3-5 familiarization trials to ensure comfortability with the device and the movement. To start the protocol the researcher passively flexed the participants elbow to the appropriate target angle by moving the mechanical arm and maintained this position for 5 seconds before returning the participant to a neutral position (0°). Participants instructed to reproduce the target angle as accurately as possible by flexing the elbow to where they perceived the target to be. The ERT consisted of 3 target angles presented in 3 blocks, block 1 had a target between 80°-90°, block 2 had a target between 90°-100° and block 3 had a target between 100°-110°. These angles were selected as participants would be using mainly muscle spindle feedback, as joint capsule stretch and accessory movements at other joints (shoulder and wrist) would be minimized. Each block was composed of one target angle and 3 replication trials. Between blocks, participants performed two full ranges of motion, moving from elbow extension to elbow flexion to reduce thixotropic contributions transferring between targets. Vision occluding goggles were worn for the duration of this task to eliminate visual feedback of the upper limb. Participants rated their perceived exertion using the Borg's Rated Perceived Exertion (RPE) scale at baseline and at the end of each block. Preliminary testing has shown that this task did not induce fatigue and revealed minimal learning effects as the average error remained similar across blocks.

2.3. Neck Muscle Vibration

Two custom built DC-motor vibrators were firmly affixed over the right sternocleidomastoid (SCM) and left cervical extensor muscles (CEM) using hypafix tape to ensure sufficient contact with the neck. Vibrators measured 4cm in diameter and were placed 2cm anterolaterally and 6cm inferior to the mastoid process for the SCM and 2-3cm lateral to the C5 spinous process for the CEM. Vibration was done at a frequency of 60Hz for a duration of 10 minutes while the participants wore vision occluding goggles to eliminate visual feedback. To eliminate bias, all participants were fitted with the vibration set-up however the vibrators were only turned on for those allocated to the vibration group. Participants in both groups were asked *"In terms of the position or direction of your head and neck, how do you feel?"* to evaluate whether participants experienced movement illusions. This question was introduced at the beginning of the protocol and was asked again after the 10-minute period.

2.4. Experimental Procedure

Participants completed the baseline ERT as outlined in section 2.2. Following proprioceptive measures, participants allocated to the vibration group received 10 minutes of neck muscle vibration while participants allocated to the control group received 10 minutes of blindfolded rest. Following the vibration or rest intervention, participants completed post-intervention ERT.

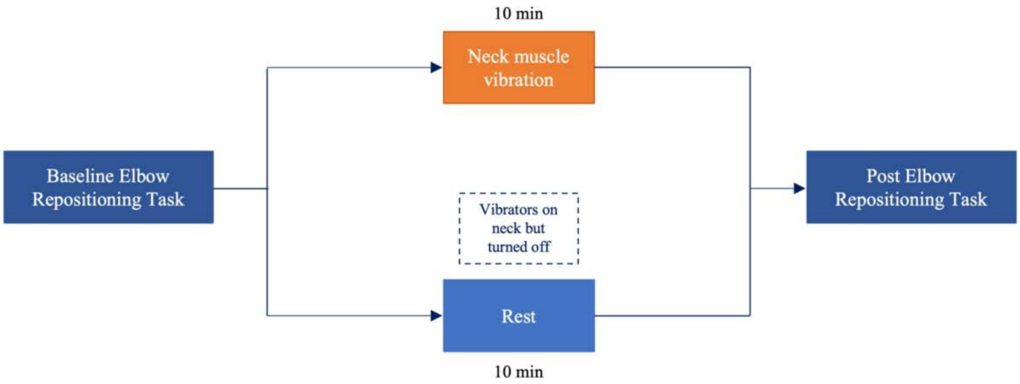

Figure 1. Flow of experimental procedures for both groups. For the rest condition, vibrators were placed on the neck but not turned on.

2.5. Data Processing

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

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

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

Absolute percent error and variable percent error were calculated at baseline and post-intervention for each target angle and normalized to baseline by dividing the post value by the baseline value before being averaged for each group.

2.6. Statistical Analysis

SPSS version 26 (Armonk, New York, USA) was used to perform all statistical analyses. Normalized absolute error and normalized variable error data were analyzed using two separate 2 x 2 two-way repeated measures multivariate analysis of variance (ANOVA) with group (vibration/control) as a factor and time (pre/post) as the repeated measure. Both ANOVAs had pre-planned simple contrasts to baseline. The Shapiro-Wilk's test was used to test for the normality assumption of ANOVA. If this assumption was violated, log transformations were applied to ensure datasets were normally distributed. Statistical significance was set as $p \leq 0.05$ for all statistical tests. Partial eta squared values are reported with small (0.2), medium (0.5) and large (0.8) effect sizes for ANOVAs [28].

3. Results

Any perceived movement of the head or neck in the absence of movement occurring described by participants was reported as an illusion of movement. 12 of the 13 participants in the vibration group reported movement illusions. The reported illusions are summed up in Table 1. No illusions were reported in the control group.

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

Reported Illusion	Frequency	Percentage

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

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

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

3.1. Accuracy: Absolute Error

For target 1, there was a significant time by group interaction ($F_{1,24} = 25.330$, $p < 0.001$, $\eta_p^2 = 0.513$) as well as a significant effect of time ($F_{1,24} = 16.414$, $p < 0.001$, $\eta_p^2 = 0.406$), where absolute error decreased by 26.08% ± 0.488 for controls and increased by 134.27% ± 1.23 for vibration (Figure 2a). There was a significant time by group interaction ($F_{1,24} = 16.157$, $p < 0.001$, $\eta_p^2 = 0.402$) as well as a significant effect of time ($F_{1,24} = 13.444$, $p = 0.001$, $\eta_p^2 = 0.359$) for target 2, where absolute error decreased by 20.39% ± 0.619 for controls and increased by 109.54% ± 1.495 for vibration (Figure 2b). There was a significant time by group interaction ($F_{1,24} = 21.923$, $p < 0.001$, $\eta_p^2 = 0.447$) as well as a significant effect of time ($F_{1,24} = 5.753$, $p = 0.025$, $\eta_p^2 = 0.193$) for target 3, where absolute error decreased by 37.11% ± 0.444 for controls and increased by 54.39% ± 0.755 for vibration (Figure 2c).

Table 1. Normalized and absolute elbow proprioception accuracy data for both groups.

		Time	
		Pre	Post
Normalized Elbow Repositioning Accuracy			
Target 1: 80° - 90°			
Absolute error controls (%)	*** $p \leq 0.001$	1 ± 0	0.74 ± 0.49 ***
Absolute error vibration (%)		1 ± 0	2.34 ± 1.23 ***
Variable error controls (%)	** $p \leq 0.01$	1 ± 0	0.79 ± 0.49 **
Variable error vibration (%)		1 ± 0	2.09 ± 1.80 **
Target 2: 90° - 100°			
Absolute error controls (%)	*** $p \leq 0.001$	1 ± 0	0.79 ± 0.62 ***
Absolute error vibration (%)		1 ± 0	2.09 ± 1.49 ***
Variable error controls (%)	** $p \leq 0.01$	1 ± 0	0.86 ± 1.06 **
Variable error vibration (%)		1 ± 0	2.19 ± 3.14 **
Target 3: 100° - 110°			
Absolute error controls (%)	*** $p \leq 0.001$	1 ± 0	0.63 ± 0.44 *
Absolute error vibration (%)		1 ± 0	1.54 ± 0.75 *

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Variable error controls (%)	** *p* ≤ 0.01	1 ± 0	0.64 ± 0.51
Variable error vibration (%)		1 ± 0	1.36 ± 0.86
Absolute Elbow Repositioning Accuracy			
Target 1: 80° - 90°			
Absolute error controls (%)		4.13 ± 1.71	3.05 ± 1.35
Absolute error vibration (%)		2.89 ± 1.59	6.79 ± 3.04
Variable error controls (%)		6.42 ± 3.21	5.11 ± 2.53
Variable error vibration (%)		4.96 ± 3.18	10.40 ± 5.66
Target 2: 90° - 100°			
Absolute error controls (%)		3.37 ± 1.82	2.68 ± 1.32
Absolute error vibration (%)		2.52 ± 1.53	5.27 ± 1.24
Variable error controls (%)		5.18 ± 2.86	4.44 ± 2.59
Variable error vibration (%)		3.72 ± 2.85	8.15 ± 3.55
Target 3: 100° - 110°			
Absolute error controls (%)		3.45 ± 1.38	2.17 ± 1.02
Absolute error vibration (%)		2.78 ± 1.63	4.28 ± 1.43
Variable error controls (%)		5.42 ± 2.37	3.45 ± 1.76
Variable error vibration (%)		4.85 ± 3.31	6.61 ± 3.01

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

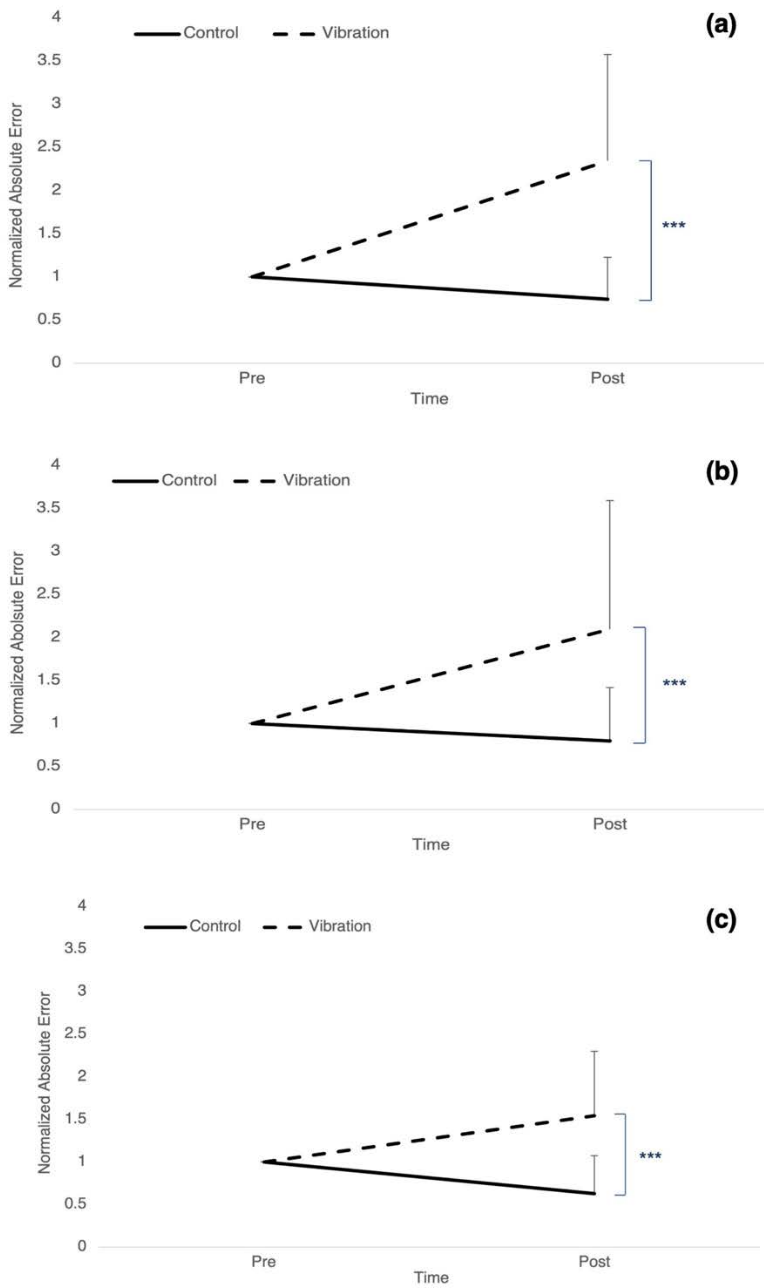

Figure 2. Normalized mean absolute error for controls (solid line) and vibration group (dashed line). Post measures have been normalized to baseline scores. (a) target angle 1 between 80-90 degrees. (b) target angle 2 between 90-100 degrees. (c) target angle 3 between 100-110 degrees. Error bars represent SD. (*** P ≤ 0.001).

3.2. Precision: Variable Error

Target 1 had a significant time by group interaction ($F_{1,24}$ = 10.510, p = 0.003, η_p^2 = 0.305) as well as a significant effect of time ($F_{1,24}$ = 7.917, p = 0.01, η_p^2 = 0.248) where variable error decreased by 20.43% ± 0.49 in controls and increased by 109.55% ± 1.80 in the vibration group (Figure 3a). For target 2, there was a significant time by group interaction ($F_{1,24}$ = 9.280, p = 0.006, η_p^2 = 0.279) as well as a significant effect of time ($F_{1,24}$ = 10.443, p = 0.004, η_p^2 = 0.303), where variable error decreased by 14.22% ± 1.06 in controls and increased by 119% ± 3.14 in the vibration group (Figure 3b). There was a significant time by group interaction ($F_{1,24}$ = 12.226, p = 0.002, η_p^2 = 0.337) for target 3, where variable error decreased by 36.26% ± 0.502 in controls and increased by 36.31% ± 0.86 in the vibration group (Figure 3c). However, there was no effect of time.

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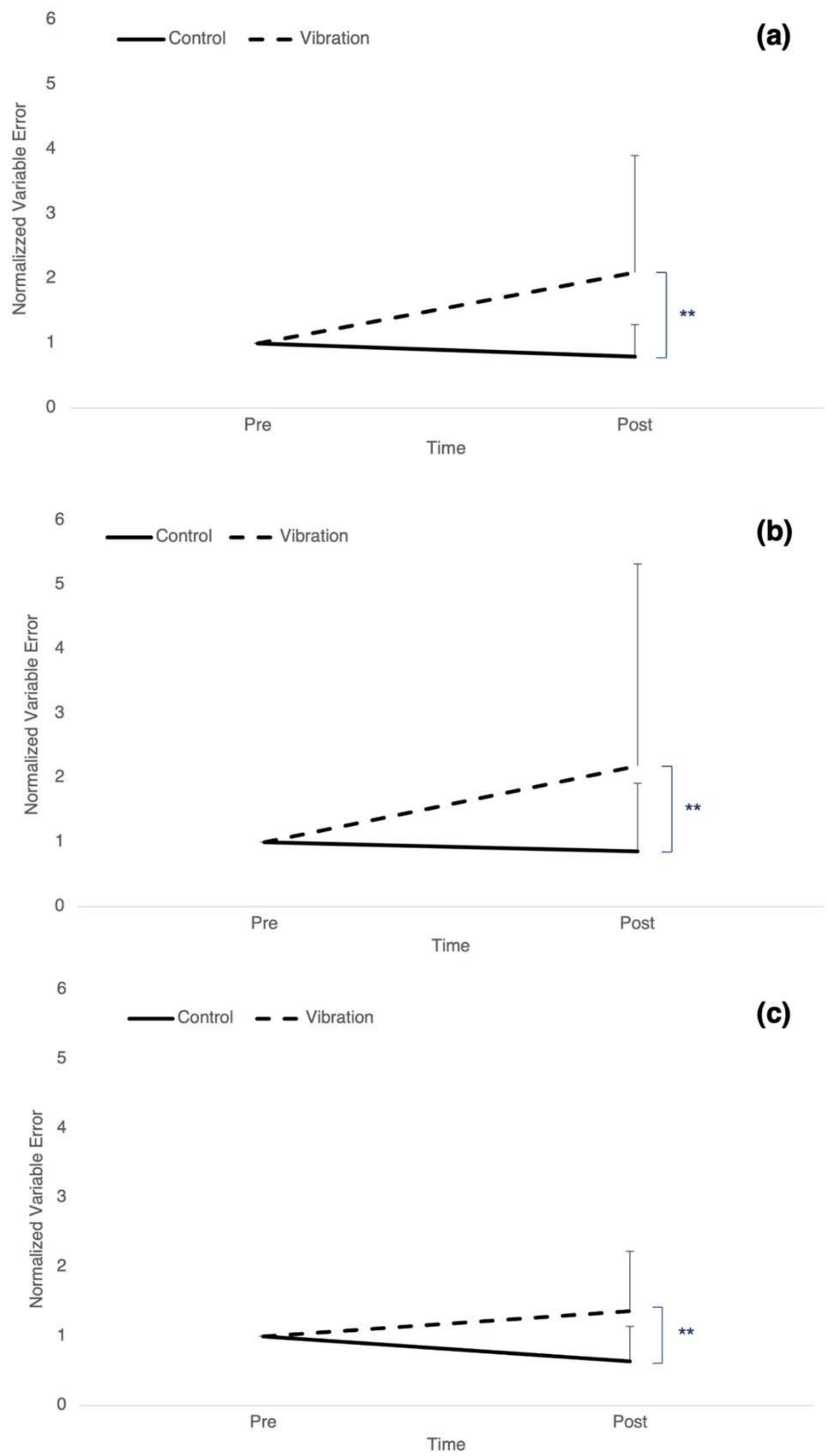

Figure 3. Normalized mean variable error for controls (solid line) and vibration group (dashed line). Post measures have been normalized to baseline scores. (a) target angle 1 between 80-90 degrees. (b) target angle 2 between 90-100 degrees. (c) target angle 3 between 100-110 degrees. Error bars represent SD. (*** $P \leq 0.001$).

4. Discussion

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

These results of this experiment illustrate vibration-induced alterations in upper limb proprioception. At target angles between 80-90 degrees and 90-100 degrees, repositioning error increased two-fold in the vibration group. By contrast, controls demonstrated 26.08% and 20.39% reductions in error respectively. Previous research supports this finding showing reduced error when the head was in a neutral position (control condition) while those who had their head rotated in either direction or flexed forward exhibited significantly increased joint position sense error [20]. This is further supported by previous research in SCNP populations which saw altered proprioceptive processing and joint position sense in an SCNP group compared to controls [10, 29]. At target angles between 100-110 degrees, repositioning error continued to increase in the vibration group while error decreased in controls. This coincides with previous work showing increased tracking error of the upper limb following SCM vibration [25, 26] as well as decreased motor accuracy of an upper limb motor sequence task following vibration of the biceps tendon [24]. Additionally, similar results were found in fatigue studies, reporting impaired upper limb proprioception following CEM fatigue protocols compared to controls [17, 30].

These results also demonstrate significant reductions in proprioceptive precision as a result of vibration. While accuracy refers to the distance between a measurement and the correct value of the quantity being measured, precision measures the variability of the measurements in reference to one another [31, 32]. At targets between 80-90 degrees and 90-100 degrees, there was a two-fold increase in variable error in the vibration group. By contrast, the control group exhibited 20.43% and 14.22% reductions in variable error respectively. At target angles between 100-110 degrees, variable error increased by 36.31% in the vibration group while it decreased by 36.26% in controls. This suggests that vibration not only impacts accuracy of the upper limb proprioception, as measured by changes in absolute error, but also precision as measured by changes in variable error. Similar results have been shown in previous work, which reported significant increases in variable error those with non-specific neck pain when examining position sense acuity and tracking position error of the upper limb [29]. These results provide strong evidence that neck muscle vibration negatively impacts precision and accuracy of the upper limb as the vibration group was consistently further from the target and exhibited higher variability in the reproduced angles when compared to controls.

While repositioning error was higher in the vibration group relative controls, both groups had the lowest degree of error when the target was between 100-110 degrees. This is likely the result of greater soft tissue approximation between the structures of the anterior upper arm and forearm as elbow flexion approaches its end range of motion. This is supported by previous studies that reported improvements in joint position sense as the target angle approached end range [33, 34], which can be attributed to increased stimulation of capsuloligamentous mechanoreceptors in the end ranges of motion due to deformation of their parent tissues [35, 36].

The CNS is dependent on accurate perception of the position of the head and neck to permit proper sensory processing and motor control via spindle inputs from cervical musculature. Transmission of sensory information from the head, neck and upper limbs is regulated by the cuneocerebellar tract, which transmits this information to cerebellar networks responsible for unconscious proprioceptive processing [37]. The cuneate nuclei are responsible for the proprioceptive component of the cuneocerebellar tract by topographically relaying precise proprioceptive information to the cerebral cortex through complex feedback-regulated cerebellar connections [38]. Previous work has demonstrated that neck muscle vibration altered cerebellar processing and cerebellar inhibition (CBI)

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patterns determined by changes in SEP peaks associated with cerebellar processing (N18 and N24) [39]. Therefore, differences in proprioceptive accuracy are likely related to altered cerebellar processing in the vibration group.

The cerebellum also provides a mechanism for adapting our movements and position to maintain a consistently updated and accurate body schema in reference to changing visual information as we navigate our environment [40]. It is considered fundamental in the neural integration of the eye and hand during visually guided tracking tasks [40, 41]. To maintain an updated body schema, several brain areas work in conjunction with the cerebellum to integrate visual and somatosensory information [7, 9]. Without visual feedback, the cerebellum is unable to cross-reference incoming muscle spindle inputs from the neck and upper limb. To accurately correct movement errors, an efference copy is sent from the primary motor cortex to the cerebellum consisting of information on the intended position, velocity and acceleration of the movement [42, 43]. The efference copy includes the expected consequences of the intended movement, including the expected sensory feedback. However, if there is a mismatch between the expected sensory feedback and the incoming inputs from muscle spindles, the cerebellum is unable to accurately modify descending motor commands. It is possible that a lack of visual information in conjunction with inaccurate proprioceptive inputs influenced the ability of the cerebellum to properly integrate ascending sensory information with descending motor output leading to impaired feedforward and feedback control. It is also feasible that alterations in body schema occurred as a result of the CNS processing inaccurate somatosensory input from muscle spindles as if it was accurate. Therefore, the observed changes in upper limb proprioception are likely due the result of the CNS receiving misinformation while updating body schema, leading to inaccurate motor output and increased repositioning error.

Due to the nature of this device, there was likely some degree of shoulder proprioceptor contribution as participants moved from elbow extension to elbow flexion. However, this contribution was very minimal as the table height, handle height and lateral position of the device were adjusted to each participant to mitigate involvement of the shoulder joint. Additionally, due to the nature of this sample, these results may not be generalizable to young children and older adults.

5. Conclusions

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

Author Contributions: All persons who meet authorship criteria are listed as authors, and all authors certify that they have participated sufficiently in the work to take public responsibility for the content, including participation in the concept, design, analysis, writing, or revision of the manuscript. The following is a breakdown of the individual contributions of each author. Conceptualization, Hailey Tabbert and Bernadette Murphy; Methodology, Hailey Tabbert and Bernadette Murphy; Validation, Hailey Tabbert and Ushani Ambalavanar; Formal Analysis, Hailey Tabbert;

Investigation, Hailey Tabbert and Ushani Ambalavanar; Data Curation: Hailey Tabbert and Ushani Ambalavanar; Writing – original draft preparation, Hailey Tabbert; writing – review and editing, Hailey Tabbert and Bernadette Murphy; Supervision, Bernadette Murphy. All authors have read and agreed to the published version of the manuscript.

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