



Does vibration frequency and location influence the effect of neck muscle vibration on postural sway? A cross-sectional study in asymptomatic participants

A. Chalimourdas^{1,2} · A. Gilles^{3,4,5} · W. De Hertogh¹ · S. Michiels^{2,3}

Received: 21 March 2023 / Accepted: 28 July 2023 / Published online: 8 August 2023
© The Author(s), under exclusive licence to Springer-Verlag GmbH Germany, part of Springer Nature 2023

Abstract

Introduction Postural control is of utmost importance for human functioning. Cervical proprioception is crucial for balance control. Therefore, any change to it can lead to balance problems. Previous studies used neck vibration to change cervical proprioception and showed changes in postural control, but it remains unknown which vibration frequency or location causes the most significant effect. Therefore, this study aimed to investigate the effect of different vibration frequencies and locations on postural sway and to serve as future research protocol guidance.

Methods Seventeen healthy young participants were included in the study. We compared postural sway without vibration to postural sway with six different combinations of vibration frequency (80, 100, and 150 Hz) and location (dorsal neck muscles and sternocleidomastoid). Postural sway was evaluated using a force platform. The mean center of pressure (CoP) displacement, the root mean square (RMS), and the mean velocity in the anteroposterior and mediolateral direction were calculated, as well as the sway area. The aligned rank transform tool and a three-way repeated measures ANOVA were used to identify significant differences in postural sway variables.

Results Neck vibration caused a significant increase in all postural sway variables ($p < 0.001$). Neither the vibration frequency ($p > 0.34$) nor location ($p > 0.29$) nor the interaction of both ($p > 0.30$) influenced the magnitude of the change in postural sway measured during vibration.

Conclusion Neck muscle vibration significantly changes CoP displacement, mean velocity, RMS, and area. However, we investigated and found that there were no significant differences between the different combinations of vibration frequency and location.

Keywords Human · Vibration · Neck muscles · Postural control

Communicated by Bill J Yates.

W. De Hertogh and S. Michiels have contributed equally.

✉ A. Chalimourdas
chalimourdas@gmail.com

¹ Department of Rehabilitation Sciences and Physiotherapy, University of Antwerp, Wilrijk, Belgium

² REVAL Rehabilitation Research Centre, Hasselt University, Diepenbeek, Belgium

³ Department of ENT, Head and Neck Surgery, Antwerp University Hospital, Edegem, Belgium

⁴ Department of Translational Neurosciences, University of Antwerp, Wilrijk, Belgium

⁵ Department of Education, Health and Social Work, University College Ghent, Ghent, Belgium

Introduction

Postural control is an essential function of the human body. The main goal of postural control is to keep the body in an upright and stable position. For this reason, even simple daily tasks cannot be performed without efficient postural control (Chiba et al. 2016). To have efficient postural control, a combination of input from the visual, vestibular, and proprioceptive systems is used (Ivanenko and Gurfinkel 2018; Winter et al. 2003). These three systems are connected via direct neural connections in the brainstem area (Edney and Porter 1986) and the central cervical nucleus (Corneil et al. 2002).

As the proprioceptive system uses input from mechanoreceptors, such as muscle spindles (Sjölander et al. 2002), changes in the input from these muscle spindles can change

a person's postural control (Gilman 2002; Riemann and Lephart 2002; Treleaven 2008). When a muscle spindle is stimulated (e.g., using vibration), this induces an illusion of muscle lengthening and joint movement. This manipulation of sensory input engenders subsequent repercussions on the integration of sensory information within the central nervous system, leading to modulations in postural control. As a reaction, this causes a shift in the body's center of gravity (Cordo et al. 2005). So, probably the response will be different when flexor or extensor muscles are stimulated. Consequently, areas with a high density of muscle spindles, such as the lower limb and cervical spine area (Treleaven 2008), will be important for maintaining balance. The proprioceptive system is extremely developed in the cervical spine due to a high density of mainly the muscle spindles in the deep segmental upper cervical muscles (Bogduk and Mercer 2000). The rectus capitis posterior muscle, for instance, contains 98 spindles per gram of muscle, sternocleidomastoid contains 72.8 spindles per muscle, compared to 55.4 spindles per gram of muscle for the posterior latissimus dorsi muscle (Kulkarni et al. 2001; Ovalle et al. 1999; Radziemski et al. 1991). Afferent proprioceptive information provided by these cervical muscle spindles will be combined with visual and vestibular afference and proprioceptive input from the lower limbs to maintain postural control (Edney and Porter 1986).

Changes in one of the systems providing somatosensory afference results in a change in postural control and related balance (Jamal et al. 2020). In studies investigating the influence of neck dysfunction on balance, neck muscle vibration is frequently used to disturb the cervical proprioceptive input (Jamal et al. 2020). Several of these studies found a significant effect of neck muscle vibration on center of pressure (CoP) displacement (Bove et al. 2006, 2004, 2007, 2001; Courtine et al. 2007; De Nunzio et al. 2018; Ivanenko et al. 1999; Kavounoudias et al. 1999; Morris et al. 2015; Mullie and Duclos 2014; Ribot-Ciscar et al. 2004; Smetanin et al. 2011; Verrel et al. 2011). From these studies, vibration of muscles with higher muscle spindle density has a greater effect on the postural sway (Cordo et al. 2005). If this is the case, the vibration of the dorsal neck muscles should, for instance, have a larger effect on postural sway than the vibration of the sternocleidomastoid muscle.

Additionally, regarding vibration frequencies, an animal study has shown that higher vibration frequencies cause a greater illusion of movement (Zhang et al. 2019) and would therefore, have a bigger effect on the postural sway. The effect of the vibration on the stimulation of the muscle spindles increases linearly with vibration frequencies up to 70–80 Hz, followed by a subharmonic increase at higher frequencies, with sharp falls often observed at frequencies between 150 and 200 Hz (Roll et al. 1980, 1989; Steyvers et al. 2003). Heterogeneity in the methodology used in the

different studies and lack of comparison between methodologies makes it currently hard to conclude the ideal vibration location and frequency in humans.

Most studies used a vibration frequency of 80 Hz (Courtine et al. 2007; Ivanenko et al. 2000; Kavounoudias et al. 1999; Mullie and Duclos 2014) or 100 Hz (Bove et al. 2006, 2009; Morris et al. 2015; Smetanin et al. 2011; Verrel et al. 2011) and one study showed the effect of 150 Hz (Seizova-Cajic and Ben Sachtler 2007). Vibration at a low frequency of 20 Hz showed no effect on postural sway, and vibration at 40 Hz and 60 Hz showed smaller postural sway changes than the 80 and 100 Hz vibrations (Pyykkö et al. 1989). Therefore, we decided not to use frequencies below 80 Hz in our study. Currently, no studies comparing the effect of different vibration frequencies are available. Both vibration on the dorsal neck muscles (DNM) (Bove et al. 2006, 2009; Ivanenko et al. 1999, 2000; Kavounoudias et al. 1999; Morris et al. 2015; Mullie and Duclos 2014; Ribot-Ciscar et al. 2004; Smetanin et al. 2011; Verrel et al. 2011) and sternocleidomastoid (SCM) muscles (Bove et al. 2006, Bove et al. 2004, 2007, Bove Diverio 2001, Courtine et al. 2007) has previously shown disturbance of postural sway, but again no studies are available comparing the effect of vibration on both locations. Additionally, several studies have shown that bilateral muscle vibration causes a shift in the center of pressure (CoP), mainly in the anteroposterior direction (Bove et al. 2006, 2009; Ivanenko et al. 1999, 2000; Kavounoudias et al. 1999; Morris et al. 2015; Mullie and Duclos 2014; Ribot-Ciscar et al. 2004; Smetanin et al. 2011). A smaller number of studies also showed the effect of unilateral vibration on the postural sway, showing a shift of the CoP in both anteroposterior and mediolateral direction (Bove et al. 2006, 2004; Courtine et al. 2007; De Nunzio et al. 2005; Dumas et al. 2013; Kavounoudias et al. 1999). Generally, the direction of the shift is expected to be opposite to the muscle function. So, if neck muscles are stimulated bilaterally, the response will be mainly in the anteroposterior direction because the muscles will produce the same illusion of the movement in the sagittal plane (flexion or extension) and an opposite illusion in the frontal plane (right vs left side flexion). In comparison, only one illusion is produced during unilateral vibration, in the frontal (flexion or extension) and sagittal plane (right or left side flexion). For this reason, we can expect a shift in both anteroposterior and mediolateral directions.

Therefore, our study aimed to compare the effect of different vibration locations (unilateral SCM and DNM (semispinalis and splenius capitis muscles)) and frequencies (80, 100, and 150 Hz) on postural sway using unilateral vibration. Our goal was first to confirm that neck muscle vibration disturbs the postural control, second to explore which vibration location results in the largest disturbance of the postural sway, thirdly to explore which vibration frequency causes

the largest disturbance on the postural sway, and finally to explore which combination of vibration frequency and location causes the largest disturbance in the postural sway, in order to be able to use this combination to alter cervical somatosensory afference in future functional neuroimaging studies.

Four research hypotheses were investigated: (1) neck muscle vibration increases the postural sway variables compared to the without vibration condition (2) DNM (semispinalis and splenius capitis muscles) vibration shows larger effects on the postural sway variables than SCM vibration, (3) Higher vibration frequencies have a larger effect on postural sway variables than lower frequencies and (4) A 150 Hz DNM vibration causes the largest effect in comparison with other combinations of vibration location and frequency.

Methods

Study design and participants

In this cross-sectional study, postural sway is measured in six different vibration conditions. The six conditions were six different combinations of different vibration locations (right sternocleidomastoid muscle and right dorsal neck muscles [semispinalis and splenius capitis muscles]) and frequencies (80, 100, and 150 Hz). Postural sway measures were compared to a baseline measurement without vibration for each vibration condition. Healthy adult participants were included in the study when they had no history of neck pain or lower limb injury in the previous three months. Participants suffering from diagnosed vestibular dysfunction or recent surgery were excluded from the study, as were participants who suffered from a recent head injury (such

as a concussion, less than 6 months before the study) and participants with a Body Mass Index greater than 30.

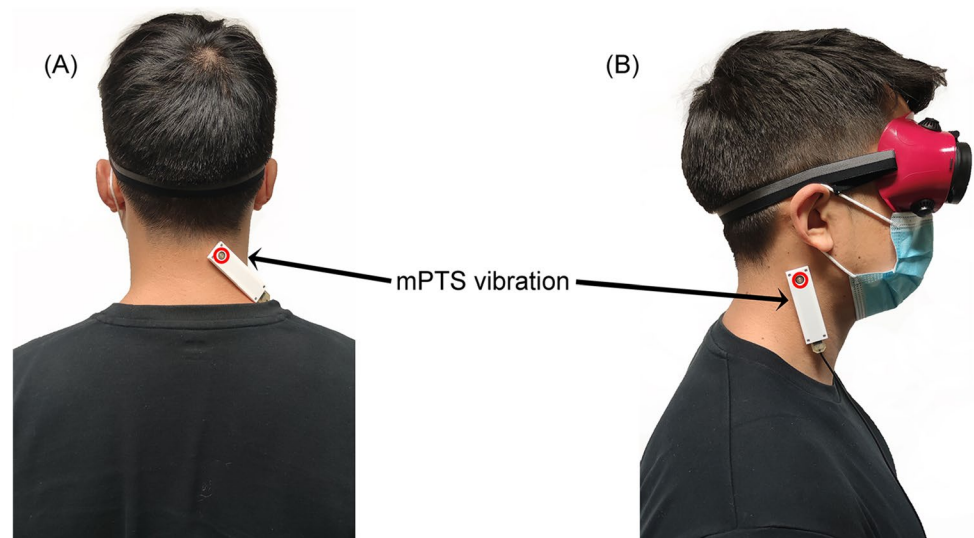
The measurements took place between January 2021 and March 2021 at the. Before inclusion, all participants were informed about the study by the primary researcher, and a consent form was signed by all participants according to the guidelines provided by the Declaration of Helsinki. The study was approved by the Ethical Committee of the with reference number (B3002020000250).

Sample size calculation (G-Power 3.1) was performed a-priori and was based on literature data from changes in CoP displacement during postural sway tests with and without vibration of the cervical spine (Lekhel et al. 1997). The sample size calculation for this repeated-measures study showed that a minimum of 12 subjects was needed to be able to reject the first null hypothesis that there is no difference in CoP displacement between the vibration of the cervical spine and no vibration and the second null hypothesis that there is no difference in CoP displacement between the six vibration conditions as compared to the no vibration condition, with 80% power and a type I error probability of 0.05.

Vibration

The vibration was applied using a micro-piezo-tactile stimulator (mPTS) system (Dancer Design, Saint Helens, UK), a nonmagnetic system that is magnetic resonance imaging compatible and has high potential for use in future functional neuroimaging studies. In total, six different combinations of different vibration locations (right sternocleidomastoid muscle and right dorsal neck muscles (semispinalis and splenius capitis muscles)) and frequencies (80, 100, and 150 Hz) were tested. The exact placement of the mPTS is specified in Fig. 1.

Fig. 1 **A** Vibrator placement on sternocleidomastoid muscle, in the center of the muscle belly, 4 cm below the insertion on the mastoid bone **B** Vibrator placement on dorsal neck muscles, below the occiput and 2–5 cm lateral to the cervical spine, red circle: vibrating area



The vibration amplitude was 1 mm based on previous studies (Andersson and Magnusson 2002; Gomez et al. 2009). Since neck muscle vibration has at most a 24 h after-effect on cervical sensorimotor performance (Beinert et al. 2018), only one combination was tested on the same day in the same participant. The six different days were evenly spread over a period of 4 weeks. The six vibration conditions were applied in a random sequence to decrease the risk of introducing a sequence bias.

Procedure

The effects of neck muscle vibration were objectified using postural sway tests. The postural sway was measured in a standing position using one embedded force plate (AMTI®, 0.4 × 0.5 m, 1000 Hz, model OR 6–5–2000, Advanced Medical Technology Inc., Massachusetts, USA) (Fig. 2). During the postural sway test, participants stood barefoot with their eyes closed on the force plate. Both feet were positioned in parallel at a distance of 10 cm (Nunzio et al. 2018). This position was marked on the force plate, and two reflective markers were placed on the heel (middle of the Achilles tendon) as reference points in order to have consistency across trials. The marker position data were captured by eight near-infrared cameras (Vicon T10, 100 Hz., Vicon Motion Systems Ltd., Oxford, UK, 100 fps, resolution 1 Megapixel (1120 × 896)) and the markers were labeled using Vicon Nexus software. During each test session, the postural sway was first tested without vibration and afterward during one of the vibration conditions. Each postural sway measurement consisted of three trials of the 40 s with 30 s rest in between (Fig. 2). The following protocol was used:

1. Postural sway (PS) test without vibration

40s PS–30s rest–40s PS–30s rest–40s PS

2. Postural sway test with vibration

40s PS + vibration–30s rest–40s PS + vibration
–30s rest–40s PS + vibration

The reliability of the protocol was assessed by examining data obtained under conditions without vibration, yielding robust test–retest Interclass Correlation Coefficient (ICC) values (ranging from 0.773 to 0.908) using a two-way mixed effects model with absolute agreement (unpublished data).

Data analysis

The raw data files were exported to MATLAB (R2020a for Windows, The MathWorks, Inc., Natick, Massachusetts, United States), and an existing MATLAB script was used

to calculate the mean CoP displacement, the RMS and mean velocity of CoP, all in the anteroposterior and mediolateral direction. Additionally, the mean sway area of CoP was calculated. The CoP positions were calculated from the ground reaction forces (F_x , F_y , and F_z) and moments of the force around the x (M_x) and y (M_y) axes (Duarte et al. 2010). A second order low pass Butterworth filter with a cut-off frequency of 12.5 Hz was used for filtering the CoP, and a second order low pass Butterworth filter with a cut-off frequency of 6 Hz was used for filtering the marker position data (Duarte and Freitas, 2010). The mean CoP displacement in the anteroposterior and mediolateral direction, the mean position between the two heel markers, was used as a reference position (Fig. 3). The sway area was calculated by fitting an ellipse corresponding to 85% of the surface CoP points (Oliveira et al. 1996) (Fig. 3). The first 10 s of each trial were not used during data analysis, as they are seen as an adaptation period (Mezzarane and Kohn 2007). The average between the three trials was calculated for each postural sway measurement. For mean CoP displacement in the anteroposterior direction, positive values represent a forward shift of the CoP, and negative values a posterior shift. For mean CoP in the mediolateral direction, positive values represent a shift of the CoP to the right side, and negative values a shift to the left. For all the other variables, higher values represent a greater effort from the participants to remain stable.

Statistical analysis

The normality of the data was tested using a Shapiro–Wilk test. Since some data were not normally distributed ($p < 0.05$), we used the aligned rank transform tool (ART tool version 0.11.1) for nonparametric factorial ANOVA as described by Wobbrock et al. (2011) and Elkin et al. (2021) using R software 4.0.4. A three-way repeated measures ANOVA was used to identify significant differences in CoP variables.

First, the interaction of the before and during vibration conditions with both frequency and location (conditions*frequency* location) was calculated to find potential differences in the effect of vibration between the combination of different frequencies and locations. This allows us to investigate if a specific combination of vibration frequency and location affects the postural sway more than other combinations. Afterward, interactions between the before and during vibration conditions and vibration frequency (conditions*frequency) were tested to find potential differences in the effect of vibration between the different frequencies. This allows us to investigate if a certain vibration frequency has a larger effect on the postural sway than other frequencies. Additionally, the interaction between the before and during vibration conditions and the vibration

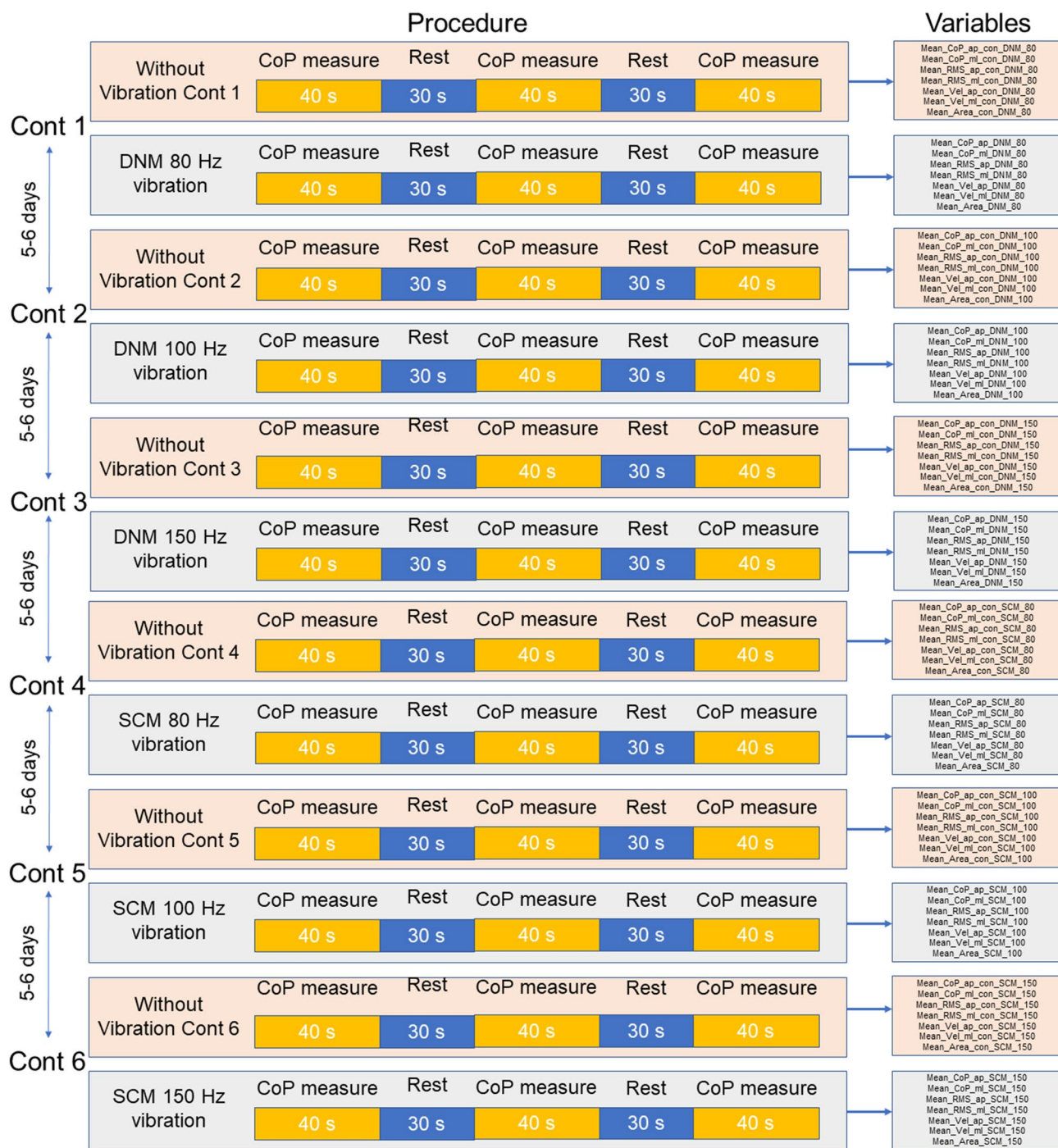


Fig. 2 The experiment procedure, *CoP* Centre of Pressure, *ap* anteroposterior, *ml* mediolateral, *RMS* Root Mean Square, *Vel* Velocity, *Cond* Condition, *Con* Control

location (conditions*location) was tested to find potential differences in the effect of vibration between the different vibration locations. This allows us to identify if one of our vibration locations causes a larger effect on the postural sway. Finally, potential differences between the before and during vibration conditions were investigated to objectify

the effect of vibration on the postural sway variables. This analysis was made to be sure that our mPTS vibration causes changes in postural sway. Post hoc pairwise comparisons were not tested due to the lack of significant interaction results. 95% confidence intervals (CI) for the mean

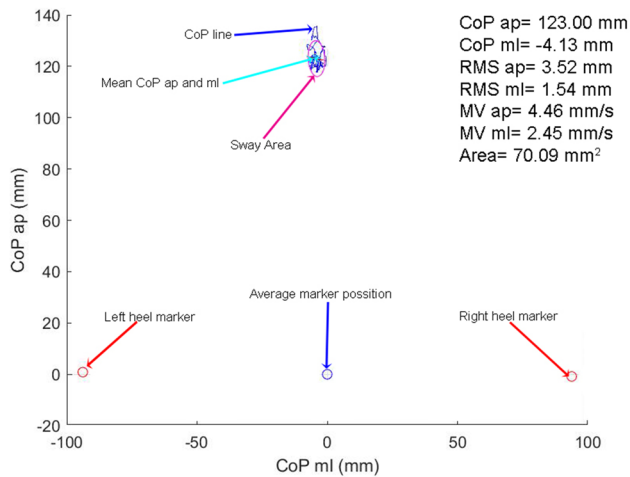


Fig. 3 An example of the CoP variables calculation. The right and left heel marker (red “o”), the average marker position (blue “o”), the CoP line (blue line), the ellipse of the sway area (magenta ellipse), and the mean CoP anteroposterior and mediolateral displacement (turquoise “*”), *CoP* Centre of Pressure, *ap* anteroposterior, *ml* mediolateral, *RMS* Root Mean Square, *MV* Mean Velocity

differences were calculated. Significance was considered when $p < 0.05$.

Results

Demographics

Seventeen healthy participants (14 women and three men, mean age: 27.69 years (SD: 3.16), mean height: 1.70 m (SD: 0.06), mean weight: 63.24 kg (SD: 7.81) were included in the study. All tolerated the mPTS vibration well, and no side effects or discomfort was reported during the vibration application.

Effect of vibration on postural sway

We found a statistically significant effect of vibration on all postural sway variables. An overview of all results can be found in Tables 1 and 2 and Fig. 4. An average anterior shift of 6.1 mm (SD: 6.6) ($F_{1,176} = 34.89$, $p < 0.001$) and a right shift of 2.8 mm (SD: 2.6) ($F_{1,176} = 11.40$, $p < 0.001$) of the CoP was observed during vibration compared to the condition without vibration. For the RMS, an increased error of 0.4 mm (SD: 0.3) ($F_{1,176} = 61.15$, $p < 0.001$) and 0.2 mm (SD: 0.2) ($F_{1,176} = 39.28$, $p < 0.001$), was observed during vibration compared to the condition without vibration, in the anteroposterior and mediolateral direction, respectively. The mean velocity was higher during vibration in comparison with the reference condition. The average difference for velocity was 0.5 mm/s (SD: 0.4) in the anteroposterior

direction ($F_{1,176} = 26.69$, $p < 0.001$) and 0.2 mm/s (SD: 0.2) in the mediolateral direction ($F_{1,176} = 18.74$, $p < 0.001$). Finally, during vibration, the average sway area was 15.4 mm² (SD: 15) larger compared with the condition without vibration ($F_{1,176} = 58.38$, $p < 0.001$).

Effect of the vibration frequency and location on the postural sway

We did not find any significant conditions*frequency or conditions*location or conditions*frequency*location interaction in our postural sway variables. (see Tables 1 and 2 and Figs. 5 and 6).

Discussion

Our study aimed to compare the effect of different vibration locations (unilateral SCM and DNM (semispinalis and splenius capitis muscles)) and frequencies (80, 100, and 150 Hz) on postural sway using unilateral vibration. Our goal was first to confirm that neck vibration disturbs the postural control, second to explore which vibration location has the largest influence on the postural sway, thirdly to explore which vibration frequency causes the larger disturbance on the postural sway, and finally to explore which combination of vibration frequency and location causes the largest disturbance of the postural sway.

Our first hypothesis was that neck muscle vibration increases the postural sway variables compared to measurements without vibration. We can confirm this hypothesis, as we found a significant increase in all postural sway variables during neck muscle vibration. Our second hypothesis was that DNM (semispinalis and splenius capitis muscles) vibration affects the postural sway variables more, than SCM vibration. In general, we rejected this hypothesis as we found that both unilateral DNM and SCM vibration has a significant effect in all postural sway variables and that this effect does not significantly differ between the two locations. Based on earlier studies, we expected that DNM (semispinalis and splenius capitis muscles) vibration would result in a larger shift of CoP due to a higher muscle spindle density compared to the SCM (Cordo, Gurfinkel, 2005). Despite that, we did not find a significant difference between the two locations, in five out of seven postural sway variables, the DNM causes a greater increase in these variables. Potentially, the difference in muscle spindle density between the DNM and SCM was too small to result in significant differences in CoP displacement, but also, the minimal detectable change of the method we used is greater than these differences. Another potential reason is that, due to the shape of the vibrator, there was better skin contact on the SCM muscles and that may engage muscles beyond solely the SCM.

Table 1 Mean center of pressure and root mean square differences between with and without vibration

Conditions	Location	Frequency	Mean CoP ap (mm)			Mean CoP ml (mm)			RMS ap (mm)			RMS ml (mm)						
			Mean	SD	F	p	Mean	SD	F	p	Mean	SD	F	p				
Mean difference between with and without vibration	SCM and DNM	80, 100 and 150 Hz	6.124	6.621	34.89*	<0.001	2.821	2.565	11.40*	<0.001	0.440	0.305	61.15*	<0.001	0.189	0.154	34.89*	<0.001
	SCM	80, 100 and 150 Hz	6.320	6.670	0.12*	0.72	2.107	2.461	1.74*	0.19	0.389	0.284	0.21*	0.65	0.187	0.193	0.02*	0.88
	DNM		5.928	7.352			3.534	3.848			0.491	0.475			0.192	0.163		
	SCM and DNM	80 Hz	7.531	7.630	0.93**	0.40	3.169	3.352	0.32**	0.73	0.386	0.531	0.79**	0.45	0.169	0.223	0.48**	0.62
		100 Hz	4.712	7.013			3.627	3.758			0.419	0.353			0.190	0.198		
		150 Hz	6.132	7.153			1.665	2.898			0.516	0.545			0.210	0.181		
	SCM	80 Hz	8.498	7.103	0.13**	0.88	2.682	3.838	0.34**	0.71	0.267	0.537	0.41**	0.66	0.152	0.247	0.30**	0.74
		100 Hz	4.269	7.024			3.534	4.302			0.342	0.490			0.166	0.303		
		150 Hz	6.194	9.307			0.101	3.344			0.559	0.530			0.242	0.277		
	DNM	80 Hz	6.562	9.310			3.656	4.418			0.505	0.811			0.186	0.325		
		100 Hz	5.152	9.468			3.719	5.541			0.496	0.513			0.213	0.211		
		150 Hz	6.071	6.421			3.228	5.319			0.472	0.710			0.177	0.182		

CoP Center of Pressure, RMS Root Mean Square, ap anteroposterior, ml mediolateral, mm millimeters, SCM sternocleidomastoid, DNM Dorsal neck muscles, *Degrees of freedom = 1, Degrees of freedom of residuals = 176 **Degrees of freedom = 2, Degrees of freedom of residuals = 176. Positive values on mean CoP ap displacement mean that during vibration the mean displacement moved forward, Positive values on mean CoP ml displacement mean that during vibration the mean displacement moved to the right direction, Positive values on RMS ap and RMS ml variables mean that during vibration we had an increase on these variables

Table 2 Mean velocity and area differences between with and without vibration

Conditions	Location	Frequency	Mean Velocity ap (mm/s)			Mean Velocity ml (mm/s)			Area (mm ²)					
			Mean	SD	F	p	Mean	SD	F	p	Mean	SD	F	p
Mean difference between with and without vibration	SCM and DNM	80, 100 and 150 Hz	0.509	0.400	39.28*	<0.001	0.178	0.176	18.74*	<0.001	15.358	14.990	58.38*	<0.001
	SCM	80, 100 and 150 Hz	0.442	0.400	1.25*	0.27	0.172	0.219	0.60	0.44	15.456	15.391	0.04**	0.84
	DNM		0.575	0.517			0.183	0.273			15.259	16.279		
SCM and DNM	SCM and DNM	80 Hz	0.507	0.646	0.06**	0.94	0.156	0.335	0.25**	0.78	16.147	21.654	1.42**	0.24
		100 Hz	0.540	0.663			0.192	0.305			11.589	12.974		
		150 Hz	0.479	0.573			0.185	0.264			18.337	23.527		
SCM	SCM	80 Hz	0.360	0.698	0.66**	0.52	0.176	0.428	0.63**	0.53	13.974	16.738	0.62**	0.54
		100 Hz	0.340	0.804			0.142	0.550			9.724	20.345		
		150 Hz	0.626	0.554			0.197	0.387			22.671	33.421		
DNM	DNM	80 Hz	0.654	1.138			0.135	0.462			18.320	33.167		
		100 Hz	0.740	0.799			0.242	0.348			13.453	12.408		
		150 Hz	0.331	1.112			0.172	0.387			14.003	18.474		

CoP Center of Pressure, RMS Root Mean Square, ap anteroposterior, ml mediolateral, mm millimeters, s seconds, SCM sternocleidomastoid, DNM Dorsal neck muscles, *Degrees of freedom = 1, Degrees of freedom of residuals = 176, **Degrees of freedom = 2, Degrees of freedom of residuals = 176. Positive values on mean velocity ap and ml variables mean that during vibration we had an increase on these variables

For the mean CoP displacement in the anteroposterior direction, our results confirm previous findings from studies investigating vibration applied unilaterally (Courtine et al. 2007, De Nunzio et al. 2018) on the DNM but contradict other studies investigating vibration applied to the SCM, who did not find significant anteroposterior CoP displacement (Bove et al. 2006, Bove et al. 2004, Bove, Diverio, 2001, Courtine et al. 2007). Methodological differences can explain these contradictory results. Specifically, we tried to vibrate the upper part of the SCM muscle. SCM function is flexion of the head relative to the shoulders and extension of the upper cervical spine. In other studies, the vibrator was placed in the middle of the SCM muscle. This might result in a combined illusion of flexion and extension, resulting in very small anteroposterior CoP displacements (Bove et al. 2006, Bove et al. 2004, Bove, Diverio, 2001, Courtine et al. 2007). The vibrator placement in our study's upper part of the SCM muscle might have resulted in an illusion of upper cervical extension rather than cervical flexion, explaining why we found an anterior CoP displacement during SCM vibration. Additionally, it is plausible that the shape of our vibrator induced an illusory effect on muscles other than SCM. Furthermore, most studies used a vibration amplitude between 0.2 and 0.8 mm (Bove et al. 2006, Bove et al. 2004, Bove, Diverio, 2001, Courtine et al. 2007). A previous study shows that a vibration amplitude between 1 and 2 mm has a larger effect on the muscle spindles (Necking et al. 1996). In our study, we used an amplitude of 1 mm which might also explain why we found a significant increase of the mean CoP displacement in the anteroposterior direction in contradiction to other studies (Bove et al. 2006, Bove et al. 2004, Bove, Diverio, 2001, Courtine et al. 2007). We measured each condition repeatedly with three trials of the 40 s and 30 s rest in between, whereas other studies only measured both conditions once (Bove et al. 2006, Bove et al. 2004, Bove, Diverio, 2001, Courtine et al. 2007). This is the most common method recently used in postural sway evaluation (Duarte and Freitas 2010; Paillard and Noé 2015). Additionally, we calculated the mean CoP displacement from the last 30 s of each measurement and discarded the first 10 s so the participant was allowed to get familiar with the procedure and find the best way to balance (Nunzio et al. 2018; Oliveira et al. 1996; Paillard and Noé, 2015). With this protocol, we calculated the longitudinal effect of the vibration on CoP displacement rather than the immediate effect of the vibration, which happens in the first 1–2 s of the vibration (Andersson and Magnusson 2002, De Nunzio et al. 2018). It is recommended not to use the mean displacement position, especially in case of repeated measures, due to the low reliability and accuracy of this method (Duarte and Freitas 2010; Paillard and Noé 2015). For this reason, we used two heel markers as reference points apart from the line markers in the force plate. In each trial, the mean

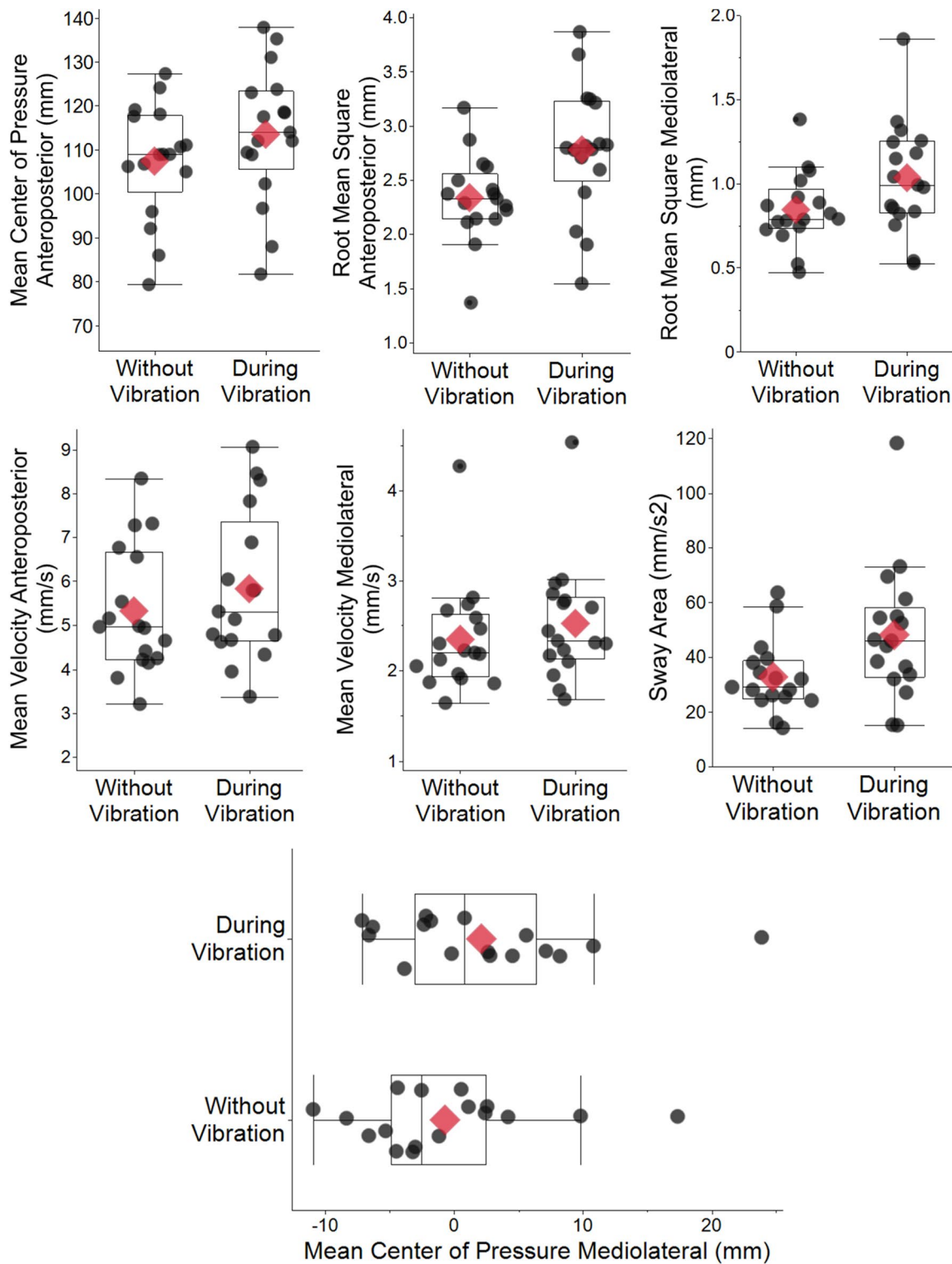


Fig. 4 Postural sway results between without and during vibration. Vibration caused a significant effect in all postural sway variables ($p < 0.001$). mm=millimeters and s=seconds. Boxplot: upper line: the highest data point in the data set excluding any outliers, lower

line: the lowest data point in the data set excluding any outliers, upper box line: third quartile, lower box line: First quartile, mid-box line: median, diamond: average value, black dots: the value of each participant

Fig. 5 Mean CoP displacement results in anteroposterior direction between without and during vibration in different locations and frequencies. The interaction between vibration*frequency*location was not significant ($p > 0.05$). mm = millimeters. Boxplot: upper line: the highest data point in the data set excluding any outliers, lower line: the lowest data point in the data set excluding any outliers, upper box line: third quartile, lower box line: First quartile, mid-box line: median, diamond: average value, black dots: the value of each participant

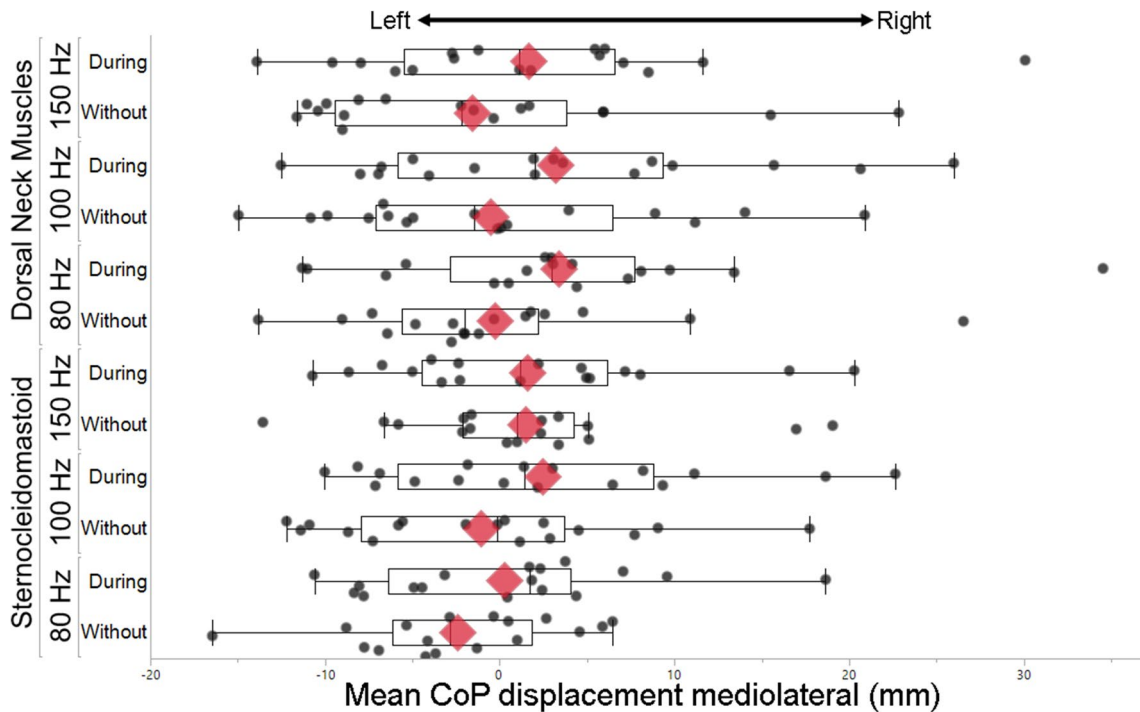
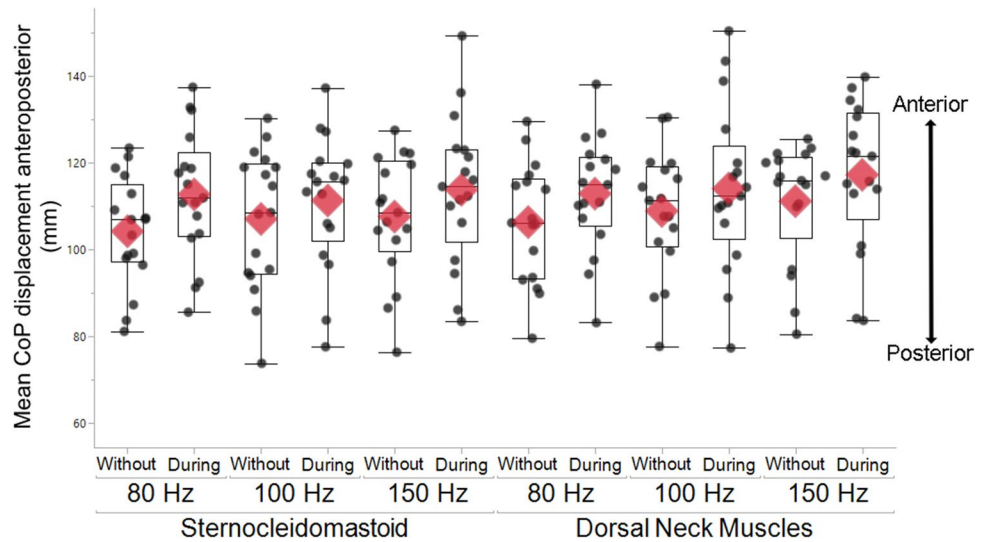


Fig. 6 Mean CoP displacement results in mediolateral direction between without and during vibration in different locations and frequencies. The interaction between vibration*frequency*location was not significant ($p > 0.05$). mm = millimeters. Boxplot: upper line: the highest data point in the data set excluding any outliers, lower line:

the lowest data point in the data set excluding any outliers, upper box line: third quartile, lower box line: First quartile, mid-box line: median, diamond: average value, black dots: the value of each participant

CoP displacement variables were calculated from the mean position between the two markers. We tested the reliability of the measurement with and without the heel markers and found that this protocol (with heel markers and line markers) is more reliable (ICC = 0.890) and accurate in calculating the mean CoP displacement in comparison to the protocols that were used in the other studies (ICC = 0.575, only line

markers without heel markers) (based on unpublished data). In the other studies, line marks in the force plate were used in order to achieve the same foot position between trials (Bove et al. 2006, Bove et al. 2004, Bove, Diverio, 2001, Courtine et al. 2007).

For the mean CoP displacement in the mediolateral direction, we observed a shift of the CoP towards the side

of vibration (right side) that does not significantly differ between DNM and SCM vibration. Our findings were in contrast to one other study when vibration was applied unilaterally on the DNM (Nunzio et al. 2018). In case the vibration was applied to the SCM, other studies found a significant displacement to the opposite side of the vibration (Bove et al. 2006, Bove et al. 2004, Bove Diverio 2001, Courtine et al. 2007). The differences in reaction to vibration on DNM and SCM muscle might be explained by the differences in data analysis used to calculate the mean CoP displacement in the mediolateral direction (ICC=0.908 with line and heel markers vs ICC=0.374 with only line markers without heel markers) (based on unpublished data). Additionally, the difference in the vibration device, like the shape, dimensions, weight, etc., it is plausible that they induced an illusory effect on muscles other than DNM and SCM and that might have contributed to the differences in mediolateral CoP displacement compared to other studies. As a conclusion, both locations cause a similar shift of the mean CoP displacement towards the side of vibration (right side).

Since mean CoP displacement largely depends on the foot position, small changes in the foot position can have a large effect on the mean CoP displacement. Therefore, we also calculated *RMS*, *the mean velocity*, and *the sway area* (Duarte and Freitas 2010; Paillard and Noé, 2015). The RMS and mean velocity were significantly higher during vibration than the reference condition in both the anteroposterior and mediolateral directions. This increase was similar between the two vibration locations. Moreover, the sway area was higher during vibration than without vibration. This increase was also similar in both vibration locations. These results confirm the findings from one other study, showing that sway area increases during neck muscle vibration (Bove et al. 2007), but this increase is shown to be similar between the two vibration locations.

An animal study has shown that higher vibration frequency causes a greater illusion of movement (Zhang et al. 2019) and, therefore, would have a larger effect on the postural sway. Additionally, the effect of the vibration on the stimulation of the muscle spindles is increased linearly with vibration frequencies up to 70–80 Hz, followed by a subharmonic increase at higher frequencies, with sharp falls often observed at frequencies between 150 and 200 Hz (Roll and Gilhodes 1980; Roll et al. 1989; Steyvers et al 2003). So, our third hypothesis was that the higher frequencies would have a larger effect on postural sway than the lower frequencies. In general, we were able to reject this hypothesis as we found that all vibration frequencies significantly increase the postural sway variables, but we did not find any statistically significant differences between the different frequencies. Despite that, we did not find a significant difference between the three vibration frequencies, in four out of seven postural sway variables, the 150 Hz caused a greater increase in these

variables. Potentially, the difference of the effect between different frequencies was too small to result in statistically significant differences in CoP displacement, but also, the minimal detectable change of the method that we used is greater than the observed differences.

The ultimate goal of our study was to define the most disturbing combination of vibration frequency and location for postural sway measurements. Our last hypothesis was that 150 Hz DNM vibration would cause the largest effect on postural sway parameters compared to other combinations of vibration location and frequency. In general, we were able to reject this hypothesis as we found that there is not one combination that results in larger changes in postural sway variables for the investigated locations and frequencies. Although not significant, higher frequency vibration on the SCM does show higher mean velocity figures. This observation confirms previous findings by Pyykkö et al. (1989).

It should be noted that this study included only asymptomatic participants, and the results may not be generalized to symptomatic populations such as neck pain patients. Furthermore, the observed disparity between the percentages of women (14) and men (3) in the sample size could potentially influence the outcomes. However, it appears unlikely that this factor significantly impacts the results. Additionally, the effect sizes observed in this study were smaller than anticipated, potentially impacting the statistical power of the investigation. It is plausible that studies with larger sample sizes could possess greater statistical power to detect potential differences between distinct locations or frequencies of vibration. Moreover, comparative studies exploring various types of vibrators may contribute to establishing the optimal properties of vibrators for neck vibration.

Generally, this procedure can be used to evaluate the cervical somatosensory afference in patients with cervical spine dysfunction caused by several non-specific conditions. One of the targets of cervical spine therapies is to increase the proprioception of the neck muscles. So, neck muscle vibration can also be used as an objective outcome measure in studies evaluating the effect of new therapies for cervical spine conditions.

Conclusion

Neck muscle vibration causes a significant increase in all investigated postural sway variables. More specifically, a forward displacement of the mean CoP was observed in the anteroposterior direction, and a displacement towards the vibration side was observed in the mediolateral direction. An increase in RMS and mean velocity was found in both anteroposterior and mediolateral directions. Additionally, we observed an increase in the sway area. No significant differences in the effect on postural sway variables were observed

between the different vibration frequencies (80 vs 100 vs 150 Hz) or between the different vibration locations (unilateral DNM vs SCM). Finally, no significant differences in the effect on postural sway variables were observed between the different vibration locations and frequencies combinations.

Funding This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest There was no conflict of interest for any of the authors in this study.

References

- Andersson G, Magnusson M (2002) Neck vibration causes short-latency electromyographic activation of lower leg muscles in postural reactions of the standing human. *Acta Otolaryngol* 122:284–288
- Beinert K, Englert V, Taube W (2018) After-effects of neck muscle vibration on sensorimotor function and pain in neck pain patients and healthy controls: a case-control study. *Disabil Rehabil* 41:1–8
- Bogduk N, Mercer S (2000) Biomechanics of the cervical spine I: normal kinematics. *Clin Biomech* 15:633–648
- Bove M, Diverio M, Pozzo T, Schieppati M (2001) Neck muscle vibration disrupts steering of locomotion. *J Appl Physiol* 91:581–588
- Bove M, Bricchetto G, Abbruzzese G, Marchese R, Schieppati M (2004) Neck proprioception and spatial orientation in cervical dystonia. *J Neurol* 127:2764–2778
- Bove M, Bonzano L, Trompetto C, Abbruzzese G, Schieppati M (2006) The postural disorientation induced by neck muscle vibration subsides on lightly touching a stationary surface or aiming at it. *Neuroscience* 143:1095–1103
- Bove M, Bricchetto G, Abbruzzese G, Marchese R, Schieppati M (2007) Postural responses to continuous unilateral neck muscle vibration in standing patients with cervical dystonia. *Move Disord off J Move Disord Soci* 22:498–503
- Bove M, Fenoglio C, Tacchino A, Pelosin E, Schieppati M (2009) Interaction between vision and neck proprioception in the control of stance. *Neuroscience* 164:1601–1608
- Chiba R, Takakusaki K, Ota J, Yozu A, Haga N (2016) Human upright posture control models based on multisensory inputs; in fast and slow dynamics. *Neurosci Res* 104:96–104
- Cordo P, Gurfinkel VS, Brumagne S, Flores-Vieira CLL (2005) Effect of slow, small movement on the vibration-evoked kinesthetic illusion. *Exp Brain Res* 167:324–334
- Corneil BD, Olivier E, Munoz DP (2002) Neck muscle responses to stimulation of monkey superior colliculus I topography and manipulation of stimulation parameters. *J Neurophysiol* 88:1980–1999
- Courtine G, De Nunzio AM, Schmid M, Beretta MV, Schieppati M (2007) Stance- and locomotion-dependent processing of vibration-induced proprioceptive inflow from multiple muscles in humans. *J Neurophysiol* 97:772–779
- De Nunzio AM, Nardone A, Schieppati M (2005) Head stabilization on a continuously oscillating platform: the effect of a proprioceptive disturbance on the balancing strategy. *Exp Brain Res* 165:261–272
- De Nunzio AM, Yavuz US, Martinez-Valdes E, Farina D, Falla D (2018) Electro-tactile stimulation of the posterior neck induces body anteropulsion during upright stance. *Exp Brain Res* 236:1471–1478
- Duarte M, Freitas SM (2010) Revision of posturography based on force plate for balance evaluation. *Rev Bras Fisioter* 14:183–192
- Dumas G, Lion A, Gauchard GC, Herpin G, Magnusson M (2013) Clinical interest of postural and vestibulo-ocular reflex changes induced by cervical muscles and skull vibration in compensated unilateral vestibular lesion patients. *J Vestib Res* 23:41–49
- Edney DP, Porter JD (1986) Neck muscle afferent projections to the brainstem of the monkey: implications for the neural control of gaze. *J Comp Neurol* 250:389–398
- Elkin LA, Kay M, Higgins JJ, Wobbrock JO. An Aligned Rank Transform Procedure for Multifactor Contrast Tests. The 34th Annual ACM Symposium on User Interface Software and Technology. Virtual Event USA: Assoc Comp Mach 2021 11: 754–68.
- Gilman S (2002) Joint position sense and vibration sense: anatomical organisation and assessment. *J Neurol Neurosurg Psychiatry* 73:473–477
- Gomez S, Patel M, Magnusson M, Johansson L, Einarsson EJ, Fransson PA (2009) Differences between body movement adaptation to calf and neck muscle vibratory proprioceptive stimulation. *Gait Posture* 30:93–99
- Ivanenko Y, Gurfinkel VS (2018) Human postural control. *Front Neurosci*. <https://doi.org/10.3389/fnins.2018.00171>
- Ivanenko YP, Grasso R, Lacquaniti F (1999) Effect of gaze on postural responses to neck proprioceptive and vestibular stimulation in humans. *J Physiol* 519(Pt 1):301–314
- Ivanenko YP, Grasso R, Lacquaniti F (2000) Neck muscle vibration makes walking humans accelerate in the direction of gaze. *J Physiol* 525(Pt 3):803–814
- Jamal K, Leplaideur S, Leblanche F, Moulinet Raillon A, Honoré T, Bonan I (2020) The effects of neck muscle vibration on postural orientation and spatial perception: a systematic review. *Neurophysiol Clin* 50:227–267
- Kavounoudias A, Gilhodes JC, Roll R, Roll JP (1999) From balance regulation to body orientation: two goals for muscle proprioceptive information processing? *Exp Brain Res* 124:80–88
- Kulkarni V, Chandy M, Babu K (2001) Quantitative study of muscle spindles in suboccipital muscles of human fetuses. *Neurol India* 49:355–359
- Lekhel H, Popov K, Anastasopoulos D, Bronstein A, Bhatia K, Marsden CD et al (1997) Postural responses to vibration of neck muscles in patients with idiopathic torticollis. *Brain : a Journal of Neurology* 120(Pt 4):583–591
- Mezzarane RA, Kohn AF (2007) Control of upright stance over inclined surfaces. *Exp Brain Res* 180:377–388
- Morris SL, Foster CJ, Parsons R, Falkmer M, Falkmer T, Rosalie SM (2015) Differences in the use of vision and proprioception for postural control in autism spectrum disorder. *Neuroscience* 307:273–280
- Mullie Y, Duclos C (2014) Role of proprioceptive information to control balance during gait in healthy and hemiparetic individuals. *Gait Posture* 40:610–615
- Necking LE, Lundström R, Dahlin LB, Lundborg G, Thornell LE, Fridén J (1996) Tissue displacement is a causative factor in vibration-induced muscle injury. *J Hand Surg* 21:753–757
- Oliveira LF, Simpson DM, Nadal J (1996) Calculation of area of stabilometric signals using principal component analysis. *Physiol Meas* 17:305–312

- Ovalle WK, Dow PR, Nahirney PC (1999) Structure, distribution and innervation of muscle spindles in avian fast and slow skeletal muscle. *J Anat* 194(Pt 3):381–394
- Paillard T, Noé F (2015) Techniques and methods for testing the postural function in healthy and pathological subjects. *Biomed Res Int* 2015:891390
- Pyykkö I, Aalto H, Seidel H, Starck J (1989) Hierarchy of different muscles in postural control. *Acta Otolaryngol Suppl* 468:175–180
- Radziemski A, Kedzia A, Jakubowicz M (1991) Number and localization of the muscle spindles in the human fetal sternocleidomastoid muscle. *Folia Morphol (Warsz)* 50:65–70
- Ribot-Ciscar E, Trefouret S, Aimonetti JM, Attarian S, Pouget J, Roll JP (2004) Is muscle spindle proprioceptive function spared in muscular dystrophies? A muscle tendon vibration study. *Muscle Nerve* 29:861–866
- Riemann BL, Lephart SM (2002) The sensorimotor system, part I: the physiologic basis of functional joint stability. *J Athl Train* 37:71–79
- Roll JP, Gilhodes JC (1980) Tardy-Gervet MF [Perceptive and motor effects of muscular vibrations in the normal human: demonstration of a response by opposing muscles]. *Arch Ital Biol* 118:51–71
- Roll JP, Vedel JP, Ribot E (1989) Alteration of proprioceptive messages induced by tendon vibration in man: a microneurographic study. *Exp Brain Res* 76:213–222
- Seizova-Cajic T, Ben Sachtler WL (2007) Adaptation of a bimodal integration stage: visual input needed during neck muscle vibration to elicit a motion aftereffect. *Exp Brain Res* 181:117–129
- Sjölander P, Johansson H, Djupsjöbacka M (2002) Spinal and supraspinal effects of activity in ligament afferents. *J Electromyogr Kinesiol* 12:167–176
- Smetanin BN, Kozhina GV, Popov AK (2011) Effects of manipulations with visual feedback on postural responses in humans maintaining an upright stance. *Neurophysiology* 43:30–37
- Steyvers M, Levin O, Verschueren SM, Swinnen SP (2003) Frequency-dependent effects of muscle tendon vibration on corticospinal excitability: a TMS study. *Exp Brain Res* 151:9–14
- Treleaven J (2008) Sensorimotor disturbances in neck disorders affecting postural stability, head and eye movement control. *Man Ther* 13:2–11
- Verrel J, Cuisinier R, Lindenberger U, Vuillerme N (2011) Local and global effects of neck muscle vibration during stabilization of upright standing. *Exp Brain Res* 210:313–324
- Winter DA, Patla AE, Ishac M, Gage WH (2003) Motor mechanisms of balance during quiet standing. *J Electromyogr Kinesiol* 13:49–56
- Wobbrock JO, Findlater L, Gergle D, Higgins JJ. 2011 The aligned rank transform for nonparametric factorial analyses using only ANOVA procedures. *ACM Conference on Human Factors in Computing Systems (CHI '11)*. Vancouver, British Columbia: New York: ACM Press. USA
- Zhang C, Wang W, Anderson D, Guan S, Li G, Xiang H et al (2019) Effect of low-frequency vibration on muscle response under different neurointact conditions. *Appl Bion Biomech* 2019:1971045

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.