



THE ROLE OF PROPRIOCEPTION IN THE SAGITTAL SETTING OF ANTICIPATORY POSTURAL ADJUSTMENTS DURING GAIT INITIATION

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ABSTRACT

Purpose. Previous studies have studied the role of proprioception on the setting of anticipatory postural adjustments (APA) during gait initiation. However, these studies did not investigate the role of proprioception in the sagittal APA setting. We aimed to investigate the role of proprioception manipulation to induce APA sagittal adaptations on gait initiation. **Methods.** Fourteen healthy adults performed gait initiation without, and with, vibration applied before movement onset, and during movement. In addition, the effects of two different vibration frequencies (80 and 120Hz) were tested. Vibration was applied bilaterally on the tibialis anterior, rectus femoris and trapezius superior. The first step characteristics, ground reaction forces and CoP behaviour were assessed. **Results.** Vibration improved gait initiation performance regardless of the moment it was applied. CoP velocity during the initial phase of APA was increased by vibration only when it was applied before movement. When vibration was applied to disturb the movement, no effects on the CoP behaviour were observed. Manipulation of vibration frequency had no effects. **Conclusions.** Rather than proprioception manipulation, the results suggest that post-vibratory effects and attentional mechanisms were responsible for our results. Taken together, the results show that sagittal APA setting is robust to proprioception manipulation.

Key words: proprioception, vibration, gait initiation, anticipatory postural adjustment

Introduction

Voluntary movements, such as gait initiation, are accompanied by postural adjustments initiated prior to movement [1], named anticipatory postural adjustments (APAs) [2]. The study of APA during gait initiation is relevant, since APA is impaired in people with movement disabilities, such as Parkinson's disease [3]. Hence, the investigation of motor processes involved in APA during gait initiation execution can lead to development of novel techniques to improve movement in people with motor disabilities.

During the first step execution, in order to unload the leading limb and to allow movement progression, a centre of mass (CoM) displacement forwards and towards the stance limb is expected [4]. This CoM displacement is elicited by a centre of pressure (CoP) shift backwards and towards the leading limb [5]. In this way, the antero-posterior CoP displacement, during APAs, is as important to define gait initiation performance as the medio-lateral displacement [6].

APAs are based on sensory information [4, 7]. In stance, previous studies have shown that during normal conditions, the initial phase of APAs is robust to proprioceptive manipulation [1, 8], suggesting that other sensory information, as those information from the tactile and vestibular system, are used in a higher scale to set APAs than proprioception [1, 4]. In common, all these studies

[1, 4, 7, 8] directly manipulated the APA medio-lateral component. Therefore, there is a lack of information about the effects of proprioceptive system manipulation in gait initiation, when it is applied to induce sagittal perturbation/facilitation.

An instrument that has been used to manipulate the proprioceptive system and to induce postural adjustments is muscle vibration [1, 4, 9]. Since muscle vibration bilaterally applied on the lower limbs during upright stance shifts the CoP in the antero-posterior direction [9–11], it is suggested that some APA adaptations could be elicited by this technique. Two major CoP behaviours are observed when vibration is applied during upright standing: (i) a CoP displacement towards (lower limb), or opposite (trunk muscles) to the vibrated muscles (i.e.: a forward CoP displacement is observed when tibialis anterior and upper trapezius are stimulated) [9–12]); (ii) a CoP over recovery in relation to its initial position after vibration cessation [10, 13, 14]: i.e. after the cessation of vibration on the soleus the CoP moves excessively backwards compared to its initial position [10].

During gait initiation, a backward CoP shift is expected at the initial APA phase [2, 6, 15]. Thus, we suggest that muscle vibration, applied bilaterally on the tibialis anterior during the movement execution, would act as a disturbing effect, since, a forward CoP shift would be elicited by vibration [9, 11]. As a result, if proprioceptive system plays any role in the sagittal APA setting we would observe a worsening in gait initiation performance. Otherwise, if vibration could be turned-off immediately before APA onset, an increased backwards CoP shift would be elicited [10] – assisting APA execution.

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Previous studies have shown that muscle vibration effects are task-, amplitude-, timing- and frequency-dependent [9–11, 16]. Polonyova et al. [11] found greater postural effects during upright standing when the gastrocnemius was stimulated by vibration frequencies around 100 Hz compared to lower frequencies (40–60 Hz). This was an unexpected result, since physiological assessments showed poorer vibratory effects with the use of vibration frequencies higher than 80 Hz [17], due to subharmonic motor units synchronization mechanisms [17, 18]. In this way, the manipulation of vibration frequency on the postural response seems to be an unsolved issue. Optimising vibration frequency to improve gait initiation performance could enhance the effectiveness of vibration as a rehabilitative strategy. Since Polonyova et al. [11] also observed that a 20 Hz step increase is not sufficient to induce different postural effects (80 Hz vs 100 Hz), we suggest that this investigation should involve higher vibration frequencies (~120 Hz) when compared to the 'optimal' one (~80 Hz) [17].

Considering all issues discussed above, the aims of this study were: (i) investigate the role of proprioception manipulation to induce APA sagittal adaptations on gait initiation performance; (ii) investigate whether the application of different vibration frequencies could influence APA and gait initiation performance. As hypotheses, (i) a worse gait initiation performance is expected when vibration is applied during movement execution and an improvement when vibration is applied exclusively before movement onset. Otherwise, if proprioception does not play any role in the sagittal setting of APA, vibration will not lead to any effects, when it is applied during movement execution; (ii) based on the results of Polonyova et al. [11], greater effects on gait initiation performance are expected with the use of higher vibration frequencies.

Material and methods

Participants

Fourteen healthy young participants (7 males; mean age: 21.40 ± 4.26 years; height: 164.61 ± 10.08 cm; mass: 66.17 ± 10.04 kg) participated in the study. Participants gave written informed consent approved by the institution's Human Ethical Committee. All subjects were self-reported right-foot preference. In order to define the foot preference, the participants were asked which foot they would kick a ball running towards them. Exclusion criteria included any neurological, orthopedic, vestibular or uncorrected visual disturbances. Subjects were asked to not perform any physical activity 24 hours before the assessment.

Vibratory devices

A custom-made vibration system was used, named RCVibro System [19]. Three pairs of cylindrical vibratory

devices (measuring $4.5 \text{ cm} \times 2 \text{ cm} \times 2 \text{ cm}$; containing constant-velocity DC motors (Faulhaber®, Croglio, Switzerland) bearing eccentric masses) were positioned bilaterally on the muscles' bellies of Trapezius superior, Tibialis anterior and Rectus femoris. For fixation, ordinary elastic bands were used. Extra care was taken to maintain vibration pressure against the skin, similar across all participants. These muscles were chosen because their stimulation elicits a forward CoP displacement [20, 21]. All devices' vibration peak-to-peak amplitude was 0.8 mm.

Task and Procedures

Subjects were asked to walk a 4-meter pathway, looking ahead, initiating the movement from an upright posture, with arms resting beside the body. The participants were asked to always start the task with their preferred lower limb and to walk at their self-selected pace. There were three trials in three different experimental conditions: a baseline condition – without vibration (NonVib); vibration applied during (Du) the movement; and vibration applied only immediately before (Be) movement onset. In addition, two different frequencies were tested: 80 Hz and 120 Hz. Therefore, each participant executed a total of 15 trials, three in each of the five experimental conditions: NonVib, 80Du, 120Du, 80Be and 120Be. For all participants, NonVib was the first condition to be tested. The other conditions were randomly distributed in blocks. A rest period of 30 seconds between trials, and 3 minutes between conditions, was given.

For all conditions, the vibration stimulus was continuously applied for 30 seconds. For the Du conditions, participants started the movement after a verbal command given at the 28th second of vibration. For the Be conditions, participants were asked to execute the movement immediately after the devices were switched-off: at the 30th second of vibration. This procedure ensured that all participants were exposed to the same period of vibration: 30 seconds. During the NonVib conditions, the vibratory units were also kept in contact with the skin and fixed with elastic bands, but no vibration was applied.

Data acquisition

Four camcorders (Panasonic®, Tokio, Japan, sampling rate of 60Hz) were used to capture the position of four passive markers attached to the following anatomic landmarks: bilaterally on the 3rd metatarsal bones and heels. Markers were digitised automatically on Digital Video for Windows software (DVIDEO) [22]. As kinematic dependent variables, we assessed the duration (from heel off until heel strike), length, width and velocity of the first step, duration of the Postural Adjustment phase (PA, from beginning of the movement – first change on the ground reaction force (GRF, manually detected), until leading limb heel-off) and duration of the entire task (PA + step duration). In order to determine the heel-off, we used the vertical impulse obtained from the force plate

(the downward peak before the last and maximal downward peak – for further description, check Caderby et al. [23]). The heel-strike was determined using the vertical acceleration of the heel marker, as described by others [24].

To assess kinetic data, two force plates (AMTI®, Watertown, USA) were positioned side by side, allowing the subjects to step on each force plate with one foot. Initial position of the feet was self-selected and kept constant across all trials. Kinetic data was assessed with a sampling rate of 100 Hz. As kinetic dependent variables, we assessed the maximal vertical and horizontal ground reaction force (GRF, normalised to participants' body weight) for the leading and stance limb. We also assessed the GRF of each limb during quiet standing (1 second before movement onset). The CoP behaviour (duration, A-P and M-L displacement and mean velocity) was also assessed in three different phases [6, 12]: Anticipatory Postural Adjustment phase (APA, from the first change in the vertical GRF until the most posterior and lateral position of the CoP towards the leading limb); the Weight Transfer phase (WT, from the end of the previous phase until the peak medial and posterior CoP position towards the stance limb); the Locomotor phase (LP, from the end of the previous phase until stance limb toe-off). While PA and total duration were determined using kinematic variables, APA, WT and LP were determined using the CoP behaviour. Therefore, these two set of variables should not be related to each other, but as complementary. All data analyses were assessed using specific MatLab (MathWork®, Natick, USA) codes.

Statistical analyses

Two rounds of analysis were used. In the first round, we analysed the effects of different vibration parameters on each variable by means of two-way repeated-measures Analysis of Variance (2×2 ANOVAs): considering Timing (Be \times Du) and Frequency (80Hz and 120Hz) as within-subjects factors. In this way, during this round of analysis, we excluded the NonVib condition. During the second round, we ran a new series of one-way repeated-measures ANOVAs, including the NonVib condi-

tion. For that, we considered only the factor that reached significance in the first round, averaging the other factor into one. For example, if for the step length we found only a Timing effect during the first round, in the second round, the conditions used for the one-way ANOVA were NonVib, Du and Be (the conditions 80 Hz and 120 Hz were averaged into Timing). Wherever necessary, we used the Tukey post-hoc test to investigate any univariate comparisons. If in the first round a statistical significance effect of both Timing and Frequency (or interaction between factors) was found, we included all experimental conditions in the second one-way repeated-measures ANOVA round.

In all cases, where in the first round of analysis no main Timing and Frequency effects or interaction between them were found, we used a Student *t* test for dependent variables considering the conditions NonVib and Vib (where all conditions were averaged). This procedure was used to guarantee that the lack of significant effects of a condition would not mask positive effects of other conditions. The Statistica 7.0 software was used for all statistical procedures.

Results

Kinematic variables

No main effects of both Frequency and Timing were observed during the first round of analysis for all kinematic variables (for all variables: Frequency: $p > 0.18$; Timing: $p > 0.12$). During the second round of analysis, we found a decrease in step duration, an increase in step length and an increase in step velocity with the use of muscle vibration, regardless the timing and frequency used (comparison between NonVib and Vib on Figure 1).

Kinetics

The leading limb vertical GRF during standing showed an influence of Timing ($F = 5.39$; $p = 0.02$) without any effect of Frequency ($F = 2.46$; $p = 0.15$). In this case, after the one-way ANOVA ($F = 3.68$; $p = 0.03$) consid-

Table 1. Mean and \pm standard deviation values of Ground Reaction Forces (GRF)

	NonVib	Vib	<i>t</i>	<i>p</i>
Maximal Vertical GRF (%BW)				
Leading Limb	64.05 \pm 7.56	65.11 \pm 8.34	-0.64	0.52
Stance Limb	113.55 \pm 7.43	114.30 \pm 5.89	-0.61	0.54
Maximal Horizontal GRF (%BW)				
Leading Limb	1.14 \pm 0.89	0.88 \pm 1.26	1.11	0.27
Stance Limb	0.84 \pm 0.29	0.89 \pm 0.41	-0.59	0.55
Vertical Standing GRF (%BW)				
Stance Limb	56.00 \pm 4.24	53.26 \pm 4.59	3.01	< 0.01

%BW – % of body weight, significant results are bolded;

only those variables that did not show any Timing or Frequency effects in the first round of analyses are shown

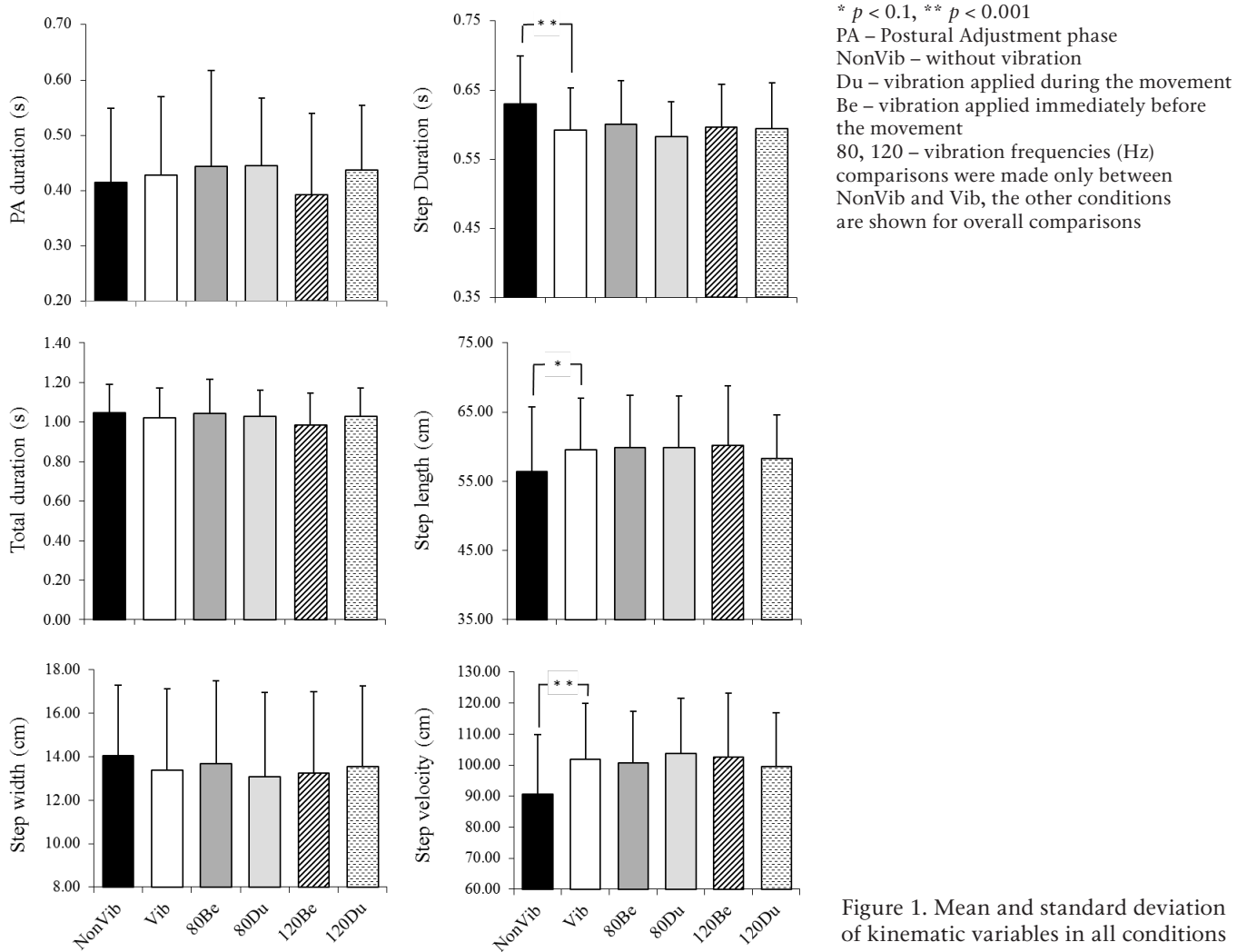


Figure 1. Mean and standard deviation of kinematic variables in all conditions

ering the conditions NonVib, Be and Du, the univariate analysis showed that Be ($48.02 \pm 2.88\%BW$) was higher ($p = 0.02$) than NonVib ($46.00 \pm 4.12\%BW$). Du ($47.00 \pm 3.58\%BW$) was not different from other conditions ($p > 0.16$). No other variable showed significance in the first round of analyses ($p > 0.12$), and therefore, were analysed through Student t tests considering NonVib and Vib. Table 1 summarises these results. Considering the GRF results, we can state that vibration decreased the body weight on the stance limb (regardless of vibration conditions) and increased the GRF on leading limb (only during the Be condition, independently of vibration frequency). It is important to highlight that these results were found during standing (1s before movement onset).

CoP behaviour

The Moment and Frequency effects in the CoP dependent variables are summarized on Table 2. As it can be seen, we found a Timing effect for APA duration and for CoP M-L velocity during LM phase. We also found a Timing and Frequency effect for APA A-P velocity.

For the APA duration, the one-way ANOVA, considering NonVib, Be and Du, showed a significant result ($F = 3.36$, $p = 0.04$), where Be ($0.33 \pm 0.12s$) was shorter than both Du ($0.38 \pm 0.11s$; $p = 0.033$) and NonVib ($0.36 \pm 0.14s$; $p = 0.042$). For CoP M-L velocity during Locomotor phase the one-way ANOVA did not reach significance ($F = 0.84$, $p = 0.43$).

The only variable that showed significance for both Timing and Frequency was the A-P velocity during APA phase (Table 2). In this case, we ran a one-way ANOVA considering all experimental conditions, and a statistical significance was found ($F = 6.12$, $p = 0.001$). The univariate comparisons showed that A-P CoP velocity in the 120Be (20.72 ± 9.45 cm/s) was higher than almost all other conditions: NonVib: 10.99 ± 5.09 cm/s ($p = 0.003$); 80Du: 10.03 ± 5.00 cm/s ($p = 0.003$); 120Du: 9.46 ± 4.79 cm/s ($p = 0.004$). However, 120Be was not different from 80Be (11.51 ± 5.91 cm/s; $p > 0.18$). All other comparisons were not significant ($p > 0.20$).

The Student t test comparing NonVib and Vib conditions, for other variables that did not show significance in the first round of analyses, are shown on Figure 2.

Table 2. ANOVAs *F* and *p* values for Moment and Frequency effects on CoP dependent variables

	<i>df</i>	Frequency		Timing	
		<i>F</i>	<i>p</i>	<i>F</i>	<i>p</i>
APA phase					
Duration (s)	1, 32	0.05	0.82	14.86	< 0.01
Velocity (cm/s)	1, 32				
Medio-Lateral		1.71	0.20	1.56	0.35
Antero-Posterior		5.05	0.03	16.66	< 0.01
WT phase					
Duration (s)	1, 32	0.46	0.50	0.03	0.86
Velocity (cm/s)	1, 32				
Medio-Lateral		0.49	0.49	3.46	0.07
Antero-Posterior		0.02	0.88	0.02	0.88
LM phase					
Duration (s)	1, 32	0.86	0.36	3.56	0.07
Velocity (cm/s)	1, 32				
Medio-Lateral		2.90	0.10	4.23	0.05
Antero-Posterior		0.04	0.84	0.10	0.76

APA – Anticipatory Postural Adjustment, WT – Weight Transfer phase, LM – Locomotor phase, *df* – degrees of freedom; significant effects are bolded

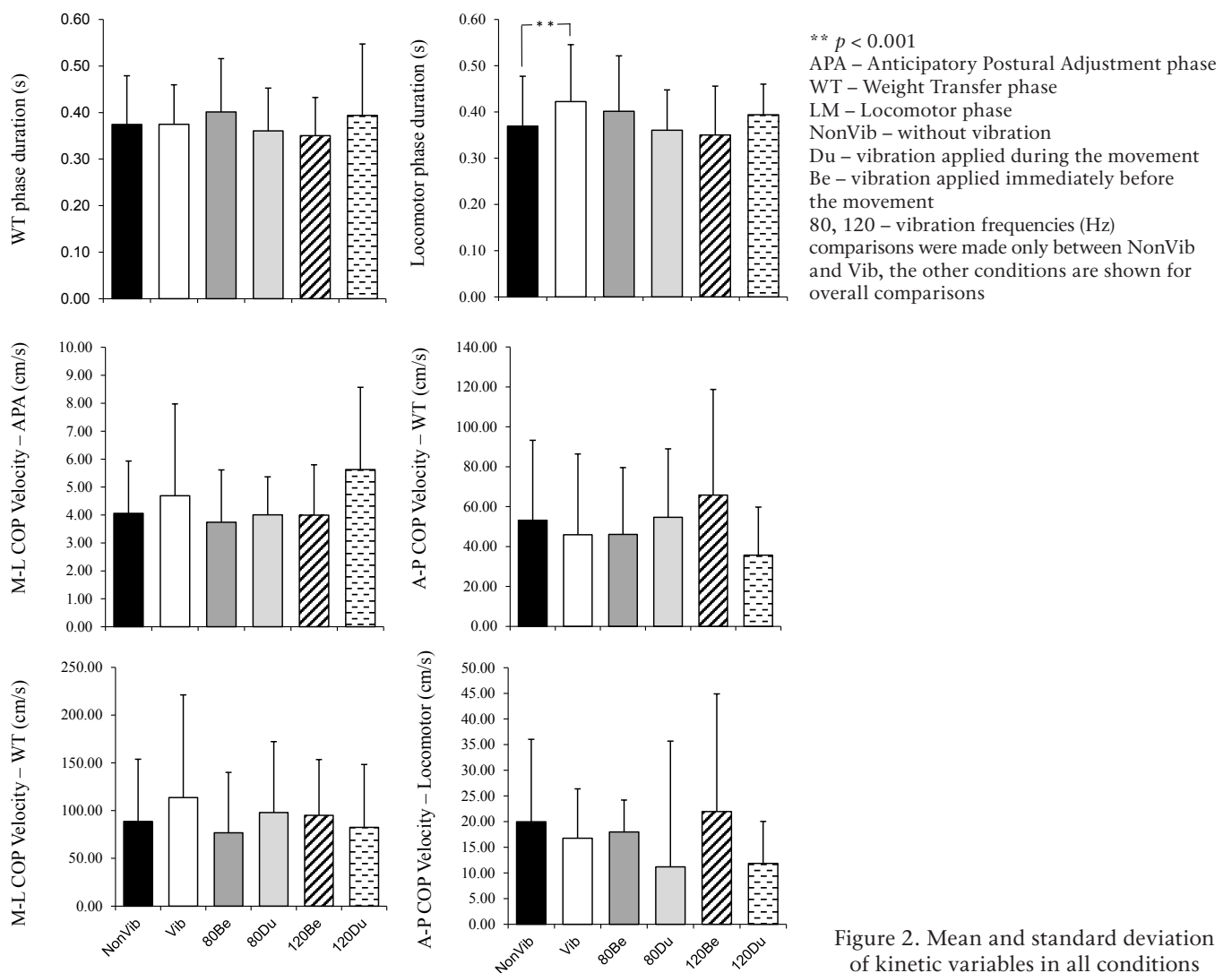


Figure 2. Mean and standard deviation of kinetic variables in all conditions

We found a vibration effect only for LM duration. No other variables showed difference between NonVib and Vib (Figure 2).

In summary, vibration reduced the duration of APA and increased its A-P velocity (especially in the 120Be and 80Be conditions). Vibration also increased the LM duration, regardless the vibration parameters that had been used.

No interactions between factors were found for any variables ($p > 0.10$).

Discussion

The main aim of this study was to investigate the effects of proprioception manipulation, through muscle vibration, on the APA during gait initiation in healthy young people. Another aim of this study was to investigate the effects of different vibration frequencies on the performance of gait initiation. As main results, we found an improvement of gait initiation performance with muscle vibration, when it was applied immediately before the task execution. No effects on APA were found when vibration was applied during the task execution. Finally, we found no vibration frequency effects. Taken together, our results suggest that APAs setting in the A-P direction is robust to proprioception perturbation.

To properly execute the gait initiation, a backward CoP displacement towards the leading limb is expected [25, 26]. As higher is the velocity and shorter is the duration of this displacement, the longer and faster is the first step [2, 15]. Since we observed a shorter APA phase and a faster A-P CoP velocity when vibration was applied only immediately before gait initiation onset, we suggest that this condition may benefit participants. A CoP position excessive recovery after vibration was already demonstrated by other studies [10, 14]: e.g. when vibration on the gastrocnemius was interrupted, an excessive forward CoP recovery in relation to its initial position was observed [10]. Since, during upright stance, we induced a forward CoP displacement, it is suggested that switching-off vibration immediately before movement execution facilitated the CoP backwards movement, which is expected during the initial phase of APA [27].

The improvement of the initial phase of APA found here is contrary to the results reported by Mouchino et al. [8]: in their study, no significant results were found when APA was facilitated by a fast change in sensory information. However, Mouchino et al. [8] facilitated APA by a postural perturbation in the medio-lateral direction, while we induced a postural facilitation in the sagittal direction. This discrepancy between our results and those reported by Mouchino et al. [8] reinforce a specific response to proprioceptive perturbations in different directions.

Since we found a Timing effect on the APA phase, we would also expect different responses to vibration application moments in the first step parameters. This

would be expected since the first step parameters are a reflex of the CoP behaviour during APA [2, 15]. However, our results (Figure 1), show that independently of the moment vibration was applied, it induced an improvement in gait initiation performance. This finding indicates that the benefits of vibration on the gait initiation performance are not exclusively explained by post-vibratory effects [10, 13, 14, 28]. Tard et al. [29] demonstrated that stimulus-driven attention modifies the gait initiation. Therefore, we suggest that any time muscle vibration was applied, it shifted the participants' attention to the task execution. This might explain why we found an improvement of the first step parameters even without changes in the APA phase (in the case of Du condition). The GRF results support this hypothesis – we found a reduction in the GRF in the stance limb regardless the moment vibration was applied, suggesting that participants were already prepared to perform a faster CoP backwards displacement with the use of vibration.

However, if attentional shifting was the only mechanism underlying our results, we should not find any Timing effects, even during APA, since in both Be and Du, vibration was being applied equally. Taken together, our results suggest that both mechanisms (postural post-vibratory effects and attentional mechanisms) played some role in the improvement of gait initiation performance in face of muscle vibration.

Another aim of this study was to investigate the effects of vibration frequency manipulation on the gait initiation performance. As main result, we found that manipulating vibration frequencies does not influence gait initiation. This was an unexpected result, since other studies showed a linear increase in postural responses with higher vibration frequencies [11]. Therefore, since gait initiation performance is highly based on postural responses executed before the first step [8], we expected a frequency manipulation effect. We suggest that vibration frequency manipulation effects are restricted to upright stance and were suppressed by superior volitional commands during the step execution [9, 19]. Voss et al. [30] findings support this hypothesis – the authors found that pre-programmed movement setting interrupts the somatosensory influx to the central neural system. Therefore, if sensory manipulation exerted during the step execution was neglected by the participants, the vibration frequency increase would not lead to different motor adaptations. This model explains why higher vibration frequencies induces postural effects on upright standing [11], but not during gait initiation.

The mechanisms underlying the first step performance improvement, considered together with the theory that volitional commands suppress the vibratory sensory effects, are in line with the results of other studies [1, 4, 7]. These studies suggested that proprioception plays a discrete role in the setting of the initial APA phase and in the first step execution performance [1, 4, 7]. The lack of effects on the Du condition reinforces this theory:

vibration, as applied here, was not relevant to the task execution, as suggested previously. In this way, if proprioception plays any role in the APA setting and on the gait initiation performance, we would expect a disturbing vibration effect in Du. However our results suggest that participants simply ignored the vibration sensory effects. Hence, we suggest that rather than proprioception manipulation, postural adaptations and attentional mechanisms elicited by vibration induced the improvements of gait initiation observed in this study.

Finally, since vibration reduced the duration of the initial phase of APA, some could argue that a reduction of the WT and LM duration would also be expected. In the Be condition, since vibration effects are discontinued as soon as the vibration is interrupted [18] and the participants took another ~0.37 seconds to perform the first APA phase, the vibration effects would already have disappeared at the WT onset. In the same way, in the Du condition, vibration effects were suppressed by volitional movement execution [9, 19]. Therefore, this lack of significant results was already expected.

The results found here are important in the rehabilitative field. They suggest that vibration applied immediately before movement execution might benefit people with motor disabilities and with gait initiation impairments, as Parkinson's disease patients. Some limitations of the study should be addressed, as the low number of participants assessed and the lack of EMG assessments. The use of EMG could have brought further information about the relationship between volitional movement execution and involuntary postural responses elicited by vibration [9, 10]. Future studies should overcome these limitations.

Conclusions

At the end of this study, we can affirm that muscle vibration, improves gait initiation performance in young healthy adults, reducing the first step time and increasing its both length and velocity. In addition, the manipulation of vibration frequency does not lead to any motor adaptation. Taken together, our results suggest that proprioception is not used to set APAs in the sagittal direction. The results also suggest that rather than proprioception perturbation, a combination of postural adaptations and attentional mechanisms elicited by vibration improved gait initiation. These results are clinically important, since they suggest that muscle vibration could be used to enhance gait initiation performance in people with movement disabilities.

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