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Effects of vibration frequency, amplitude, and direction on human gait metrics

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ABSTRACT

The effect of vibrations on gait is a topic that has not been sufficiently analyzed. Thirty-one volunteers underwent 50 walking trials on a modified treadmill with three degrees of freedom including normal walking and walking in the presence of sinusoidal roll, pitch, and vertical vibration. A full factorial design of experiments was adopted, using two vibration amplitudes (4 or 8 cm for linear displacements, 4° or 8° for angular oscillations), four frequencies (0.25, 0.5, 0.7, and 1 Hz), and two walking speeds (0.7 or 1 m/s). A significant alteration of all the gait metrics was found in the presence of vibration, but the step width and cadence resulted in the most affected. A combined effect of all factors was found, with the major impact on gait in the case of rotational vibration, mainly in the case of roll, at higher amplitude and frequencies. Understanding the most detrimental vibration conditions contributes to updating the ISO standard for whole-body vibration considering exposed walking workers.

1. Introduction

Many workers are exposed to mechanical vibration (Bovenzi and Hulshof, 1999; Smith and Leggat, 2005). Gait is altered by the surface motion and characteristics (Kerdok et al., 2002). In transportation industries, standing passengers and crew members' postural stability may be compromised and the ISO standard coding whole-body vibration (WBV) measurements (ISO 2631–1, 1997) does not consider walking.

Foot-transmitted vibration (FTV) has been recognized as a distinct category acknowledging the unique transmission pathway of vibrations through the feet. Depending on the vibration conditions (i.e., combinations of different frequency, amplitude and direction factors), various potential impacts could arise: vascular and neurological issues in the feet, similar to what occurs with hand-arm vibration exposure at higher frequencies (Eger et al., 2014; Goggins et al., 2016; Marelli et al., 2021, Marrone et al., 2025a), and alterations in locomotion and postural stability at lower frequencies (Bertozzi et al., 2024; Choi et al., 2022; Marrone et al., 2024, 2025b, 2025b; Moorhead et al., 2021; Sari and Griffin, 2014). In each of these cases, specific weighting procedures are required to update the current regulations on human vibration.

Specifically conducted to investigate biomechanical alteration while walking, field studies assessed the effect of low-frequency vibration on ships and it was observed that the roll and pitch motion affect the stride regularity (Haaland et al., 2015), the center of mass, the margin of stability, and step time (Choi et al., 2022); it was not possible to study the effect of vibration on gait, since the magnitude and the frequency were determined by the ship characteristics and sea conditions.

Other studies (Ayık and Griffin, 2019; Bertozzi et al., 2024; Brady et al., 2009; Chadefaux et al., 2021; Marrone et al., 2025a, 2025b, 2024; Moorhead et al., 2021; Sari and Griffin, 2014, 2009) analyzed the effect of FTV on gait in laboratory settings. Only one study has also considered rotational FTV (roll and pitch) (Marrone et al., 2025b), whereas all the others have focused solely on translations (mediolateral, anteroposterior, and vertical directions), resulting in a partial understanding of how FTV affects postural stability and gait, increasing the risk of falls and injuries in occupational fields.

Most of the studies focused on mediolateral FTV up to 10 Hz. Brady and colleagues (2009) studied the effect of 254 mm peak-to-peak lateral vibration on balance at 0.2 and 0.3 Hz. Results showed that, at such low frequencies, participants tended to either fix themselves in space, allowing the treadmill to move laterally beneath them, or to move laterally with the base. In contrast to later studies that considered higher

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frequencies in the mediolateral direction, the average step width was unaffected by the vibration.

Sari and Griffin (2014, 2009) investigated how postural stability depends on the magnitude and frequency of lateral oscillations. Twenty males walked on a treadmill with vibrations between 0.1 and 2 m/s^2 and frequencies between 0.5 and 2 Hz. The results showed an increased step width and rate, and a lower subjective probability of losing balance as the vibration frequency decreases and magnitude increases. Using the same apparatus, Ayik and Griffin (2019) investigated the effect of mediolateral waveforms with different r.m.s. and peak acceleration at 1 and 2 Hz. Walking stability was influenced by peak and r.m.s. magnitude, especially at 1 Hz in terms of self-reported probability of losing balance and increased center of pressure velocity. These studies applied short-duration stimuli without considering gait adaptation to the continuous FTV.

Marrone and colleagues (2024) investigated the effect of mediolateral vibration in twenty male participants. They found an increase of 4.2 % in step width while walking with FTV exposure compared to unperturbed walking but limited the investigation to a single frequency of 1.25 Hz and amplitude of 1 m/s^2. With the same setup, Bertozzi et al. (2024) investigated gait metrics and kinematics of lower limb joints in forty participants subjected to 1 m/s^2 of amplitude at higher frequencies (2, 4, 6, 8, and 10 Hz). The exposure at 2 Hz reduced stride length and time, step length, and stance, while increased step width and cadence. Still using the same setup, Marrone et al. (2025a) tested sinusoidal mediolateral FTVs given by the combination of different frequencies (range: 0.2–8 Hz) and magnitudes (range: 0.05–0.1 m/s) and they found a significant increase in the stride time and the step width at 1–2 Hz.

Mediolateral vibration effects were also studied by McAndrew and colleagues (2010), but in comparison with the anteroposterior direction in the case of pseudo-random FTV with four components between 0.16 and 0.49 Hz. The variability of gait was greater in the mediolateral case; however, the conclusion may be limited to the specific stimulus used.

Moorhead and colleagues (2021) exposed subjects walking on a treadmill to vertical vibration at frequencies between 2 and 12 Hz. Results evidenced that vertical vibration affects the stride frequency and length, velocity of the center of pressure and ground reaction force (Chadefaux et al., 2021).

Finally, the study by Marrone and colleagues (2025b) compared four different directions (i.e., mediolateral, anteroposterior, roll, and pitch) between 0.5 and 1.5 Hz. At a constant displacement (2 cm and 1° peak-to-peak for translations and rotations, respectively), the study found a frequency-dependent gait alteration, with the greatest impact in the mediolateral direction.

Studies on FTV have used non-standardized protocols, varying in amplitude (displacement, velocity, or acceleration) and stimuli (sinusoids or pseudo-random). Walking speed is often preset and constant at different intensities. This complicates comparison across studies, except for direction and frequency. Fig. 1 summarizes all the studies, providing an overview of the FTV conditions studied to date.

Fig. 1 shows that the current literature lacks studies focused on rotational (roll, pitch, and yaw) and vertical vibration at low frequencies.

Recognizing that vibration can influence gait and postural stability, this study focused on the effects of less-explored FTV conditions. We hypothesize that the characteristics of direction, frequency, and amplitude of the ground vibration, the walking speed, as well as their interactions, modulate the gait pattern. Such a modulation would be consistent with previous findings; however, prior research has typically investigated vibratory factors in isolation rather than exploring their combined effects and interactions. To test this hypothesis, we conducted controlled laboratory experiments to examine the impact of vertical, roll, and pitch vibrations at two amplitude levels and at frequencies representative of real-world environments, such as those experienced on ships and trains, using two treadmill walking speeds. We expect that specific combinations of these factors would elicit measurable

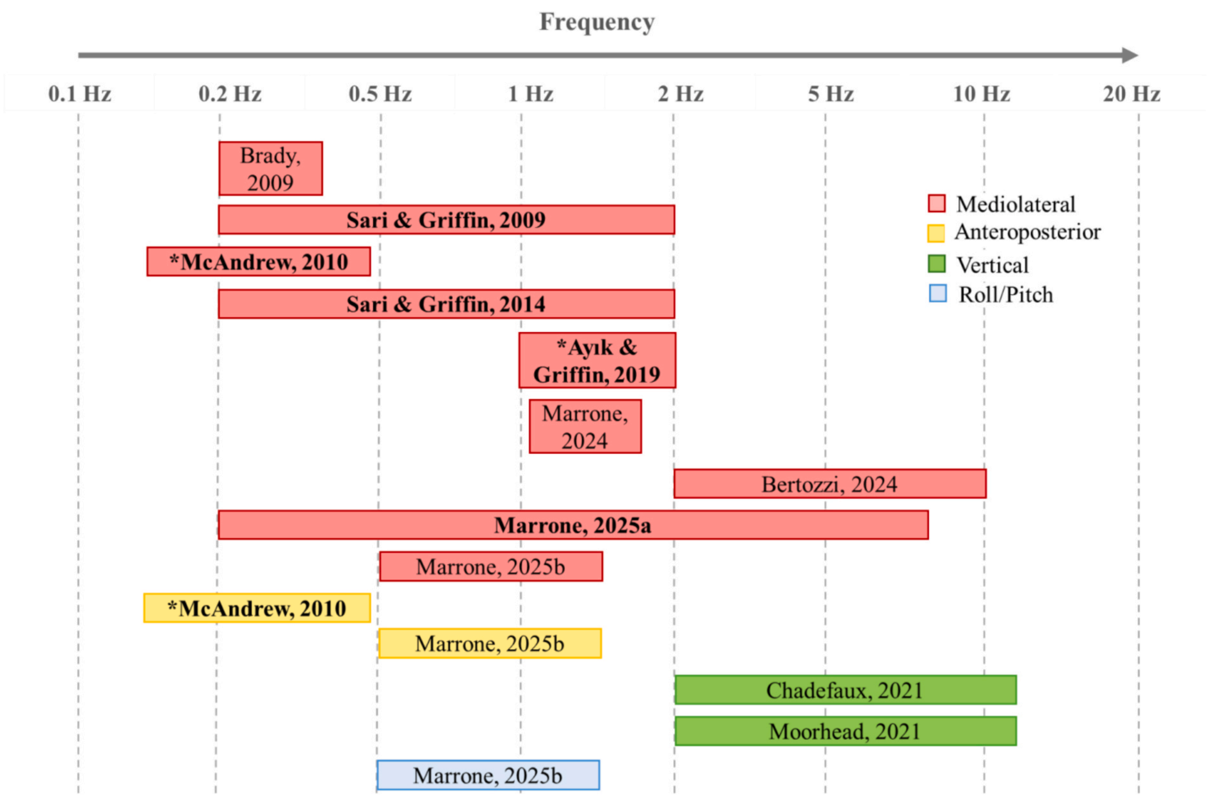

Fig. 1. Summary scheme of laboratory studies on gait perturbed by FTV, grouped by direction and positioned in the grid according to the frequency range tested. In bold are those studies where multiple amplitudes were considered. All studies used sinusoidal FTV except those marked with * where a pseudo-random vibration was applied.

adaptations in key spatiotemporal gait metrics, including stride time, stance phase duration, cadence, and step width. The results offer insights into how gait is altered in response to different vibration conditions, providing useful reference information for updating the current regulations and weighting procedure for FTV exposure during walking.

2. Method

2.1. Subjects

Thirty-one healthy volunteers took part in the experiments after a medical visit for eligibility. Subjects were between 18 and 40 years of age (twenty-seven were under 25 – thirteen of whom were under 20, and four were over 25 – two of whom were over 30). Older subjects and people without a regular sporting activity (e.g., walking a few kilometers a day) were not included because of the possible risk of falls. The exclusion criteria were:

- musculoskeletal, neurological, pulmonary or cardiovascular problems;
- mobility or balance problems (assessed with static test (Ledin et al., 1991) and with normal walking on the treadmill);
- long-term treatments;
- medication that may affect balance;
- hospitalization in the 6 months before the study;
- visual acuity deficits;
- pregnancy;
- motion sickness.

The study was approved by the Ethics Committee (CPP: 2022–12, RCB: 2021-A02429-32) and each subject signed the consent form for participation and data protection. The experiments included 17 male and 14 female subjects whose anthropometric data are in Table 1.

2.2. Experimental setup

The experimental facility was manufactured by the Institut National de Recherche et de Sécurité (INRS), Centre De Lorraine (Vandœuvre-lès-Nancy, France). One standard treadmill (Horizon Fitness T40 Decathlon, France) has been modified to obtain a 950 mm width to guarantee freedom of movement (Bertozzi et al., 2024; Marrone et al., 2024). The treadmill has been mounted on a motion platform with three degrees of freedom: two rotations (roll and pitch) and one linear translation (vertical). In front of the treadmill, the virtual scene of a corridor was projected on a screen (Fig. 2.a) with its point of view continuously adjusted based on treadmill and the platform movement. Six infrared cameras (Vicon 460, Vicon Motion Systems Ltd, UK) were placed around the treadmill (Fig. 2.b).

Forty-one markers were positioned on the anatomical landmarks as shown in Fig. 3, and four markers were glued on the treadmill's frame.

2.3. Test protocol

Subjects wore sports suits and a protective helmet and completed 50 walking trials of 1 to 3 min each. Between each trial, 2 min of rest were given.

The entire experimental session was performed in a single day for each subject. To avoid the confounding effect of fatigue and exposure familiarization (i.e., learning effect), the trials were executed in a different random order for each subject. Trials were divided into two groups:

- *Baseline trials.* The subject is instructed to walk on the treadmill at two different speeds, 0.7 and 1 m/s, for 1 min without platform motion to define the baseline.
- *FTV trials*. Trials and motion capturing started with normal walking and then the displacement of the platform progressively increased until the steady state sinusoidal vibration was reached at the given FTV amplitude; the motion transition was announced orally to the subject. The 48 *FTV trials* are given by a full factorial design of experiments. The factors were vibration direction (3 levels: roll, pitch, vertical), amplitude (2 levels: 4 or 8 cm for the vertical vibration, or 4° or 8° for the angular motion), frequency (4 levels: 0.25, 0.5, 0.7 and 1 Hz) and walking speed (2 levels: 0.7 or 1 m/s).

Among vibration directions, we focused on pitch and roll rotations because they are the primary rotational motions experienced in public transportation; instead, yaw is not representative in this context. While horizontal vibrations are also relevant, especially in the railway sector, they have been extensively studied in previous research. Therefore, we focused on the vertical direction, which has been less explored. Regarding FTV frequencies and amplitudes, we selected the most experienced in transportation (Marrone et al., 2025b; Sari and Griffin, 2014). The amplitude was controlled in displacement to guarantee a repeatable perturbation condition and the comparability of the gait pattern outcomes among the frequencies (Marrone et al., 2025b).

The two walking speeds were selected based on preliminary tests to mitigate the risk of falls. Although these speeds are lower than typical self-selected walking speeds on a treadmill, this choice was necessary as participants moved freely without a harness. This approach ensured subject safety while remaining consistent with the pre-selected speeds used in previous studies of perturbed walking on a treadmill (Brady et al., 2009; Marrone et al., 2025a; Sari and Griffin, 2014, 2009).

2.4. Gait metrics

In the present study, only heels and the posterior-superior iliac spines (PSIS) markers were considered to calculate the gait metrics. For each trial, we considered 30 s of steady-state walking in the presence of sinusoidal perturbation and extracted 15 gait cycles (GCs). Each GC was defined by identifying (Zeni et al., 2008) (Fig. 4):

- *Heel Strike (HS)*: instant in which the maximal distance of the heel from the PSIS in the walking direction is reached.
- *Toe Off (TO)*: instant in which the maximal distance of the PSIS from the heel in the walking direction is reached.

For each trial, the mean and the standard deviation of the main spatiotemporal gait metrics (Table 2) over the 15 GCs were calculated (Table 2).

To investigate any potential asymmetries between right and left lateralities, the symmetry index (*SI*) of stance and swing phase and stride time was calculated as the ratio between the right and the left values for each considered metric *m* (Patterson et al., 2010; Viteckova et al., 2018):

$$SI_m = \frac{m_{RIGHT}}{m_{LEFT}} \tag{1}$$

2.5. Statistical analysis

The statistical analysis was performed with Minitab software with a

Table 1
Subjects' characteristics for height, body mass, and age. Values are presented as the mean ± standard deviation with range in parentheses.

Group	Number	Body Mass [kg]	Height [m]	Age [years]
Male	17	70.9 ± 10 (53 – 85.5)	1.79 ± 0.08 (1.62 – 1.92)	21 ± 4 (18 – 38)
Female	14	60.5 ± 7 (50 – 72)	1.66 ± 0.06 (1.55 – 1.82)	23 ± 5 (18 – 40)
All	31	66 ± 10 (50 – 85.5)	1.73 ± 0.09 (1.55 – 1.92)	22 ± 5 (18 – 40)

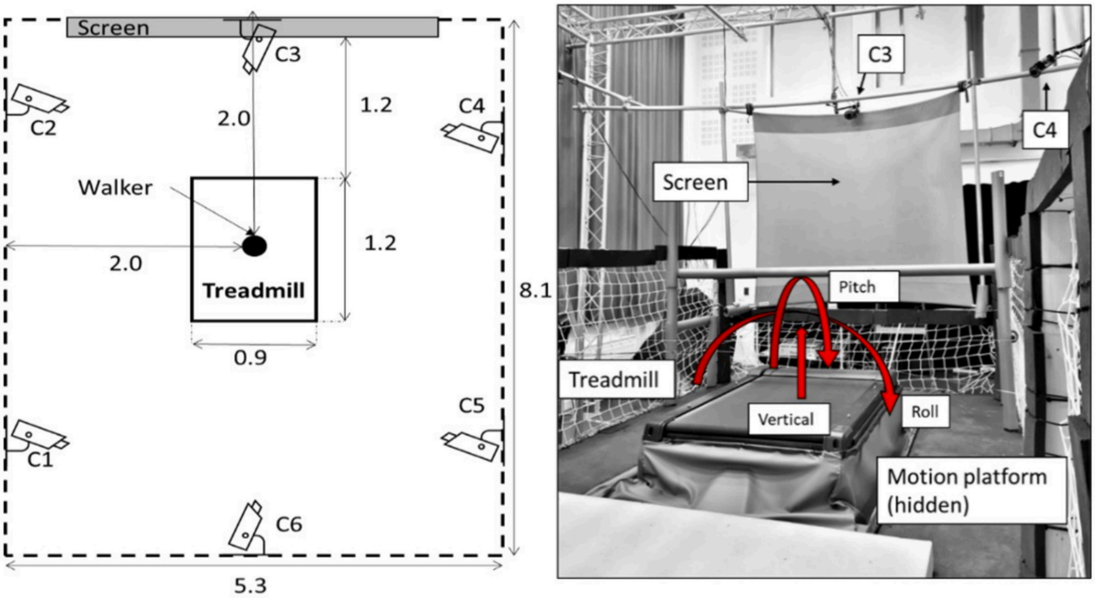

Fig. 2. On the left is the scheme of the setup with cameras, treadmill, and screen (values in meters). On the right is the pictorial view of the setup. The modified treadmill is mounted on a motion platform with three degrees of freedom: two rotations (roll and pitch) and one linear (vertical).

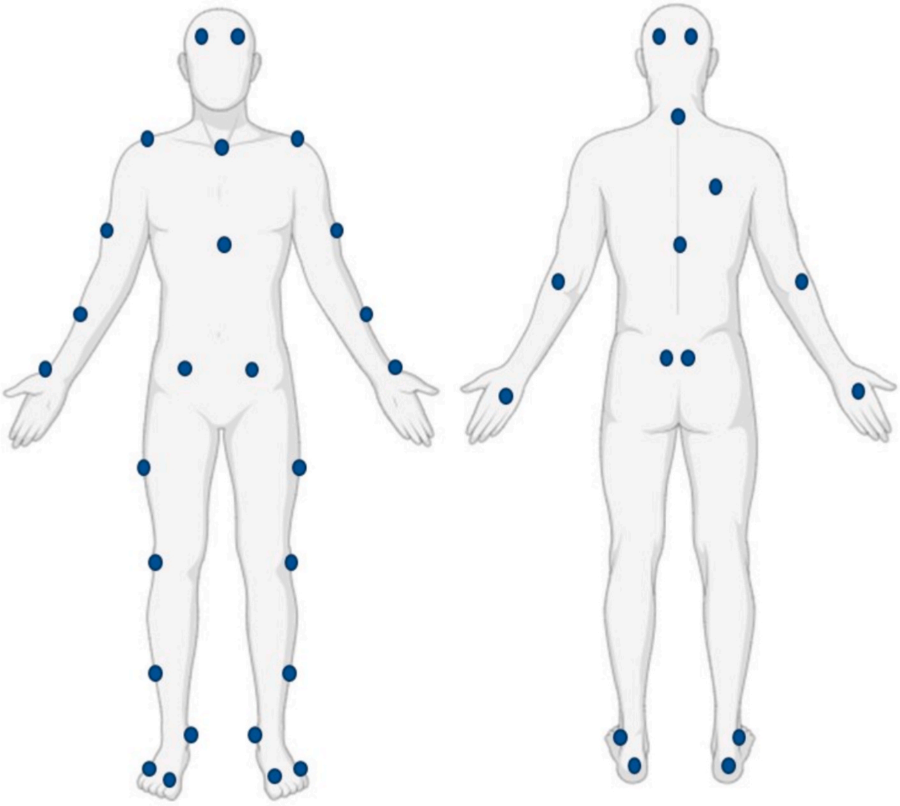

Fig. 3. Marker set in the frontal and back views.

significance of 95 % (alpha = 0.05). A full factorial design was defined considering walking speed (0.7 or 1 m/s), vibration direction (roll, pitch, vertical), vibration amplitude (4 or 8 cm, 4 or 8°), and vibration frequency (0.25, 0.5, 0.7, 1 Hz) as factors. In cases of asymmetry, the laterality factor (2 levels: right and left) was also considered within the experimental design, following the statistical approach of (Marrone et al., 2025b). The main and combined statistical effects of the factors on the gait metrics of the *FTV trials* were investigated. In the case of the main significant factor, we performed a specific one-way ANOVA with the Tukey correction for multiple comparisons. Then, a one-way ANOVA test was used to compare the *Baseline* and *FTV trials* grouped by walking speed. In case of significance, the Dunnett correction (with *Baseline* as reference) was applied.

To identify the most affected gait metrics during FTV exposure from

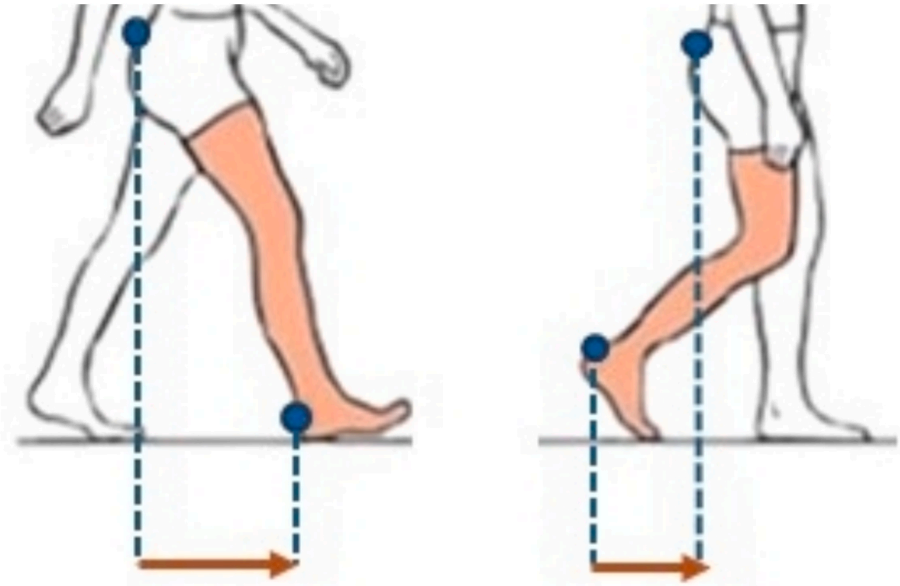

Fig. 4. On the left is the heel strike, and on the right is the toe off instants.

Table 2

Descriptions of the mean gait metrics.

Parameter	Unit	Description
Stance Phase	%	Stance phase is the time between HS and TO of the same foot normalized throughout the entire GC and expressed as a percentage of gait cycle.
Swing Phase	%	Swing phase is the time between TO and HS of the same foot normalized throughout the entire GC and expressed as a percentage.
Stride Time	s	Duration of the GC is defined as the time between two successive HSs of the same foot.
Step Time	s	Duration of the step is defined as the time between two successive HSs of the two feet.
Step Width	m	Distance between the heels in the mediolateral direction at two successive right and left HSs.
Cadence	steps/ min	Number of steps per minute.

the baseline condition, we calculated the percentage deviation for each vibration direction, as follows:

$$\overline{m}_d = \frac{\sum_{i=1}^{N} m_{d,i}}{N} \tag{2}$$

$$\overline{m}_{Baseline} = \frac{\sum_{i=1}^{N} m_{Baseline,i}}{N} \tag{3}$$

where $\overline{m}_{fl}$ is the mean value of any metric m(i.e., stance and swing phase, step and stride time, step width, or cadence) for the d-th direction (roll, pitch, and vertical). It was calculated as the arithmetic average on the N metrics of all subjects at d-th direction. Analogously, $\overline{m}_{Baseline}$ was obtained as the average of the *Baseline* values of all subjects. Then a normalization was carried out:

$$\overline{M}_d = \frac{\overline{m}_d}{\overline{m}_{Baseline}} * 100 \tag{4}$$

where $\overline{M}_d$ is the ratio between $\overline{m}_d$ and $\overline{m}_{Baseline}$ expressed in percentage.

3. Results

The *SI* of the stance and swing phase and stride time was calculated to investigate the effect of vibration on gait symmetry (Table 3).

Given that all the *SIs* demonstrated no effect of perturbation on gait symmetry, we did not consider the laterality as a factor, and we executed the statistical tests only on the right metrics as performed by Bertozzi and colleagues (2024).

The analysis of variance revealed that all the factors present significant ($p < 0.001$) main and combined effects on the gait metrics recorded in the *FTV Trials* (Table 4). Significant interactions were consistently observed between two factors, and in some cases, three-factor interactions were also present, indicating that gait adaptations arise from the combined action of multiple factors. For example, step width increased with higher FTV amplitude and frequency, but this effect was particularly pronounced in the presence of roll vibration at faster treadmill speeds.

Given that all four factors were significant, a one-way ANOVA and the Tukey correction (Table A in the Appendix) were performed on each of them. All metrics, except swing phase (which is complementary to stance) and cadence, present higher values at 0.7 m/s with respect to 1 m/s. Faster walking determines a shorter swing phase and a higher number of steps. Regarding the vibration factors (i.e., direction, amplitude, and frequency), stance phase, stride, and step time are affected with the same trend by the same factors, as well as the swing phase, step width, and cadence. The first three metrics are higher in vertical vibration at the smaller amplitude and frequencies. This vibration is less influential because the subjects tend to keep their feet on the ground for a longer period with slower steps. Swing phase, step width, and cadence, instead, are higher in the case of rotational vibrations (roll and pitch) at higher amplitude and frequencies. In this case, because of the higher instability, the time in contact with the floor is reduced and the support base is enlarged.

The comparison between *Baseline* and *FTV trials* grouped by walking speed revealed significance ($p < 0.001$) for each metric. Given that the

Table 3

Mean ± standard deviation of the SI of the Stance, Swing, and Stride metrics grouped by type of trials (Baseline and FTV).

Trials	$SI_{Stance\ Phase}$	$SI_{Swing\ Phase}$	$SI_{Stride\ Time}$
Baseline	0.997 ± 0.013	1.005 ± 0.013	1.000 ± 0.002
FTV	0.999 ± 0.018	1.004 ± 0.037	1.000 ± 0.019

Table 4
Factorial model results for the effects of the vibration factors and walking speed factors (and their combined effect) in the experimental subjects during perturbed trials. The F test and the effect size η_p^2 (p-value).

Metrics	Walking speed (S)	Vibration direction (D)	Vibration amplitude (A)	Vibration frequency (F)	Significant interactions
Stance/ Swing phase	F (1,1487) = 1052.90 $\eta_p^2 = 0.43$ (<.001)	F(2,1487) = 70.34 $\eta_p^2 = 0.09$ (<.001)	F(1,1487) = 14.71 $\eta_p^2 = 0.01$ (<.001)	F(3,1487) = 9.08 $\eta_p^2 = 0.02$ (<.001)	All
Stride time	F (1,1487) = 896.43 $\eta_p^2 = 0.39$ (<.001)	F(2,1487) = 41.87 $\eta_p^2 = 0.05$ (<.001)	F(1,1487) = 40.55 $\eta_p^2 = 0.03$ (<.001)	F(3,1487) = 43.00 $\eta_p^2 = 0.08$ (<.001)	All
Step time	F (1,1487) = 744.03 $\eta_p^2 = 0.35$ (<.001)	F(2,1487) = 38.90 $\eta_p^2 = 0.05$ (<.001)	F(1,1487) = 32.77 $\eta_p^2 = 0.02$ (<.001)	F(3,1487) = 33.61 $\eta_p^2 = 0.07$ (<.001)	All except D*A*F
Step width	F (1,1487) = 41.71 $\eta_p^2 = 0.03$ (<.001)	F(2,1487) = 139.36 $\eta_p^2 = 0.17$ (<.001)	F(1,1487) = 37.12 $\eta_p^2 = 0.03$ (<.001)	F(3,1487) = 25.09 $\eta_p^2 = 0.05$ (<.001)	D*A, D*S, D*F, D*A*F
Cadence	F (1,1487) = 719.72 $\eta_p^2 = 0.34$ (<.001)	F(2,1487) = 41.30 $\eta_p^2 = 0.06$ (<.001)	F(1,1487) = 45.42 $\eta_p^2 = 0.03$ (<.001)	F(3,1487) = 46.02 $\eta_p^2 = 0.09$ (<.001)	All except D*S*F

swing is complementary to the stance phase with the same but opposite trend, and the step is part of the calculation of the stride time showing its same behavior, Fig. 5 represents the main effect of vibration direction with respect to the *Baseline* only for stance phase, stride time, step width, and cadence.

Step width and cadence are the metrics most affected by the exposure to FTV for all directions, with greater variation in roll. The comparison between each *FTV trial* and the *Baseline* at the same walking speed revealed that the alterations occurred at the highest frequencies and amplitude for both walking speeds (Table B in the Appendix). This is also confirmed by Fig. 6. It shows the combination of the effects of all the tested factors on step width and cadence metrics (see Table C in the Appendix for the detailed mean and standard deviation values).

Except for the vertical direction in which no clear trend was found, for roll and pitch direction, the step width and the cadence alterations increase by increasing both the frequency and the amplitude, resulting in the highest alteration at 8° at 0.7–1 Hz. However, cadence increases with frequency except at 1 m/s and 8 cm in the vertical direction in which a counter-trend is observed. Also, amplitude plays a role in the cadence variation. Both amplitudes show the same trend in the case of rotational FTV, but with a greater increase in the number of steps at 4°. The walking speed is also significant but with opposite influence: the step with and the cadence increase by decreasing and increasing the speed, respectively. In fact, for cadence, as it is defined, the number of steps per minute increases with speed.

4. Discussion

4.1. *Effects of vibration on gait metrics*

Results confirmed that the analyzed FTV conditions, which had never been examined in the literature, lead to significant alterations in locomotion strategies. FTV impacts how individuals utilize visual, vestibular, and somatosensory inputs to preserve equilibrium (Halmai et al., 2024), determining specific strategies at the level of muscular activity (Taleshi et al., 2022). This led to the adoption of specific neuromechanical compensations based on the vibration factors aimed at maintaining stability and efficient locomotion. Modifications in gait metrics, such as step width and cadence, suggest the combined influence of altered proprioceptive and vestibular signals on gait control. In general, participants minimize foot contact time with the moving floor and widen their base of support (e.g., stance phase: −0.6 %, cadence: +3.6 steps/min, step width: +0.05 m) to stabilize the body on the moving floor. The obtained findings confirm the significant combined effects on gait of all FTV factors: frequency, amplitude, and direction, and the differential gait responses provide an indirect measure of the relative influence of each factor on locomotor control.

Although among the tested conditions, rotational was more impactful than vertical FTV, all directions influenced the most step width and cadence, mainly at the combination of high amplitude and frequency that correspond to higher acceleration values. Roll and pitch vibrations have comparable effects on temporal metrics. McAndrew and

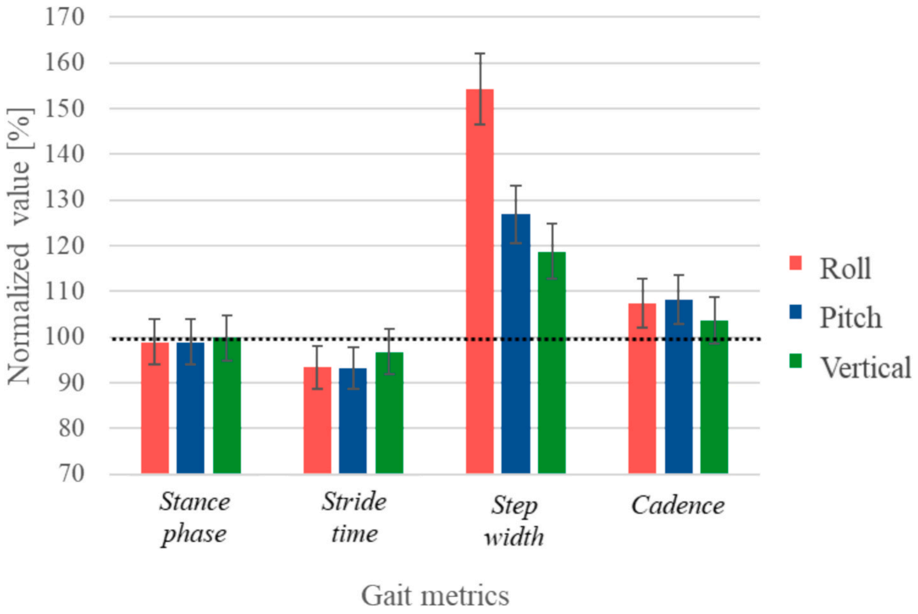

Fig. 5. Mean and standard deviation values of the normalized metrics grouped by vibration direction. The dotted line at 100% indicates the Baseline.

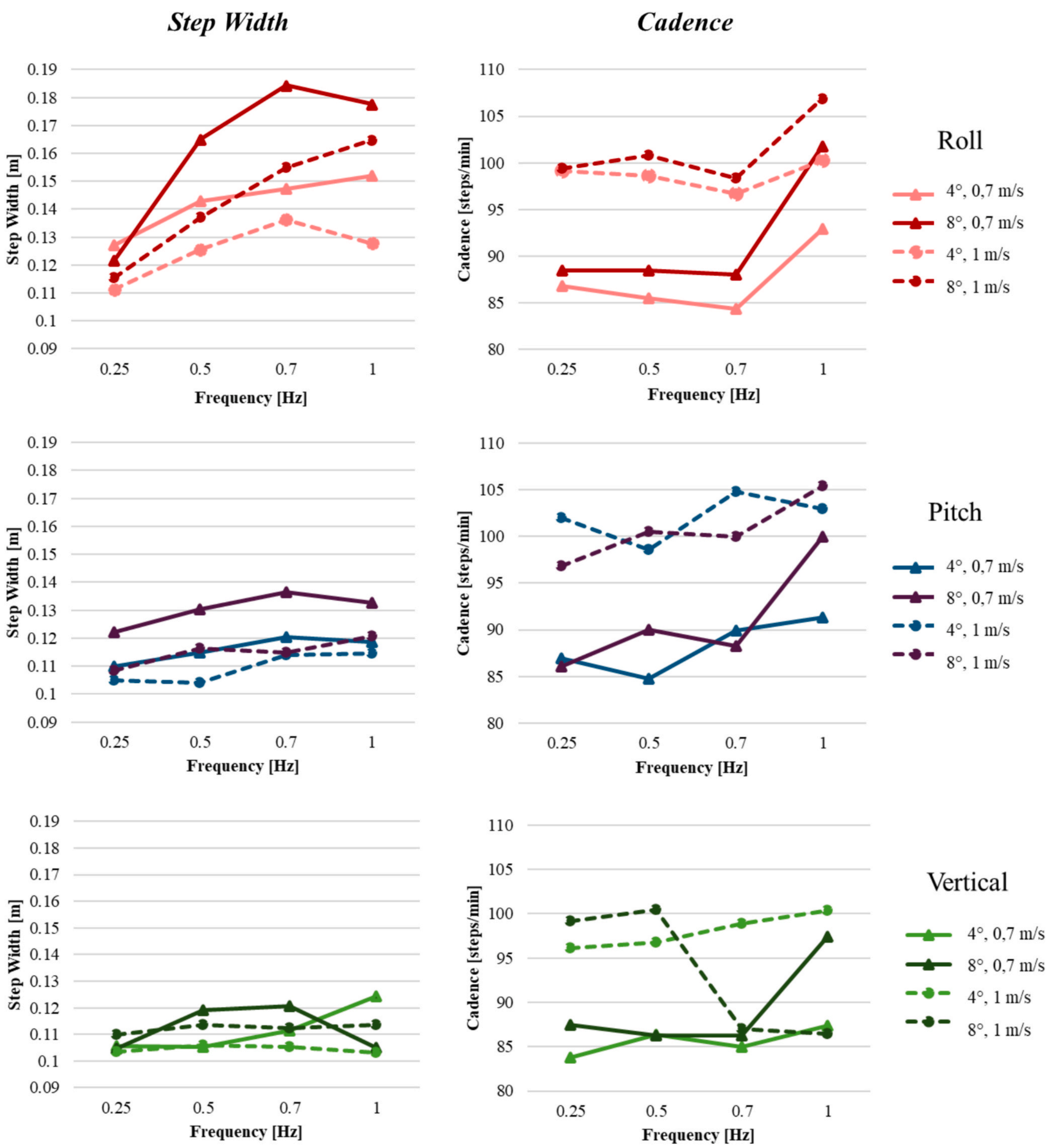

Fig. 6. Mean trend of the most altered metrics, step width (left) and cadence (right), as a function of frequency for roll (top), pitch (middle), and vertical (bottom) directions. The continuous lines with the –▲- represent the slower walking speed (0.7 m/s) and the dotted lines with –●- the faster walking speed (1 m/s). The light colors represent the lowest amplitude (4° or 4 cm) and the dark colors the highest amplitude (8° or 8 cm).

colleagues (2010) reported similar findings when comparing pseudo-randomized FTV in the mediolateral and anteroposterior directions. The step width is more altered in the case of roll with an increase of about 9 cm at 8° and 0.7–1 Hz. Results are in agreement with the findings of Marrone and colleagues (2024), who found an increase in the step width during exposure to a sinusoidal mediolateral FTV at 1.25 Hz and 1 m/s^2 with respect to normal walking. When considering mediolateral vibration at frequencies up to 10 Hz (Bertozzi et al., 2024; Marrone et al., 2025a), a significant increase in the base of support is observed at low frequencies, followed by a decreasing trend at higher values. Compensatory strategies to prevent loss of balance appear to be adopted in the same plane as the applied perturbation. For both mediolateral and roll FTV, an increase in the base of support in the frontal plane is observed, with significant alterations occurring around 0.7–2 Hz and in conjunction with larger treadmill displacements.

The combination of vibration frequency and amplitude significantly contributed to the observed gait alterations. The impact of FTV was most pronounced at frequencies of 0.7 and 1 Hz, as well as at the highest displacement values. These results align with other studies that have observed increased instability with high lateral displacement on a treadmill (Bertozzi et al., 2024; Marrone et al., 2025a). Our findings are also consistent with Marrone et al. (2025b), who found the most significant effect in the mediolateral direction at the highest frequency tested (1.5 Hz), which corresponded to the highest acceleration values by imposing constant displacement.

Our results showed that walking speed influences gait temporal metrics. This is valid regardless of vibration exposure (Schmitz et al., 2009); however, walking speed proved to be a highly influential factor in all *FTV trials,* both on their own and in combination with vibration factors. With roll and pitch FTV, cadence, which is higher at higher speed, rises with vibration frequency and amplitude, regardless of walking speed, resulting in a more unstable gait condition with lower swing phase, step, and stride time. In contrast, no clear trend in cadence was observed for vertical vibration in the range between 0.25 and 1 Hz at both walking speeds. Moorhead and colleagues (2021) measured cadence during vertical FTV at higher frequencies (2 to 10 Hz) with a constant displacement of 2.5 mm. They found a decreasing trend in the frequency, suggesting an effect of acceleration. However, the trend was not statistically significant, probably due to the low-magnitude displacement being insufficient to induce a meaningful response. Both our results and theirs demonstrate the need for future studies to better understand the effect of vibration factors in the vertical direction.

4.2. *Limitations and future studies*

While this study provides valuable insights, a number of limitations should be considered when interpreting the results. The application of a harmonic FTV is not representative of a real working environment. However, to update the normative weighting procedure, testing the response to FTV at specific frequencies is fundamental. Studying the effect of the vibration factors requires considering only the sinusoidal steady state vibration, i.e., when the amplitude has reached the imposed value. The amplitude was limited to a maximum of 8° or 8 cm, and a frequency of 1 Hz. The number of conditions investigated was also limited. Further tests are needed to study the combined effect of frequency and amplitude, possibly extending the frequency range. An analysis of the transient period of vibration could also be conducted in the future to investigate the motor strategies adopted during the recovery and adaptation phases of walking during the application of platform motion (Marrone et al., 2025b).

Another limitation derives from the experimental setup: walking on a treadmill is different from walking on the ground, and the gait speeds were imposed independently of natural walking; this choice may have forced subjects to walk uncomfortably, influencing the results. In all *FTV trials*, walking speed was significant in determining gait metrics alteration. In particular, in the vertical direction, it is evident that the walking speed can influence the effect of FTV, with opposite effects between speeds at 0.7 and 1 m/s. Further studies with self-selected speed could clarify the effect under realistic walking conditions.

Although a randomization of the trials order was applied to minimize the familiarization with the exposure and fatigue effects, in the future, a comparison between the normal walking performed at the beginning (i.e., baseline) and one at the end of the session could be useful to identify if there is a significant overall fatigue's influence caused by the long duration of the session. In addition, this study used a fully randomized trial order to minimize anticipation and learning effects; however, this design may have introduced additional intra-subject variability compared to a block randomization approach, which could offer a more balanced exposure to experimental conditions.

The present study limited the analysis to spatiotemporal gait metrics. Although interesting results to understand the compensation strategies adopted to increase stability during FTV were found, in the future, a more comprehensive biomechanical analysis has to be carried out, including also kinematic, dynamic, and muscular features, to study the motor control strategies for maintaining balance.

It is also known that lateral stabilization is age-dependent (Dean et al., 2007): older adults walked with approximately 50 % more step width variability and 20 % higher energetic cost. An inactive lifestyle could also affect the neuromuscular system, influencing postural stability. A combination of sedentary and aging could exacerbate issues in postural control (Pirôpo et al., 2021). The results of our work can be extended to the healthy and young population, but no conclusion can be made about older and untrained individuals, people with disabilities, or workers with an occupational history of FTV exposure. Further studies are necessary to identify how FTV exposure affects gait in a larger population, which includes subjects with different personal characteristics.

4.3. *Normative implications*

Vibration causes unnatural walking conditions, potentially leading to musculoskeletal disorders. The link between WBV exposure and low back pain (LBP) is widely documented in the literature, though research has primarily focused on a seated posture (Bovenzi, 1996; Bovenzi and Hulshof, 1999). For walking subjects, exposure to mediolateral and roll vibrations causes them to walk with wider steps. Based on this observation, we deduce that there is an increase in the mediolateral inertial force on the spine that is typically minimal during normal walking. In the case of transportation (i.e., maritime workers), individuals are not only exposed to vibration but also perform other tasks, such as lifting and pushing heavy objects, which significantly increase the risk of developing LBP (Belz et al., 2024). So, even if it is known that, in the presence of floor vibrations, a muscular overload and strain occur in the lumbar region to stabilize the spine (Jensen and Jepsen, 2014), it is not currently possible to establish a dose-muscular response relationship due to the lack of adequate epidemiological data. Therefore, future research must investigate the role of the other confounding factors on LBP to clarify their bias effect.

Walking on a moving floor also poses a high risk of falling and injuries. Although a perturbation-based approach is used to improve balance in clinical settings (Mansfield et al., 2015), exposure to uncontrolled vibration could lead to greater instability. This can be even more severe in subjects with LBP because trunk stiffening causes altered postural coordination, which results in a higher potential for musculoskeletal issues and instability when exposed to perturbation (Henry et al., 2006; Jubany et al., 2017).

Although the present study has the limitations mentioned above, and the results cannot be generalized to all populations, the preliminary findings, together with those of the studies cited in Fig. 1, demonstrate the lower safety conditions of walking workers during FTV. This evidences the necessity of limiting the vibration exposure with an appropriate weighting procedure. ISO 2631–1 evaluates the effect of vibration starting from acceleration measurements and frequency weighting curves, instead, in our case, a constant displacement was applied. However, a frequency-dependent gait alteration was found in accordance with Marrone and colleagues (2025b). This finding paves the way for a specific experimental design to test a complete matrix of vibration conditions (i.e., different combinations of frequency, amplitude, and direction) on a larger population in order to develop a specific weighting procedure.

Nonetheless, the results obtained contribute to understanding the role of each vibration factor in motor control. The observed changes in gait metrics are likely the result of neuromotor control strategies adopted in response to altered proprioceptive and vestibular inputs. This study contributes to understanding how these neuromechanical mechanisms elicit different responses depending on the type of vibrational stimulus and, consequently, lays the groundwork for developing a specific weighting approach for workers walking on vibrating floors. Our findings are reasonable given their analogy to the already existing weighting curves. Among the tested conditions, the observed alterations in step width and cadence indicate that FTV primarily impacts gait at frequencies of 0.7 and 1 Hz, where accelerations are inherently higher at constant displacement. The observed trends in gait metric alterations appear compatible with the W_d curve, which gives more relevance to frequencies between 0.5 and 2 Hz and is used for horizontal WBV vibration in standing posture, which is the most similar position to walking. However, our investigation was limited to frequencies up to 1 Hz, preventing us from concluding the compatibility of W_d at higher frequencies.

The suitability of W_k for vertical FTV seems instead more limited, since gait alterations did not exhibit consistent trends. Moorhead and colleagues (2021) observed small effects in all measured gait metrics during vertical FTV, although statistical significance was not broadly achieved for changes in stride frequency or length. This suggests that the impact of vertical vibration on gait can still induce observable alterations, but the adoption of the frequency weighting W_k for the quantification of effects seems questionable and requires further in-depth studies.

Finally, since the effect of vibration on gait metrics is relevant for reducing the possibility of injuries or accidents, it seems reasonable to suggest an evaluation of the balance performance of seafarers, aircraft crews, and other workers exposed to vibration. From this point of view, the static balance test that we performed at the inclusion visit was not predictive of balance performance during perturbed walking. Instead, a dynamic balance test could be more suitable (Ringhof and Stein, 2018).

5. Conclusions

Exposure to sinusoidal FTV alters gait strategies. Compared to normal walking, the most affected gait metrics are the step width and the cadence, which increase to minimize instability. The rotational directions, mainly roll, are more detrimental than the vertical direction. Alterations in gait are observed as a result of combined changes in frequency and amplitude. The worst conditions, with the greatest adaptation of the gait pattern, occur with the highest amplitude and frequencies of those tested. Adopting compensatory strategies can expose workers to an increased risk of falls and injury. Starting with the identification of the more challenging vibrational condition in terms of balance control and gait adaptation, the current standard could be updated to include the effect of FTV on walking workers.

CRediT authorship contribution statement

Flavia Marrone: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Filippo Motta:** Writing – original draft, Software, Methodology, Formal analysis, Data curation. **Stefano Marelli:** Software, Methodology, Data curation. **Manuela Galli:** Writing – review & editing, Supervision. **Marco Tarabini:** Writing – review & editing, Supervision, Investigation, Conceptualization. **Pierre Lemerle:** Writing – review & editing, Supervision, Resources, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jbiomech.2025.113100.

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