Spatiotemporal gait parameter changes due to exposure to vertical whole-body vibration

Alex P. Moorhead [a,e,*], Delphine Chadefaux [a,b,c,d], Matteo Zago [e], Stefano Marelli [a], Enrico Marchetti [f], Marco Tarabini [a,g]

[a] Dipartimento di Meccanica, Politecnico di Milano, via Privata Giuseppe la Masa 1, 20156, Milano, Italy
[b] Université Sorbonne Paris Nord, Institut de Biomécanique Humaine Georges Charpak, IBHGC, UR 4494, F-93000, Bobigny, France
[c] Arts et Métiers Institute of Technology, F-75013, Paris, France
[d] Département STAPS, Université Sorbonne Paris Nord, Bobigny, France
[e] Dipartimento di Elettronica, Informazione e Bioingegneria, Politecnico di Milano, Italy
[f] INAIL, Via di fontana candida, 00040, Monte Porzio Catone (Roma), Italy
[g] Laurentian University, Bharty School of Engineering, Sudbury, ON, P3E 2C6, Canada

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A B S T R A C T

Background: Vertical whole-body vibration (vWBV) during work, recreation, and transportation can have detrimental effects on physical and mental health. Studies have shown that lateral vibration at low frequencies (<3 Hz) can result in changes to spatiotemporal gait parameters. There are few studies which explore spatio-temporal gait changes due to vertical vibration at higher frequencies (> 3 Hz). This study seeks to assess the effect of vWBV on spatiotemporal gait parameters at a greater range of frequencies (≤ 30 Hz).
Methods: Stride Frequency (SF), Stride Length (SL), and Center of Pressure velocity (CoPv) was measured in seven male subjects (23 ± 4 years, 1.79 ± 0.05 m, 73.9 ± 9.7 kg) during *In-Place Walking* and nine male subjects (29 ± 7 years, 1.78 ± 0.07 m, 77.8 ± 9.9 kg; mean ± SD) during *Treadmill Walking* while exposed to vWBV. Load cells measured ground reaction forces during *In-Place Walking* and sensorized insoles acquired under-foot pressure during *Treadmill Walking.* Statistical tests included a one-way repeated-measures ANOVA, post-hoc two way paired T-tests, statistical power (1-β), correlation (R^2), and effect size (Cohen's *d*).
Results: While statistical significance was not found for changes in SF, SL, or Mean CoPv, small to large effects were found in all measured spatiotemporal parameters of both setups. During *Treadmill Walking*, vWBV was correlated with a decrease in SF ($R^2 = 0.925$), an increase in SL ($R^2 = 0.908$), and an increase in Mean CoPv ($R^2 = 0.921$) and Max CoPv ($R^2 = 0.952$) with a significant increase ($p < 0.0083$) in Max CoPv at frequencies of 8 Hz and higher.
Significance: Study results demonstrated that vWBV influences spatiotemporal gait parameters at frequencies greater than previously studied.

1. Introduction

Spatiotemporal parameters of human gait such as stride length (SL) and stride frequency (SF) have been studied at different velocities, slopes, and loads [1,2] as well as during artificial gaits such as race walking [3], or even skipping with modified gravity [4]. While there is an abundance of literature pertaining to how a human's gait will adapt to natural external influences, the literature investigating the interaction between human gait and mechanical factors like whole-body vibration (WBV) is still relatively sparse. Until recently, the majority of research concerning the interaction between humans and WBV has been focused on the biodynamic responses of apparent mass (AM) and transmissibility (T) in quasi-static subjects (seated or standing). It was demonstrated that the response of AM and T to vertical WBV (vWBV) is non-linear in both seated [5] and standing [6–8] subjects and is dependent upon magnitude, and direction of the vibration [9] as well as posture [10] of the subject. As the biodynamic responses of exposure to vWBV on static subjects were becoming clearer, studies also began emerging regarding the effects of vWBV in dynamic conditions. Chadefaux et al. [11] recently found that the T of a walking subject decreases with greater

* Corresponding author.
E-mail address: Alexpatten.moorhead@polimi.it (A.P. Moorhead).

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distance from the driving point and that the AM response was between that of a standing subject in the neutral posture and a standing subject with bent knees.

Recent studies have begun investigating gait adaptation strategies to WBV exposure. However, most studies have focused on horizontal WBV (hWBV) rather than vWBV. Nonetheless, these studies serve as a basis for understanding the dynamic human response to WBV. Outcomes have shown that at a constant speed, hWBV is destabilizing which causes subjects to increase their Step Width (SW) [12] and SF, resulting in shorter, faster, and wider strides to maintain their balance [13–16]. Sari and Griffin [17] observed that subjects who walked while exposed to hWBV not only had larger displacement of Center of Pressure (CoP) but also a higher lateral CoP velocity (CoPv) as vibration frequencies increased. Nessler et al. [18] was the first study which imposed vWBV to understand if it could be used as a form of rehabilitation by synchronizing SF with the vWBV phase. This study found both increases and decreases in SL and SF depending on the vWBV frequency [18]. While current literature has begun to offer an understanding of the effects of WBV, two common shortcomings are the primary focus on hWBV, and that the imposed WBV frequencies rarely exceed 3 Hz – often they are less than 1 Hz. Meanwhile, millions of people are exposed daily to vWBV while commuting, during occupational activity [19], and even in recreational activity [20] which exceeds 3 Hz. To further the investigation of gait adaptions during vWBV, this study expanded on the experimental design of Chadefaux et al. [11].

Exposure to vWBV has been shown to have a significant effect on the biodynamic response of quasi-static subjects [5–10] which was also recently confirmed in dynamic conditions [11]. Additionally, significant spatiotemporal changes have been found in subjects exposed to low frequency ($>$3 Hz) hWBV [12–18]. Consequently, we expected that vWBV would also have a significant effect on spatiotemporal gait parameters at a higher range of frequencies ($\leq$30 Hz). This study aimed to evaluate the effect of vWBV on SL, SF, and CoPv across a larger range of frequencies than has been published thus far – with frequencies as great at 30 Hz for both *In-Place Walking* and *Treadmill Walking*.

2. Materials and methods

This experimental design is similar to that adopted in previous experiments [11] for measuring AM and T of walking subjects exposed to vWBV.

2.1. Participants

Seven male participants (23 ± 4 years old, 1.79 ± 0.05 m tall, 73.9 ± 9.7 kg; mean ± SD), were tested during *In-Place Walking*, and nine male participants (29 ± 7 years old, 1.78 ± 0.07 m tall, 77.8 ± 9.9 kg; mean ± SD) were tested during *Treadmill Walking*. Exclusion criteria for both experiments included diagnosis by a physician to have diabetes, vibration-induced pathologies, a lower body musculoskeletal injury or concussion within the last six months, or sensitivity to motion sickness. All testing protocols were in accordance with the Declaration of Helsinki and the University's ethics guidelines and standards. An informed consent was provided to all subjects prior to participation and all sensitive data were stored confidentially.

2.2. In-place walking

2.2.1. Experimental setup

In-Place Walking experiments were performed atop a rigid platform mounted to an electrodynamic shaker LDS V930 (LDS, England) used to create vWBV. Four PCB 212B (PCB Piezotronics, NY, USA) load cells supported the platform to acquire the ground reaction forces (GRF) of each step. A previous study regarding the design and testing of the shaker [21] proved that the platform was rigid and that its first resonant frequency (33 Hz in the horizontal axis) was greater than any of the vertical frequencies used during these tests (30 Hz). The system bandwidth limited the maximum vibration frequency to 30 Hz. Six test vibration frequencies (5, 10, 15, 20, 25, 30 Hz) were imposed in random order and walking was also performed without vibration as the baseline condition. Vibration amplitude was chosen based on the higher range of vibrations to which workers are exposed as outlined in the EU directive 2002/44/EC (1.15 m/s^2, 8 h of exposure). In order to stay within the safety guidelines of vibration exposure while achieving higher vibration frequencies, a constant root mean squared (r.m.s.) acceleration of 2 m/s^2 was maintained. When accounting for the total exposure time (31.5 min) and amplitude (2 m/s^2), the adopted vibration dose was much smaller than the current limits of EU legislation. This is a similar procedure as to what has been adopted by many other studies regarding the human response to vWBV [5,6,11,22,23].

2.2.2. Walking tests

Subjects performed three repetitions of seven walking tests lasting 90 s with a 10 s familiarization period to become comfortable while walking with WBV. In total, each test lasted 100 s. Subjects rested one minute between each 100-s test and five minutes after each full repetition. All three repetitions were completed in the same day. To avoid any discrepancies due to shoe design, subjects were asked to walk without shoes.

2.2.3. Stride segmentation

Prior to stride segmentation, force signals provided by the load cells were passed through a lowpass filter with a zero phase shift (30 Hz; 4th order Butterworth) and the total force was computed. Finally, the inertial force of the plate (mass of the plate times the acceleration input) was subtracted from the measured GRF as typically done in all studies in this sector [10,11,24,25]. As done by Chadefaux et al. [11], stride segmentation was performed by detecting heel strikes as the instant when the vertical component of the load cell force data exceeded a threshold of 50 N. Heel strike detection was initiated 10 s after the beginning of the trial and stopped 5 s before the end of the trial. In each frequency, there were 35 strides analyzed for each subject. Seven subjects, times 35 strides resulted in 245 strides per frequency, for seven frequencies (including the baseline), for a total of 1715 strides analyzed.

2.3. Treadmill walking

2.3.1. Experimental setup

For the *Treadmill Walking* experiments, a treadmill was mounted to a six-axis vibration platform designed by MTS (Monticello Conte Otto, Italy) for the "National Institute for Safety Against Injuries at Work" (INAIL) Research Center of Monte Porzio Catone (Rome, Italy). Subjects were provided identical low-profile shoes with sensorized insoles (Pedar®, Novel Gmbh, Germany) consisting of 99 capacitive sensors in each insole which sampled at 100 Hz to measure the contact pressure beneath the feet. The treadmill's natural frequency limited the vibration exposure to 12 Hz. Six tests vibration frequencies were imposed (2, 4, 6, 8, 10, 12 Hz) in random order with a vibration amplitude of 2.5 mm. Walking was also performed without vibration as the baseline condition. A photo and diagram of both setups can be seen in Fig. 1.

2.3.2. Walking tests

Subjects performed seven 90 s walking tests with a 10 s familiarization period as done with the in-place walking for a total test time of 100 s. As the energetically optimal rate of walking without wind resistance has been found to be between 1 and 1.4 m/s [26], an approximate midway speed of 1.25 m/s was chosen. Since it has been demonstrated that humans will naturally move at their most efficient stride frequency [27], subjects were permitted to walk at a freely chosen stride frequency. After putting on the shoes with the insoles inserted, subjects were helped to mount the treadmill. Treadmill speed was slowly increased until reaching 1.25 m/s. Upon reaching a 1.25 m/s, the 100-s

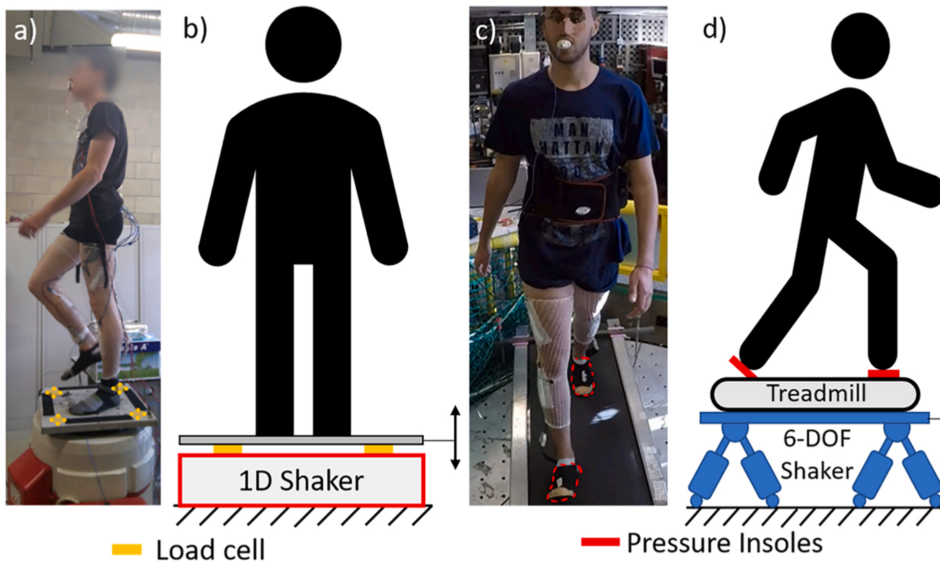

Fig. 1. Photos of the *In-Place Walking* (A) and *Treadmill Walking* (C) experiments as well as the schematic representations of the *In-Place Walking* (B) and *Treadmill Walking* (D) setups. In the *In-Place Walking*, a vertical harmonic shaker with load cells between the platform and the shaker can be seen whereas the *Treadmill Walking* uses a 6 DOF vibration platform with sensorized insoles within the shoes.

test began. All trials were performed in a single day, and after each test, the subjects were provided a five-minute rest.

2.4. Stride segmentation

To calculate the spatiotemporal parameters, pressure signals from the sensorized insoles were first processed according to Saggin et al. [28] to correct for artifacts and calibration issues typical to the pressure sensors used in the insoles. Stride segmentation was then performed to calculate the time between consecutive heel strikes of the same foot. As done by Chadefaux et al. [11], heel strikes were identified as the time when the pressure signal from the insoles exceeded 400 kPa with an increasing slope. In each frequency, there were 48 strides analyzed for each subject. Nine subjects, times 48 strides resulted in 432 strides per frequency, for seven frequencies (including the baseline), for a total of 3024 strides analyzed.

2.5. Data analysis

In both experiments, once stride segmentation was performed, the inverse of stride duration provided SF.

2.5.1. In-place walking

Mean and standard deviation of SF were calculated for all subjects at each vibration frequency. To understand the relative change across different vibration frequencies, the percent difference of SF was calculated compared to no vibration.

2.5.2. Treadmill walking

Since the gait speed was constant during *Treadmill Walking*, SL was obtained as the product of stride duration and speed. Mean and standard deviation of SF and SL were computed across all subjects for each vibration frequency. The CoP was estimated at each instant by calculating the barycentre of the 99 capacitive cell responses of the insoles. Knowing the instantaneous cell CoP position, CoPv was estimated with a time derivative of CoP displacement in cells/s in both the anterior-posterior direction and the mediolateral direction. To convert the CoPv from cells/s into m/s, it was expressed relative to the length and width of the subject's foot based on reference values according to their height [29]. The Mean CoPv, Maximum CoPv, and Mean Trajectory were calculated during each stride of the 48-stride samples, for each subject, at each frequency. The percent difference of SF, SL, Mean CoPv, and Max CoPv was calculated for each frequency compared to no vibration.

2.6. Statistical analysis

Due to rare occurrences of sensor malfunction, stride data occasionally resulted in outliers. Outliers were defined as any stride whose value was more than two standard deviations greater or lesser than the sample mean for the chosen parameter (SF, SL, CoPv). Prior to performing the statistical analysis, all outliers were eliminated. After removing outlier strides from the entire population, the subjects' mean CoPv, SF, and SL values were also compared for outlier removal for that parameter. Outlier removal resulted in the elimination of 122 strides out of 4739 (approximately 3%) and one subject from all CoPv variables. After all outliers were removed from the population, a Ryan-Joiner test for normality was performed for all groups and responses in Minitab 19 (State College, Pennsylvania, USA) revealing normal data (p-value $>$ 0.10) for all tests. Subsequently, a one-way repeated-measures ANOVA was performed for SF, SL, CoPv Mean, and CoPv Max with a set alpha level of 0.05. Where appropriate, post-hoc two-tailed, paired t-tests vs. the 0-Hz condition were then run on all parameters for statistical significance. In doing so, an adjusted alpha value was applied following the Bonferroni correction for multiple tests ($\frac{\alpha}{n} = \frac{0.05}{6} = 0.0083$) with n set to 6 due to the six conditions compared to the baseline condition. Statistical Power (1-β) was then computed for all variables using G*Power © (version 3.1.9.6, Franz Faul, Universität Kiel, Germany) [30]. To provide an additional statistical test which was not dependent upon sample size, the Effect Size was then calculated using Cohen's *d* [31]. To calculate the proportion of change in the dependent variable which could be attributed to vibration frequency change, a least-squares fit linear regression was performed for the SF of both experiments as well as the SL of *Treadmill Walking*. For the CoPv variables, a 2nd degree polynomial regression was performed. The R-squared values were calculated in all cases.

3. Results

3.1. In-place walking

While the p. values did not confirm statistical significance, Effect Size showed a small effect at 15 Hz, a medium effect at 10, 20, and 25 Hz, and a large effect at both 5 and 30 Hz. These results are summarized in Table 1. There was a minimum percentage increase of 9.9 % at 10, 15 and 25 Hz with a maximum of 17.2 % at 5 Hz. As seen in Fig. 2, while the correlation of the linear regression between vWBV and SF was weak ($R^2 = 0.141$), the increase in mean values of SF at all frequencies of vWBV reflect the effects found.

3.2. *Treadmill walking*

Similar to the *In-Place Walking* condition, the p. values did not find statistical significance. However, Effect Size showed a small effect between 2–8 Hz, a medium effect at 10 Hz, and a large effect at 12 Hz; all of which can be found in Table 1. The regression curves for *Treadmill Walking* shown in Fig. 2 also revealed a strong inverse relationship between vWBV frequency and *Treadmill Walking* SF ($R^2 = 0.925$) and a strong direct relationship between the vWBV frequency and SL ($R^2 = 0.908$).

In both measures of the CoPv, velocity was shown to initially decrease, followed by an increase. Although no statistically significant changes were detected in the Mean CoPv due to vWBV, small effects were found at 4, 8, and 10 Hz with a medium effect at 2 Hz and large effects at 6 and 12 Hz. The slowest Mean CoPv (0.34 m/s; -5.6 %) was measured at 2 and 6 Hz with the fastest (0.38 m/s; +5.6 %) measured at 12 Hz. For Max CoPv, statistically significant increases were found at vWBV frequencies of 8 Hz and greater. The slowest Max CoPv was found at 2 Hz (0.87 m/s; -2.2 %) but no effect was found. At 6 Hz, a small effect was found, and all other frequencies showed a large effect, with the largest increase at 12 Hz (1.42 m/s; +59.6 %). A summary of all the percent differences and statistical results are presented in Table 1.

Table 1
Statistical Results.

	In-Place Walking - Stride Frequency (strides/s)					
Vib. Freq. (Hz)	5	10	15	20	25	30
% diff.	+17.3	+9.9	+9.9	+12.3	+9.9	+13.6
p. value	0.063	0.328	0.239	0.165	0.334	0.164
Statistical Power	0.90	0.78	0.49	0.68	0.76	0.80
Effect Size	$1.4^{\delta\delta\delta}$	$0.69^{\delta\delta}$	0.45^{δ}	$0.77^{\delta\delta}$	$0.66^{\delta\delta}$	$0.93^{\delta\delta\delta}$
	Treadmill Walking - Stride Frequency (strides/s)					
Vib. Freq. (Hz)	2	4	6	8	10	12
% diff.	−1.1	−1.1	−1.1	−1.1	−2.2	−3.2
p. value	0.173	0.101	0.051	0.032	0.018	0.009
Statistical Power	0.33	0.28	0.25	0.17	0.32	0.30
Effect Size	0.32^{δ}	0.38^{δ}	0.48^{δ}	0.46^{δ}	$0.76^{\delta\delta}$	$0.88^{\delta\delta\delta}$
	Treadmill Walking – Stride Length (m)					
Vib. Freq. (Hz)	2	4	6	8	10	12
% diff.	+1.2	+0.97	+1.6	+1.7	+2.4	+3.1
p. value	0.173	0.107	0.059	0.036	0.014	0.010
Statistical Power	0.37	0.27	0.26	0.20	0.27	0.78
Effect Size	0.36^{δ}	0.36^{δ}	0.47^{δ}	0.48^{δ}	$0.75^{\delta\delta}$	$0.89^{\delta\delta\delta}$
	Treadmill Walking – Mean CoPv (m/s)					
Vib. Freq. (Hz)	2	4	6	8	10	12
% diff.	−5.6	−2.8	−5.6	−2.8	0	+5.6
p. value	0.128	0.218	0.049	0.421	0.349	0.059
Statistical Power	0.65	0.34	0.55	0.59	0.58	1.00
Effect Size	$0.69^{\delta\delta}$	0.26^{δ}	$0.80^{\delta\delta\delta}$	0.32^{δ}	0.37^{δ}	$1.83^{\delta\delta\delta}$
	Treadmill Walking – Max CoPv (m/s)					
Vib. Freq. (Hz)	2	4	6	8	10	12
% diff.	−2.2	+15.7	+7.9	+24.7	+40.5	+59.6
p. value	0.765	0.037	0.264	0.004*	<0.001*	<0.001*
Statistical Power	0.78	0.73	0.62	0.78	1.00	1.00
Effect Size	0.13	$1.04^{\delta\delta\delta}$	0.49^{δ}	$1.66^{\delta\delta\delta}$	$3.06^{\delta\delta\delta}$	$4.02^{\delta\delta\delta}$

A summary of the percent differences and statistical results of the paired t-test, statistical power, and effect size for all variables measured in respect to no vibration (0 Hz).
* statistical significance after the Bonferroni correction (p. value <0.0083). Effect Size: $^{\delta}$Small (>0.2), $^{\delta\delta}$Medium (>0.5), $^{\delta\delta\delta}$Large (>0.8).

The 2nd degree polynomial regressions found strong correlations between both vWBV and the Mean CoPv ($R^2 = 0.921$) as well as Max CoPv ($R^2 = 0.952$) which can be seen in Fig. 3.

In Fig. 4, the mean trajectory and velocity across all subjects and frequencies of vWBV is shown with a relatively smooth curve and a slight increase in velocity across the mid-foot in the no-vibration (0 Hz) condition. As the vWBV frequency increases, the trace of the CoP becomes more jagged from the heel strike and the path of the trajectory becomes longer. It can also be seen that the Mean CoPv has multiple positions where the velocity is elevated.

4. Discussion

While the statistical significance of changes due to vWBV was not confirmed for SF in either setup or SL and Mean CoPv in *Treadmill Walking,* vWBV was shown to have at least a small effect on all of the measured spatiotemporal variables with a large effect at the highest frequencies of vWBV. During *Treadmill Walking*, exposure to vWBV was correlated with a decrease in SF, an increase in SL, and an increase in both Mean and Max CoPv. As explained in previous studies, subjects exposed to hWBV will also adapt their SF and SL [12–16,18]. While both scenarios demonstrate increased gait instability during WBV exposure, there is one important difference to note when comparing the responses to hWBV and vWBV. In all other studies cited thus far [12–16], hWBV leads to shorter and quicker steps. Instead, this study shows that vWBV during *Treadmill Walking* leads to longer, slower steps. This is partially in agreement with Nessler et al. who found variable SL alterations depending on vWBV frequency [18]. Previous literature suggested that these stride changes were a potential stepping strategy in response to postural instability during hWBV [14,15]. A similar conclusion can be drawn from this study of vWBV when also considering the CoPv results.

Max CoPv was the only variable found to show a statistically significant increase. Particularly of note is the percent increase in Max CoPv of nearly 60 % at 12 Hz. The changes seen in the Mean and Max CoPv of Fig. 3, as well as the visibly perturbed trajectory of the CoP traces in Fig. 4 suggest that a person is less stable while walking on a vertically vibrating surface. This agrees with the CoPv results previously found in Sari and Griffin's hWBV experiments [17]. These results in addition to the effects and correlations seen in the other tested parameters indicate that vWBV induces spatiotemporal gait adaptions to account for instability. These adaptations also serve to reinforce the significant findings regarding the biodynamic responses to vWBV demonstrated by Chadefaux et al. [11]. These two results together may offer an explanation to the discomfort and musculoskeletal injuries already reported in the literature [32].

To improve the outcome of future studies, some limitations of this study should be addressed. Because *In-Place Walking* is an artificial gait which would not be typically practiced in normal life, it was common that even the 'steady state' achieved after familiarization resulted in a SF with high variation, which we did not expect. While small, medium, and even large effects indicate a relative increase in SF with vWBV exposure, the elevated SD values renders the differences statistically insignificant. Future experiments should only investigate treadmill gait. While the sample size chosen is in accordance with other similar WBV studies [8,10,11,25], the time of data acquisition could also be increased to have a larger number of strides and potentially increase the likelihood of achieving statistical significance. Unfortunately, SW was not measured in this study due to a lack of compatibility between the constraints of the lab environment and available hardware for data acquisition. This may have also helped confirm the instability of gait and would have offered another comparison between vWBV and hWBV studies. Moreover, as shown in previous studies [1,4,27] any change to the naturally chosen SF results in an increased cost of transport. This should also be investigated using spirometry to understand the metabolic impact of WBV.

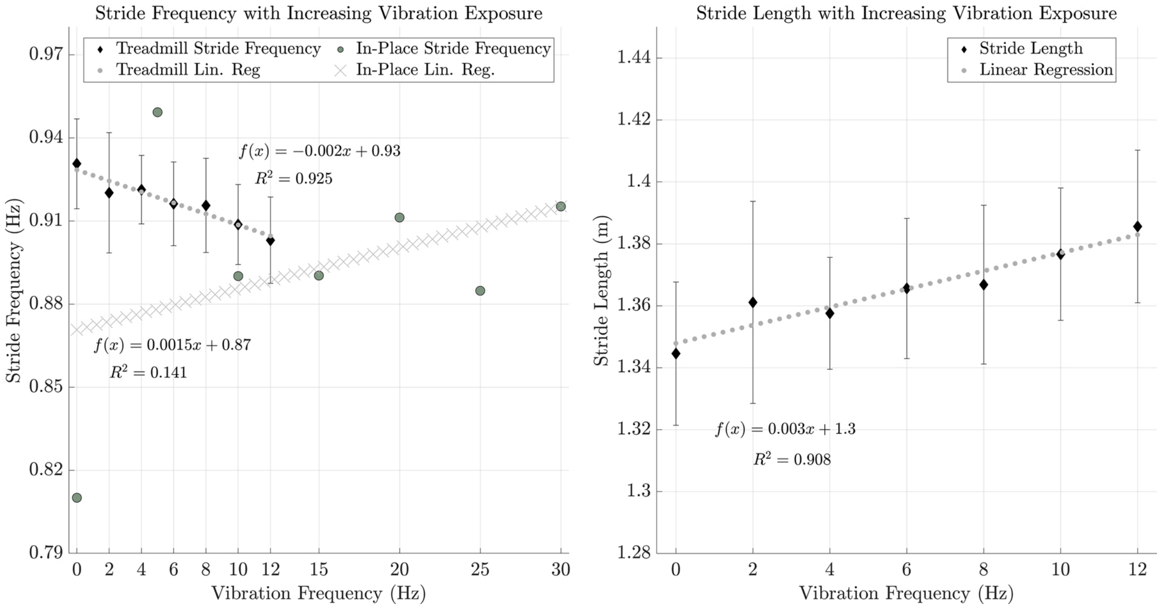

Fig. 2. The left plot presents the mean stride frequency calculated during both *In-Place Walking* (dark grey circles) and *Treadmill Walking* (black diamonds). The right plot depicts the stride length changes during *Treadmill Walking*. A linear regression has been fit to the *In-Place Walking* (light grey X's) stride frequency and the *Treadmill Walking* (light grey circles) on both plots. All the respective R^2 values are presented. Positive and negative error bars were displayed with the *Treadmill Walking* plots which represent one Standard Deviation.

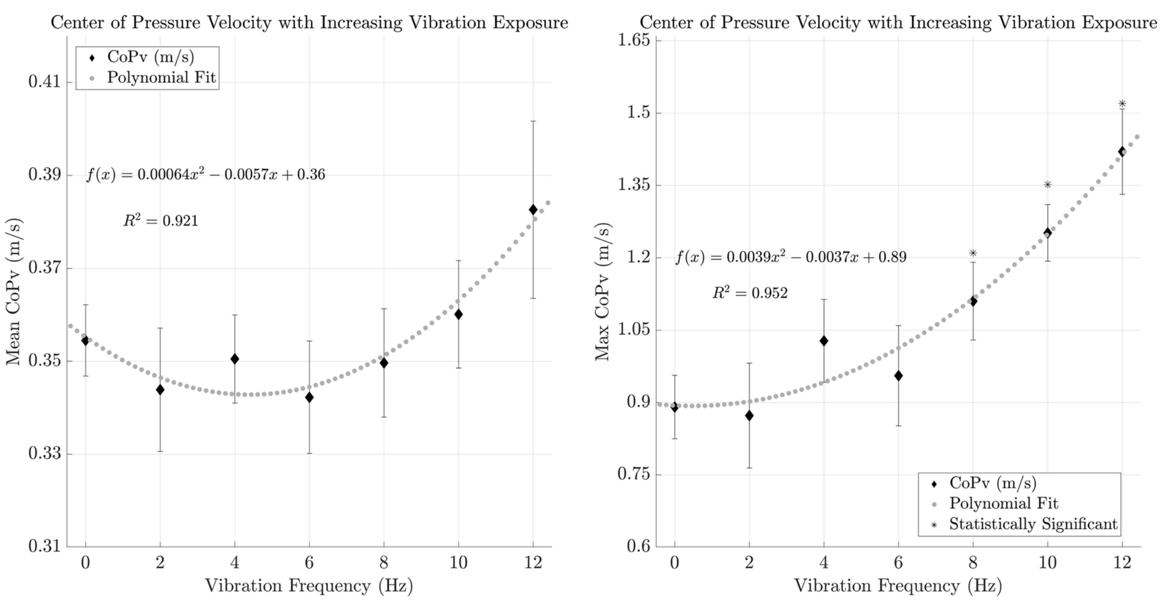

Fig. 3. Plots depict the calculated mean center of pressure velocity (left) and maximum center of pressure velocity (right) during *Treadmill Walking* as vibration exposure increases. A polynomial fit has been applied, and the respective R^2 values are shown. * denotes vibration frequencies at which the results were statistically significant ($p < 0.0083$) from those measured without vibration (0 Hz).

5. Conclusion

Exposure to increasing frequencies of vWBV has been revealed to have an effect on all the measured spatiotemporal parameters of both *In-Place* and *Treadmill Walking*. During *Treadmill Walking*, SF decreased resulting in an increased SL with a significant increase was also found in the Max CoPv.

The SF and SL response to vWBV found in this study is opposite to the response shown in studies with hWBV. To further understand the effects of WBV on walking stability and the metabolic cost, future treadmill studies will be developed to include SW and spirometry using both vWBV and hWBV.

Data availability

The authors are willing to provide any and all data corresponding to the study upon request.

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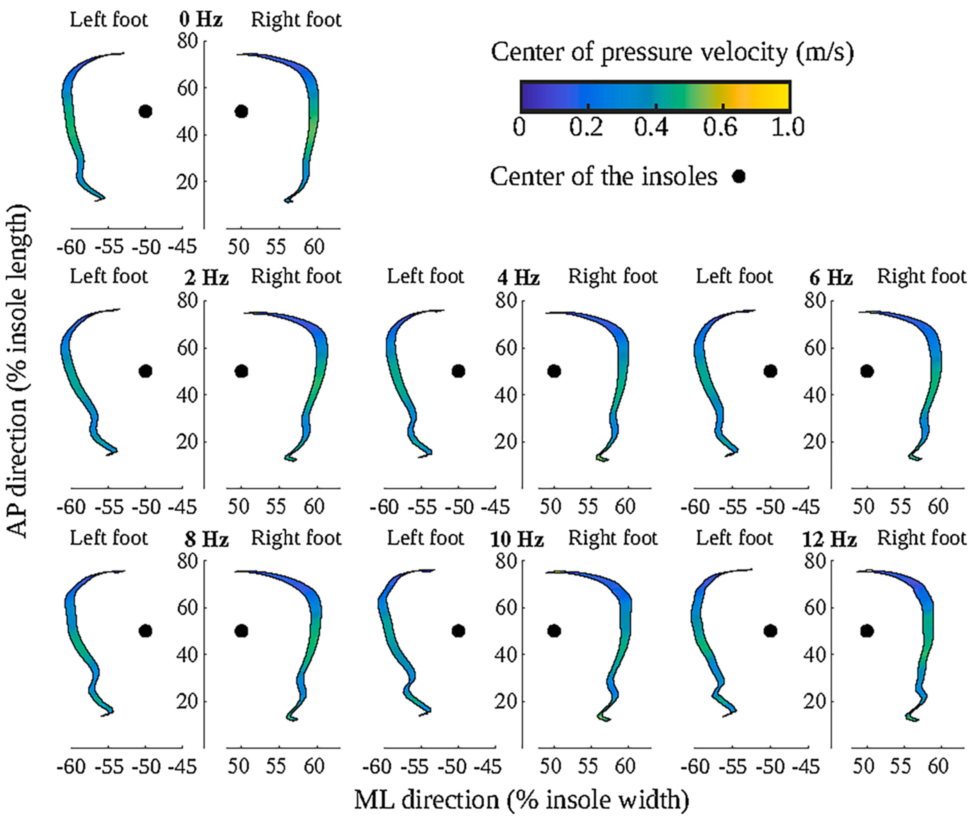

Fig. 4. Speed-representative color traces are shown of the Mean CoPv during *Treadmill Walking* at all vWBV frequencies which depict the mean velocity and mean path taken during walking.

Declaration of Competing Interest

None.

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