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Title Page

Full Title:

Spatiotemporal Gait Parameter Changes Due to Exposure to Vertical Whole-Body Vibration

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Highlights

- Vertical and horizontal whole-body vibration create opposite gait responses.
- Vertical whole-body vibration frequency and stride frequency are inversely related.
- Maximum center of pressure velocity is significantly faster at and above 8 Hz.
- Gait instability occurs while walking exposed to vertical whole-body vibration.

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Abstract

Background

Many people are exposed to vertical whole-body vibration (vWBV) on a daily basis during work, recreation, and transportation with 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 spatiotemporal gait changes due to vertical vibration exposure at higher frequencies (> 3Hz). Thus, this study seeks to assess the effect of vWBV on spatiotemporal gait parameters at a greater range of frequencies.

Methods

Nine male subjects (29 ± 7 years, 1.78 ± 0.07 m, 77.8 ± 9.9 kg; mean ± SD) during *Treadmill Walking* and seven male subjects (23 ± 4 years, 1.79 ± 0.05 m, 73.9 ± 9.7 kg) during *In-Place Walking* were tested in this observational case series study while exposed to six randomly ordered vertical vibration frequencies. Load cells measured ground reaction forces during *In-Place Walking* and sensorized insoles acquired under-foot pressure during *Treadmill Walking*. Using a two-tailed, paired t-test, effects were assessed for Stride Frequency (SF) in both scenarios and for Center of Pressure velocity (CoPv) and Stride Length (SL) during *Treadmill Walking*.

Results

No significant differences were found between vibration exposure and SF during *In-Place Walking*. Mean SF during *In-Place Walking* increased between 9.2 - 17.2% when exposed to vWBV without a marked trend. During *Treadmill Walking*, vWBV exposure was correlated with a decrease in SF, increase in SL, and increase in both Mean and Max CoPv with a significant increase (p-value <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. It is expected that these effects may also result in a higher physiological and cognitive fatigue while moving in a vibrating environment.

Keywords

Perturbed Gait, Whole-body vibration, Spatiotemporal, Health and Safety

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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 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 on dynamic subjects. Chadefaux et al. [11] recently found that the TM of a walking subjects decreases with greater 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 velocity, 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 positive and negative changes in SL and SF depending on the vWBV frequency

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[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 static subjects [5–10] which was also recently confirmed in dynamic subjects [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 (≤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 *Treadmill Walking* and *In-Place 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*, 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.

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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. A photo and diagram of the experiment can be seen in Figure 1.

[Figure 1 here]

Four PCB 212B (PCB Piezotronics, NY, USA) load cells supported the platform to acquire the ground reaction forces of each step. 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 with a vibration amplitude of 2m/s^2. 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 hours of exposure). When accounting for the total exposure time (31.5 minutes) 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 [5,6,11,21,22].

2.2.2 Walking Tests

Subjects performed three repetitions of seven walking tests lasting 90 s each. Subjects rested one minute between each 90-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

To perform stride segmentation, heel strikes were identified using the load cell data to detect when the vertical component of the force exceeded the 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. Trimming the initial and final portions of the data set resulted in 35 strides as the largest sample size obtained per subject

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across all frequencies resulting in 245 strides per frequency (including the baseline) for a total of 1,715 strides.

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.

[Figure 2 here]

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.

2.3.2 Walking Tests

Subjects performed seven 100 s walking tests at 1.25 m/s during the course of a single day. After each test, the subjects were provided a five-minute rest. Since it has been demonstrated that humans will naturally move at their most efficient stride frequency [23], 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 velocity was slowly increased until reaching 1.25 m/s. Upon reaching a 1.25 m/s, the 100-s test began.

2.4 Stride Segmentation

To calculate the spatiotemporal parameters, pressure signals from the sensorized insoles were first processed according to Saggin et al. [24] 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. Heel strikes were identified as the time when the pressure signal from the insoles exceeded 400 kPa with an increasing slope. Using the same data trimming criteria as the *In-Place Walking* experiments, 48 valid strides was the largest sample size obtained per subject across all frequencies resulting in 432 strides per frequency (including the baseline) for a total of 3,024 strides.

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. 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 and the R-squared value was calculated. Both are shown in Figure 3.

2.5.2 Treadmill Walking

Since the gait velocity was constant during *Treadmill Walking,* SL was obtained as the product of stride duration and velocity. 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. 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 [25]. The Mean CoPv and Maximum CoPv during each stride of the 48-stride samples were calculated 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

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Due to rare occurrences of sensor malfunction, stride data occasionally resulted in outliers. 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 3,024 (approximately 4%) 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.

3. Results

In-Place Walking

Results in Table 1 show no significant differences in SF during *In-Place Walking*. However, all means were greater when exposed to vWBV than those without vibration. There was a minimum percentage increase of 9.2% at 25 Hz and a maximum of 17.2% at 5 Hz. Observing Figure 3, while there is not a defined trend, it can be seen that any exposure to vWBV results in an increase in SF compared to the baseline condition.

Treadmill Walking

There were no significant effects in SF or SL due to vWBV. While the p-values scores of SF approached 0.05 at 6 Hz (p=0.051) and became even lower at 12 Hz (p=0.009), after applying the Bonferroni correction, statistical significance ($\alpha < 0.0083$) was not achieved. These results were also reflected in SL with a minimum p-value score of 0.010 at 12 Hz.

[Table 1]

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Figure 3 shows an inverse relationship between *Treadmill Walking* SF and vWBV frequency with an R^2=0.925 as well as a direct relationship between the SL and vWBV frequency with an R^2=0.908. A least-squares fit linear regression was performed for the change in SF and SL and the R-squared value is presented in Figure 3.

[Figure 3]

No significant effects were detected in Mean CoPv due to vWBV. Slight increases and decreases were observed, however, with the slowest Mean CoPv (0.34 m/s; -5.6%) measured at 2 and 6 Hz and the fastest Mean CoPv (0.38 m/s; +5.6%) measured at 12 Hz. Statistically significant effects were found in Max CoPv for vWBV of 8 Hz and greater vibration. For the change in CoPv, a binomial fit was applied to both the Mean and Max CoPv plots with the R-squared values presented in Figure 4. Mean CoPv and Max CoPv had a correlation of 0.921 and 0.952 with vWBV, respectively.

[Figure 4]

4. Discussion

During *In-Place walking*, SF was shown to have a mean increase of 12.2% while exposed to vWBV. During *Treadmill Walking*, exposure to vWBV was correlated with a decrease in SF, an increase in SL. As explained in previous studies, subjects exposed to hWBV will also adapt their SF and SL to compensate for instability [12–16,18]. While both scenarios demonstrate increased gait instability during WBV exposure, there was one very 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 leads to longer, slower steps. This is partially in agreement with Nessler et al. who found variable SL alterations depending on vWBV frequency. Previous literature suggested that these stride changes were a potential stepping strategy in response to postural instability during hWBV. Results from this study also suggest spatiotemporal changes due to postural instability during vWBV. The type of change, however, seems to be relative to the direction of the WBV imposed.

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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. To better understand why the Mean CoPv had small changes, while Max CoPv showed significant changes, Figure 5 displays a plot of the mean trajectory and velocity for one subject across all frequencies of vibration exposure.

[Figure 5]

In the no-vibration condition, a relatively smooth curve is observed with a slight increase in velocity across the mid-foot. 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. The changes seen in the Mean and Max CoPv, as well as the visibly perturbed trajectory of the CoP traces 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]. All of these results together indicate that vWBV induces spatiotemporal gait adaptions. The gait adaptations demonstrated here also serve to reinforce the significant findings regarding the human body responses to vWBV demonstrated by Chadefaux et al. [11].

To improve the outcome of future studies, some limitations of this study should be addressed. First, the relationship between vWBV and *In-Place Walking* was difficult to confirm due to the imposed movement already being a somewhat artificial gait which would not be practice in daily life. This likely contributed to the high SD values in SF. While *In-Place Walking* still helped to understand the effect of vWBV on dynamics movements, future studies should focus solely only *Treadmill Walking*. In addition, a small sample size likely contributed to not achieving statistical significance. With an increased sample size, statistically significant results may also be found for SF and SL. 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. To further investigate these interactions, studies will be developed concentrating on treadmill walking with more subjects and including SW.

5. Conclusion

Exposure to increasing frequencies of vWBV during *Treadmill Walking* has been shown to cause a decrease in SF and an increase in SL while also increasing the Max CoPv. This is opposite to the response shown in SF and SL with exposure to hWBV. In any case, these dynamic changes demonstrate decreased stability which may contribute to the discomfort and musculoskeletal injuries already reported in the literature [26]. These factors could also potentially lead to an increased cognitive and physiological strain. To better understand the interaction between dynamic subjects and WBV, future studies should be developed to evaluate the physiological and cognitive effects of 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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Declaration of Interest

None.

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References

[1] G.A. Cavagna, P. Franzetti, N.C. Heglund, P. Willems, The determinants of the step frequency in running, trotting and hopping in man and other vertebrates., J. Physiol. 399 (1988) 81–92. https://doi.org/10.1113/jphysiol.1988.sp017069.

[2] A.E. MINETTI, L.P. ARDIGO, F. SAIBENE, The transition between walking and running in humans: metabolic and mechanical aspects at different gradients, Acta Physiol. Scand. 150 (1994) 315–323. https://doi.org/10.1111/j.1748-1716.1994.tb09692.x.

[3] G. Pavei, A. La Torre, The effects of speed and performance level on race walking kinematics, Sport Sci. Health. 12 (2016) 35–47. https://doi.org/10.1007/s11332-015-0251-z.

[4] A.E. Minetti, G. Pavei, C.M. Biancardi, The energetics and mechanics of level and gradient skipping: Preliminary results for a potential gait of choice in low gravity environments, Planet. Space Sci. 74 (2012) 142–145. https://doi.org/10.1016/j.pss.2012.06.004.

[5] N. Nawayseh, M.J. Griffin, Non-linear dual-axis biodynamic response to vertical whole-body vibration, J. Sound Vib. 268 (2003) 503–523. https://doi.org/10.1016/S0022-460X(03)00254-2.

[6] G.H.M.J. Subashi, Y. Matsumoto, M.J. Griffin, Modelling resonances of the standing body exposed to vertical whole-body vibration: Effects of posture, J. Sound Vib. 317 (2008) 400–418. https://doi.org/10.1016/j.jsv.2008.03.019.

[7] M. Tarabini, S. Solbiati, G. Moschioni, B. Saggin, D. Scaccabarozzi, Analysis of non-linear response of the human body to vertical whole-body vibration, (2014). https://doi.org/10.1080/00140139.2014.945494.

[8] M. Tarabini, S. Solbiati, B. Saggin, D. Scaccabarozzi, Apparent mass matrix of standing subjects exposed to multi-axial whole-body vibration, Ergonomics. 59 (2016) 1038–1049. https://doi.org/10.1080/00140139.2015.1108459.

[9] N.J. Mansfield, S. Maeda, The apparent mass of the seated human exposed to single-axis and multi-axis whole-body vibration, J. Biomech. 40 (2007) 2543–2551.

https://doi.org/10.1016/j.jbiomech.2006.10.035.

[10] N. Nawayseh, S. Hamdan, Apparent mass of the standing human body when using a whole-body vibration training machine: Effect of knee angle and input frequency, J. Biomech. 82 (2019) 291–298. https://doi.org/10.1016/j.jbiomech.2018.11.003.

[11] D. Chadefaux, A.P. Moorhead, P. Marzaroli, S. Marelli, E. Marchetti, M. Tarabini, Vibration transmissibility and apparent mass changes from vertical whole-body vibration exposure during stationary and propelled walking, Appl. Ergon. 90 (2021). https://doi.org/10.1016/j.apergo.2020.103283.

[12] R.A. Brady, B.T. Peters, J.J. Bloomberg, Strategies of healthy adults walking on a laterally oscillating treadmill, Gait Posture. 29 (2009) 645–649. https://doi.org/10.1016/j.gaitpost.2009.01.010.

[13] P.M. McAndrew, J.B. Dingwell, J.M. Wilken, Walking variability during continuous pseudo-random oscillations of the support surface and visual field, J. Biomech. 43 (2010) 1470–1475. https://doi.org/10.1016/j.jbiomech.2010.02.003.

[14] L. Hak, H. Houdijk, F. Steenbrink, A. Mert, P. Van der Wurff, P.J. Beek, J.H. Van Dieën, Speeding up or slowing down?: Gait adaptations to preserve gait stability in response to balance perturbations, Gait Posture. 36 (2012) 260–264. https://doi.org/10.1016/j.gaitpost.2012.03.005.

[15] P.M. McAndrew Young, J.B. Dingwell, Voluntary changes in step width and step length during human walking affect dynamic margins of stability, Gait Posture. 36 (2012) 219–224. https://doi.org/10.1016/j.gaitpost.2012.02.020.

[16] L. Hak, H. Houdijk, F. Steenbrink, A. Mert, P. van der Wurff, P.J. Beek, J.H. Van Dieën, Stepping strategies for regulating gait adaptability and stability, J. Biomech. 46 (2013) 905–911. https://doi.org/10.1016/j.jbiomech.2012.12.017.

[17] H.M. Sari, M.J. Griffin, Postural stability when walking: Effect of the frequency and magnitude of lateral oscillatory motion, Appl. Ergon. 45 (2014) 293–299.

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https://doi.org/10.1016/j.apergo.2013.04.012.

[18] J.A. Nessler, S. Heredia, J. Belair, J. Milton, Walking on a vertically oscillating treadmill: Phase synchronization and gait kinematics, PLoS One. 12 (2017) 1–15. https://doi.org/10.1371/journal.pone.0169924.

[19] Eurofound (2017), Sixth European Working Conditions Survey - Overview Report (2017 Update), Luxembourg, 2017.

[20] H. Seidel, R. Heide, Long-term effects of whole-body vibration: a critical survey of the literature, Int. Arch. Occup. Environ. Health. 58 (1986) 1–26. https://doi.org/10.1007/BF00378536.

[21] C. Hulshof, B. Veldhuijzen van Zanten, Whole-body vibration and low-back pain - A review of epidemiologic studies, Int. Arch. Occup. Environ. Health. 59 (1987) 205–220. https://doi.org/10.1007/BF00377733.

[22] M. Bovenzi, C.T. Hulshof, M.B.C.T.J. Hulshof, An updated review of epidemiologic studies on the relationship between exposure to whole-body vibration and low, Int.Arch.Occup.Environ.Health. 72 (1999) 351–365. https://doi.org/90720351.420 [pii].

[23] A.E. Minetti, C. Capelli, P. Zamparo, P.E. di Prampero, F. Saibene, Effects of stride frequency on mechanical power and energy expenditure of walking., Med. Sci. Sports Exerc. 27 (1995) 1194–202. http://www.ncbi.nlm.nih.gov/pubmed/7476065 (accessed September 6, 2019).

[24] B. Saggin, D. Scaccabarozzi, M. Tarabini, Metrological performances of a plantar pressure measurement system, IEEE Trans. Instrum. Meas. 62 (2013) 766–776. https://doi.org/10.1109/TIM.2013.2245185.

[25] V.M. Zatsiorsky, Kinetics of Human Motion, Human Kinetic Publishers, Champaign, IL, 2002.

[26] E. Johanning, Whole-body vibration-related health disorders in occupational medicine – an international comparison, Ergonomics. 58 (2015) 1239–1252. https://doi.org/10.1080/00140139.2015.1005170.

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Figure 1.

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Figure 2.

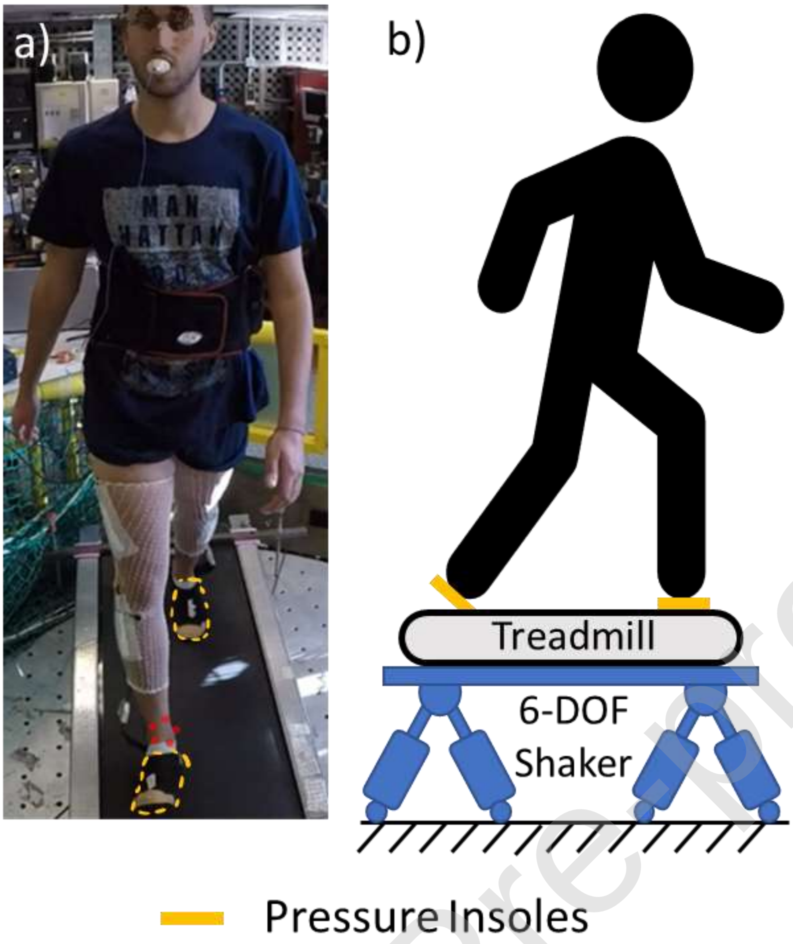

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Figure 3.

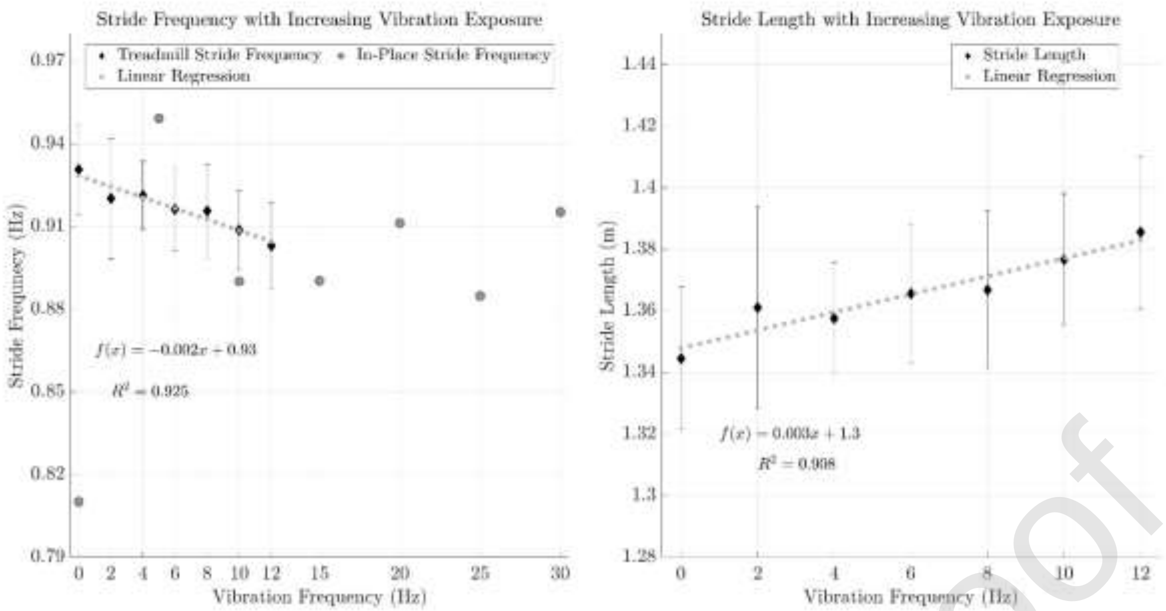

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Figure 4.

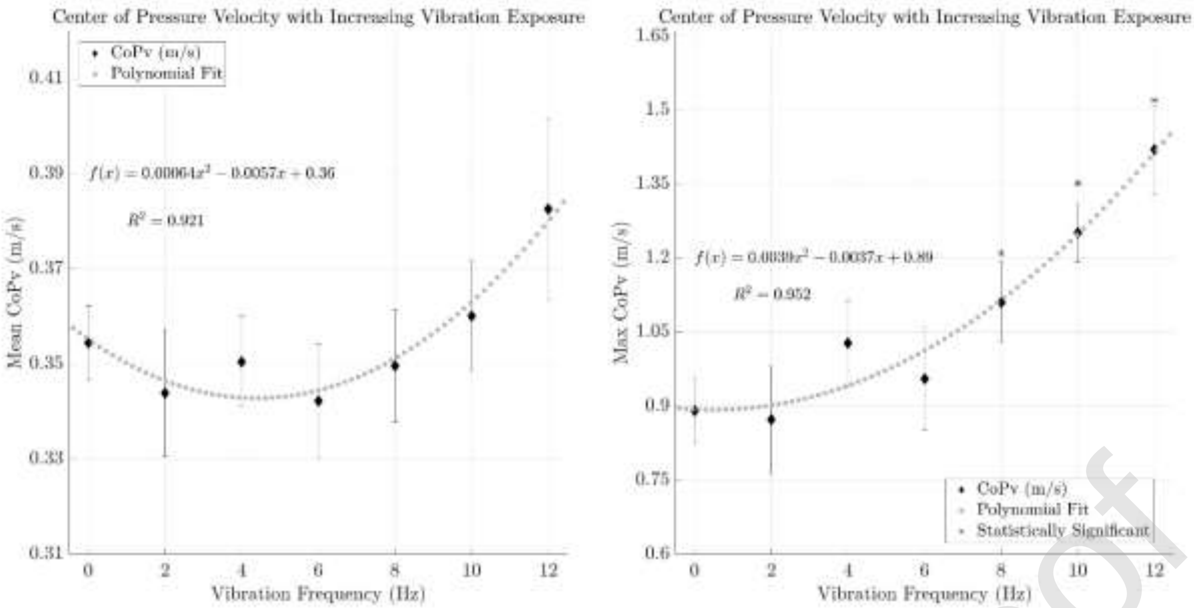

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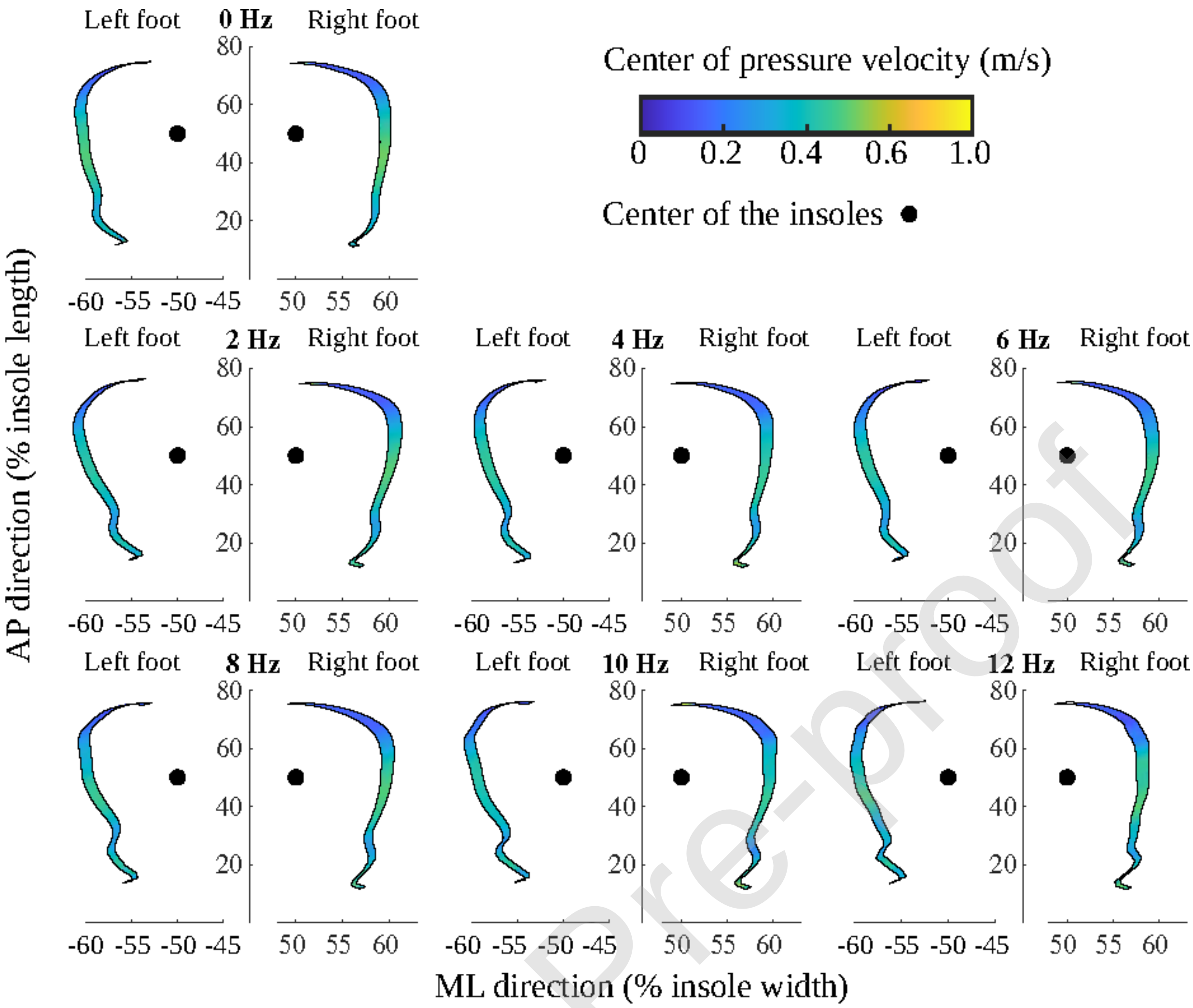
Figure 5.



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Captions

Figure 1. a) Photo of a subject performing the *In-Place Walking* experiments atop a vertical harmonic shaker with load cells between the platform and the shaker as well as the b) schematic representation of the experimental setup.

Figure 2. a) Photo of a subject performing a *Treadmill Walking* test atop the treadmill mounted to a 6 DOF vibration platform with sensorized insoles within the shoes as well as the b) schematic representation of the experimental setup.

Figure 3. The left plot presents the changes in stride frequency during both *Treadmill Walking* (black diamond) and *In-Place Walking* (grey circles). The right plot depicts the stride length change during *Treadmill Walking*. A linear regression (light grey dotted line) has been fit to the *Treadmill Walking* results on both plots and the respective R^2 values are shown. Positive and negative error bars were displayed with the *Treadmill Walking* plots which represent one Standard Deviation. Asterisks denote vibration frequencies at which the results were statistically significant ($p < 0.0083$) from those measured without vibration (0 Hz).

Figure 4. Plots depict the changes in mean center of pressure velocity (left) and maximal 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. Asterisks denote vibration frequencies at which the results were statistically significant ($p < 0.0083$) from those measured without vibration (0 Hz).

Figure 5. Speed-representative color traces are shown of the Mean CoPv during *Treadmill Walking.* Traces describe not only the mean velocity of the center of pressure during walking but also the mean path which is taken.

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Table 1.

	In-Place Walking - Stride Frequency (strides/s)						
Vib. Freq. (Hz)	0	5	10	15	20	25	30
Mean SF (strides/s)	0.81	0.95	0.89	0.89	0.91	0.89	0.92
SD	0.18	0.10	0.12	0.35	0.13	0.11	0.11
p. value	-	0.063	0.328	0.239	0.165	0.334	0.164
% diff.	-	+17.3	+9.9	+9.9	+12.3	+9.9	+13.6
	Treadmill Walking - Stride Frequency (strides/s)						
Vib. Freq. (Hz)	0	2	4	6	8	10	12
Mean SF (strides/s)	0.93	0.92	0.92	0.92	0.92	0.91	0.90
SD	0.032	0.043	0.025	0.030	0.034	0.029	0.031
p. value	-	0.173	0.101	0.051	0.032	0.018	0.009
% diff.	-	-1.1	-1.1	-1.1	-1.1	-2.2	-3.2
	Treadmill Walking – Stride Length (m)						
Vib. Freq. (Hz)	0	2	4	6	8	10	12
Mean SL (m)	1.35	1.36	1.36	1.37	1.37	1.38	1.39
SD	0.046	0.065	0.036	0.045	0.051	0.043	0.049
p. value	-	0.173	0.107	0.059	0.036	0.014	0.010
% diff.	-	+1.2	+0.97	+1.6	+1.7	+2.4	+3.1
	Treadmill Walking – Mean CoPv (m/s)						
Vib. Freq. (Hz)	0	2	4	6	8	10	12
Mean CoPv (m/s)	0.36	0.34	0.35	0.34	0.35	0.36	0.38
SD	0.015	0.027	0.019	0.024	0.023	0.023	0.038
p. value	-	0.128	0.218	0.049	0.421	0.349	0.059
% diff.	-	-5.6	-2.8	-5.6	-2.8	0	+5.6
	Treadmill Walking – Max CoPv (m/s)						
Vib. Freq. (Hz)	0	2	4	6	8	10	12
Max CoPv (m/s)	0.89	0.87	1.03	0.96	1.11	1.25	1.42
SD	0.13	0.22	0.17	0.21	0.16	0.12	0.18
p. value	-	0.765	0.037	0.264	0.004*	<0.001*	<0.001*
% diff.	-	+2.2	+15.7	+7.9	+24.7	+40.5	+59.6

The mean and SD of all variables measured are presented with percent differences and p. values of a paired, two-tail t-test in respect to no vibration (0 Hz). * statistical significance (p. value <0.0083) which reflect those shown in Figure 4.

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