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Effects of vibration intensity on lower limb joint moments during standing

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ABSTRACT

Muscle activity and joint moment of the lower limbs can provide different information about the stimulation of controlled whole-body vibration (CWBV) on human body. Previous studies investigated the immediate effects of the intensity of CWBV on enhancing lower-limb muscle activity. However, no study has examined the possible influence of CWBV intensity on joint loading. It remains unexplored how CWBV intensity impacts joint loading. This study was carried out (1) to quantify the effects of CWBV intensity in terms of vibration frequency and amplitude on the lower limb joint moments and (2) to examine the relationship between leg joint moments and vibration intensity characterized by the platform's acceleration, that is determined by frequency and amplitude, during standing among young adults. Thirty healthy young adults participated in this study. Each participant experienced nine vibration intensity levels dependent upon the frequency (10, 20, and 30 Hz) and amplitude (1, 2, and 3 mm) while standing on a side-alternating vibration platform. Their body kinematics and vertical reaction forces between the feet and platform were collected. Inverse dynamics was employed to calculate the resultant moment for the ankle, knee, and hip joints in the sagittal plane. Our results revealed that the root-mean-square moment significantly increases with increasing vibration frequency or amplitude for all three joints. Further, all joint moments are strongly and positively correlated with the platform acceleration.

1. Introduction

Controlled whole-body vibration (CWBV) training is an alternative and practical exercise technique that uses the mechanical oscillations generated by a vibration platform to stimulate the human body. The stimulation causes the tonic vibration reflex and thus physiological and neuromuscular changes (Madou and Cronin, 2008; Rittweger, 2010). CWBV has been used in rehabilitation sites, recreation centers, and clinical settings primarily due to its inherent advantages, such as portability, safety, ease of operation, and low-cost (Rittweger, 2010; Zago et al., 2018).

CWBV has the potential to stimulate not only the muscles but other tissues like ligaments and tendons of the human body (Rittweger, 2010; Zago et al., 2018). Former studies have focused on the effects of vibration intensity on muscular activity (Abercromby et al., 2007a; Alizadeh-Meghrazi et al., 2014; Di Gimiani et al., 2013; Fratini et al., 2009; Hazell et al., 2007; Krol et al., 2011; Lam et al., 2016; Lienhard et al., 2017; Pollock et al., 2010; Ritzmann et al., 2013; Tankisheva et al., 2013). They reported that muscle activity in the lower limb muscles increase with the increase of vibration frequency and amplitude in both young and older adults. Notably, it has been reported that the vibration platform acceleration is strongly and linearly related to the lower limb muscle activity (Lienhard et al., 2017). As components other than just the muscles contribute to joint moment, examining how joint moment interacts with vibration intensity may be more informative than just focusing on muscles. Whereas, no study has examined how vibration intensity interacts with joint loading. It still remains unclear if and to what extent vibration intensity affects joint loading during vibration.

It has long been suggested that excessive exposure to intense vibration could lead to bodily hazards (International Organization for Standardization, 1997). Although some guidelines regulating the exposure of the body to vibration in occupations have been developed by the International Organization for Standardization (ISO 2631-1: 1997), the guidelines are not applicable to the CWBV situations (Lienhard et al., 2017). Specifically, this standard is not recommended for the evaluation of health effects of CWBV exposure during standing (Abercromby et al., 2007a). Furthermore, the frequency (up to 80 Hz) of the occupational vibration is much

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higher than the one adopted in CWBV (usually < 40 Hz). It has been proposed that an acceleration threshold could be defined. This threshold is enough to induce significant muscle activity but minimize the potential detrimental effects (Lienhard et al., 2017, 2015).

Substantial efforts have been dedicated to studying the transmission of acceleration from the platform to different body parts during CWBV (Abercromby et al., 2007b; Kiiski et al., 2008; Muir et al., 2013; Pel et al., 2009; Pollock et al., 2010; Rubin et al., 2003; Tankisheva et al., 2013). However, the causal-effect between the acceleration level and tissue injuries is not direct. As indicated by a study conducted in mice, excessive dynamic loading induced by repeated vibration exposure can lead to knee injuries (McCann et al., 2015). Thus the mechanical loading (either force or moment) on the human body resulting from CWBV could be the immediate cause of the injury. Therefore, it is of great interest to understand how vibration affects the mechanical load acting on the human body, particularly the joints.

The primary purposes of this study were to (1) examine how vibration intensity, comprised of vibration frequency and amplitude, influences leg joint moments and (2) explore the correlation between the vibration platform acceleration and leg joint moments in the sagittal plane during CWBV among healthy young adults. We hypothesized that the lower limb joint moments would increase as the vibration frequency increases while maintaining the vibration amplitude. We additionally hypothesized that the joint mechanical loading would increase when the vibration amplitude increases with unchanged frequencies. Our final hypothesis was that the platform's acceleration would be significantly and positively correlated with the magnitude of leg joint moments.

2. Methods

2.1. Study design and participants

This study adopted a cross-sectional design and was approved by the Institutional Review Board at Georgia State University. Thirty healthy young participants without known history of musculoskeletal disorders, neurological disorders, orthopedic conditions, and cardiovascular conditions were enrolled (Table 1). Prior to participation, all participants signed an informed consent document. During the study, each participant underwent nine conditions of vibration determined by the vibration frequency (10 vs. 20 vs. 30 Hz) and amplitude (1 vs. 2 vs. 3 mm) following a standing trial without vibration. Lower limb joint moments were calculated for each condition and compared among conditions.

2.2. Experimental protocol

A side-alternating vibration platform (Galileo Med-L, Germany) was used to generate all vibration conditions while participants stood on it. The platform oscillates around an anteroposterior axis, giving alternating upward and downward thrusts to the legs. Its frequency and amplitude can be adjusted between 0 and 30 Hz, and 0 and 5.2 mm, respectively.

After a warmup exercise, a pair of 0.5-mm thin and 30-g insoles (Orpyx, CAN) and 26 reflective markers were applied to each participant. The insoles were attached onto the soles and markers were affixed to the skin of each participant. Another marker was applied to the vibration platform. Each insole contains eight sensors scatted in the areas of toes (2), metatarsals (3), middle section of the lateral sole (2), and the heel (1). Its validity and reliability of collecting force have been established. Participants then stepped on clearly-marked positions on the platform barefoot. They were instructed to evenly distribute their body weight over the forefoot and hind foot bilaterally. They were also told to look ahead and to keep their legs and trunk straight during each condition. To avoid any external force other than the reaction forces from the platform and the gravity acting on the participant's body, participants were asked to place their hands on the hips.

Following a standing trial on the platform without vibration, three frequencies and three amplitudes were applied to each participant, resulting in 10 conditions per participant in total. For the vibration trials, we started with the condition of 10 Hz and 1 mm and increased them to 30 Hz (10 Hz incremental) and 3 mm (1 mm incremental). Each condition lasted 10 s with a 1-min break/wash-out period between conditions.

During each trial, the insole system was activated first, followed by the motion capture system (Vicon, UK). Then participants lifted their heels and held the position for about one second. Subsequently, participants would return to the standing posture to finish the entire trial. This heel movement was used to align the data from the motion capture and the insole systems given that they did not start simultaneously. During the vibration, the insoles collected the bilateral vertical reaction forces between the platform and the feet at 100 Hz. The center of pressure of the reaction forces were also registered by the insoles. An 8-camera motion capture system was used to collect full-body kinematics and the platform's movement at 100 Hz.

2.3. Data reduction

Marker paths and the platform reaction forces along with their center of pressure were low-pass filtered using 18th-order, zero-lag Butterworth filters. The cutoff frequency was 5 Hz higher than the respective vibration frequency (Pollock et al., 2010). The joint centers and the positions of heel and toe were calculated from the filtered marker paths based on gender-dependent segmental inertial parameters (de Leva, 1996). During our offline data process, the kinematic data from the motion capture system was aligned with the kinetic data from the insole system based on the heel-lift movement. A 7-segment, sagittal-plane human model that included the head-arms-trunk, bilateral thighs, legs, and feet was developed for each participant (Pai et al., 2006). The resultant joint moments at the ankle, knee, and hip in the sagittal plane were computed using an inverse dynamics approach based on the collected forces and center of pressure (Winter, 2009). The vertical acceleration of the vibration platform was calculated as the second derivative of its vertical displacement with respect to time. A custom Matlab (Mathworks, MA) program was developed to conduct the calculations. Only the middle two seconds of the data were

Table 1
Demographic information of all participants ($n = 30$) among which 14 were females.

Parameter	Mean	Standard deviation	Minimum	Maximum
Age (years)	26.2	5.1	20	43
Height (m)	1.72	0.09	1.57	1.91
Mass (kg)	71.7	14.0	48.1	97.5

used to calculate the joint moments and platform acceleration for each condition. The joint moments were normalized to the body mass. The root-mean-square (RMS) value during the 2-second segment was computed for all joint moments and the platform acceleration in each condition. We only performed the joint moment calculation on the right leg considering the between-side kinematic/kinetic symmetry.

2.4. Statistical analysis

Although the non-vibration standing trial was not included in the statistical analysis, its values were reported as a reference for the vibration conditions. Analyses of variance (ANOVA) with repeated measures were adopted to examine the impact of vibration parameters (including both frequency and amplitude) on the platform reaction force and joint moments. The two within-subject factors were the frequency (three levels: 10 vs. 20 vs. 30 Hz) and amplitude (three levels: 1 vs. 2 vs. 3 mm). The dependent variables were the RMS of the platform reaction force and the moments at the right ankle, knee, and hip joints. If a significant frequency by amplitude interaction appeared, then one-way ANOVAs with repeated measures were used to resolve the interaction followed by post-hoc analyses which employed paired *t*-tests with Bonferroni corrections. Pearson's correlation analysis was used to determine the association between the vertical acceleration of the platform and the four dependent variables. For the correlation analyses, the average values of both the independent variable (platform acceleration) and the four dependent variables across all participants in each condition were used. All statistical analyses were performed using SPSS 24.0 (IBM, NY) with a significance level of 0.05.

3. Results

All thirty participants finished the protocol and no adverse effects caused by vibration were reported. Repeated measures ANOVA showed a significant difference in the platform reaction force for frequency ($F(2, 58) = 43.42$, $p < 0.001$), amplitude ($F(2, 58) = 21.69$, $p < 0.001$), and their interaction ($F(4, 116) = 6.48$, $p = 0.009$) (Fig. 1). All joint moment measurements displayed significant main effects associated with both the frequency (ankle: $F(2, 58) = 56.18$; knee: $F(2, 58) = 59.77$; and hip: $F(2, 58) = 38.05$; $p < 0.001$ for all) and amplitude (ankle: $F(2, 58) = 44.38$; knee: $F(2, 58) = 46.49$; hip: $F(2, 58) = 40.56$; $p < 0.001$ for all) and frequency by amplitude interaction effect (ankle: $F(4, 116) = 8.08$ and $p = 0.004$; knee: $F(4, 116) = 8.43$ and $p = 0.001$; and hip: $F(4, 116) = 5.06$ and $p = 0.006$). Given the statistical interaction effect, one-way ANOVAs with repeated measure were conducted within each frequency and amplitude.

3.1. Effects of frequency

Repeated measure one-way ANOVAs revealed that all four measurements (platform reaction force and three joint moments) showed significant differences between frequencies within each amplitude ($p < 0.001$ for all amplitudes, Table 2). Post-hoc paired *t*-tests indicated that these measurements were statistically larger at 20 Hz ($p \leq 0.008$ for all measurements) and 30 Hz ($p < 0.001$ for all) than at 10 Hz. At 30 Hz, the platform reaction force, ankle moment, and knee moment were significantly greater ($p \leq 0.003$ for all amplitudes) than at 20 Hz. The hip joint moment did not exhibit significant difference between 20 and 30 Hz ($p > 0.05$ for all amplitudes).

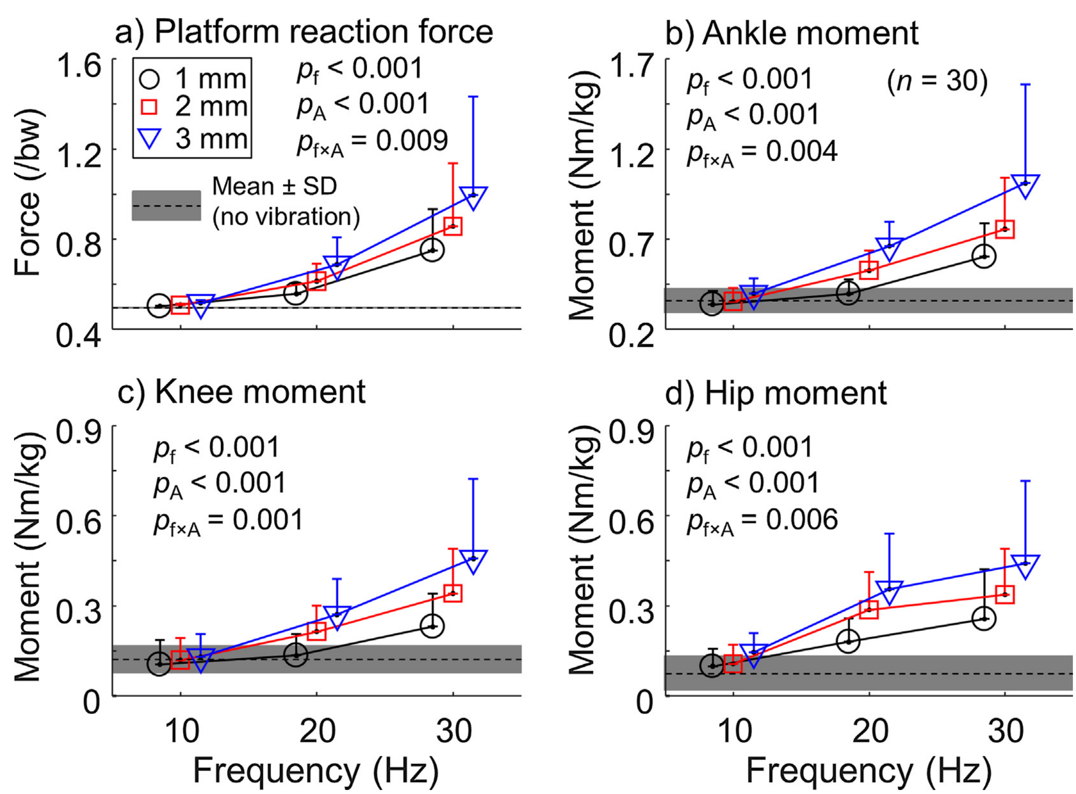

Fig. 1. The root-mean-square of (a) the vibration platform reaction force, (b) ankle joint moment, (c) knee joint moment, and (d) hip joint moment as a function of vibration frequency and amplitude. Also shown is the value of these four measurements expressed in mean ± standard deviation during standing without vibration (as the shaded band). For the platform reaction force, its standard deviation is too small to clearly show the band in the current y-axis scale. The platform reaction force is normalized to the body weight (*bw*) and moments are normalized to the body mass. p_f: the *p* value for the main effect of frequency; p_A: the *p* value for the main effect of amplitude; $p_{f\times A}$: the *p* value for the frequency by amplitude interaction effect.

Table 2
Group mean (standard deviation) of the root-mean-square platform reaction force (/body weight) and moments (in N m/kg) for ankle, knee, and hip joints at frequencies (10 vs. 20 vs. 30 Hz) within each amplitude (1, 2, and 3 mm). Also listed are the *p* values for the one-way ANOVAs with repeated measures, followed by paired *t*-tests with Bonferroni corrections, which were used to analyze the effects of *frequency* on platform reaction force and joint moments. The non-significant *p* values are highlighted.

Amplitude (mm)	Measurement	Frequency (Hz)			ANOVA	Post-hoc		
		10	20	30		10 vs. 20	20 vs. 30	10 vs. 30
1	Reaction force	0.50 (0.01)	0.56 (0.05)	0.75 (0.18)	< 0.001	< 0.001	< 0.001	< 0.001
	Ankle	0.34 (0.07)	0.40 (0.08)	0.60 (0.18)	< 0.001	< 0.001	< 0.001	< 0.001
	Knee	0.10 (0.08)	0.13 (0.07)	0.23 (0.11)	< 0.001	0.008	< 0.001	< 0.001
	Hip	0.10 (0.06)	0.18 (0.08)	0.26 (0.16)	< 0.001	< 0.001	**0.051**	< 0.001
2	Reaction force	0.51 (0.01)	0.62 (0.08)	0.86 (0.28)	< 0.001	< 0.001	< 0.001	< 0.001
	Ankle	0.36 (0.07)	0.53 (0.11)	0.75 (0.28)	< 0.001	< 0.001	< 0.001	< 0.001
	Knee	0.12 (0.07)	0.21 (0.08)	0.34 (0.14)	< 0.001	< 0.001	< 0.001	< 0.001
	Hip	0.11 (0.06)	0.29 (0.12)	0.34 (0.15)	< 0.001	< 0.001	**0.428**	< 0.001
3	Reaction force	0.52 (0.02)	0.69 (0.12)	0.99 (0.43)	< 0.001	< 0.001	0.001	< 0.001
	Ankle	0.40 (0.08)	0.66 (0.13)	1.01 (0.54)	< 0.001	< 0.001	0.003	< 0.001
	Knee	0.13 (0.08)	0.27 (0.17)	0.46 (0.26)	< 0.001	< 0.001	0.002	< 0.001
	Hip	0.15 (0.06)	0.36 (0.18)	0.44 (0.27)	< 0.001	< 0.001	**0.357**	< 0.001

Table 3
The *p* values for the comparisons of the root-mean-square platform reaction force, ankle joint moment, knee moment, and hip moment between amplitudes (1 vs. 2 vs. 3 mm) within each frequency (10, 20, and 30 Hz). One-way ANOVAs with repeated measures, followed by paired *t*-tests with Bonferroni corrections, were used to analyze the effects of vibration *amplitude* on the platform reaction force and joint moments. The non-significant *p* values are highlighted.

Frequency (Hz)	Measurement	ANOVA	Post-hoc		
			1 vs. 2 mm	2 vs. 3 mm	1 vs. 3 mm
10	Reaction force	< 0.001	< 0.001	0.005	< 0.001
	Ankle	< 0.001	**0.295**	0.001	< 0.001
	Knee	0.011	**0.302**	0.008	0.036
	Hip	< 0.001	**0.736**	< 0.001	< 0.001
20	Reaction force	< 0.001	< 0.001	< 0.001	< 0.001
	Ankle	< 0.001	< 0.001	< 0.001	< 0.001
	Knee	< 0.001	< 0.001	0.041	< 0.001
	Hip	< 0.001	< 0.001	0.003	< 0.001
30	Reaction force	0.002	0.025	0.013	0.008
	Ankle	< 0.001	< 0.001	0.006	0.001
	Knee	< 0.001	< 0.001	0.041	< 0.001
	Hip	< 0.001	0.005	0.035	0.001

3.2. Effects of amplitude

Within the frequencies of 20 and 30 Hz, all four measurements showed significant amplitude-related differences ($p \le 0.002$ for all, Table 3). Further analyses showed that all measurements were statistically different between all three amplitudes ($p \le 0.041$ for all measurements) within 20 and 30 Hz. The higher the amplitude, the greater the measurements. For the frequency of 10 Hz, all four outcome variables displayed significant amplitude-associated differences ($p \le 0.011$ for all). The four measurements were significantly higher at 3 mm than at 2 mm ($p \le 0.008$ for all measurements) at 10 Hz. Similarly, the values of the four measurements were significantly larger at 3 mm than at 1 mm ($p \le 0.036$ for all measurements) within 10 Hz. The platform reaction force was statistically larger at 2 mm than at 1 mm ($p < 0.001$) but the three moments were comparable between these two amplitudes ($p \ge 0.295$ for all) at 10 Hz.

3.3. Correlations between platform acceleration and joint moments

All four outcome measurements (the RMS values of the platform reaction force, ankle moment, knee moment, and hip moment) were significantly and positively correlated with the RMS value of the platform acceleration (Fig. 2, $p < 0.001$ for all correlations; the coefficient of correlation $r = 0.964$ for the platform force, 0.939 for ankle moment, 0.952 for knee moment, and 0.988 for hip moment).

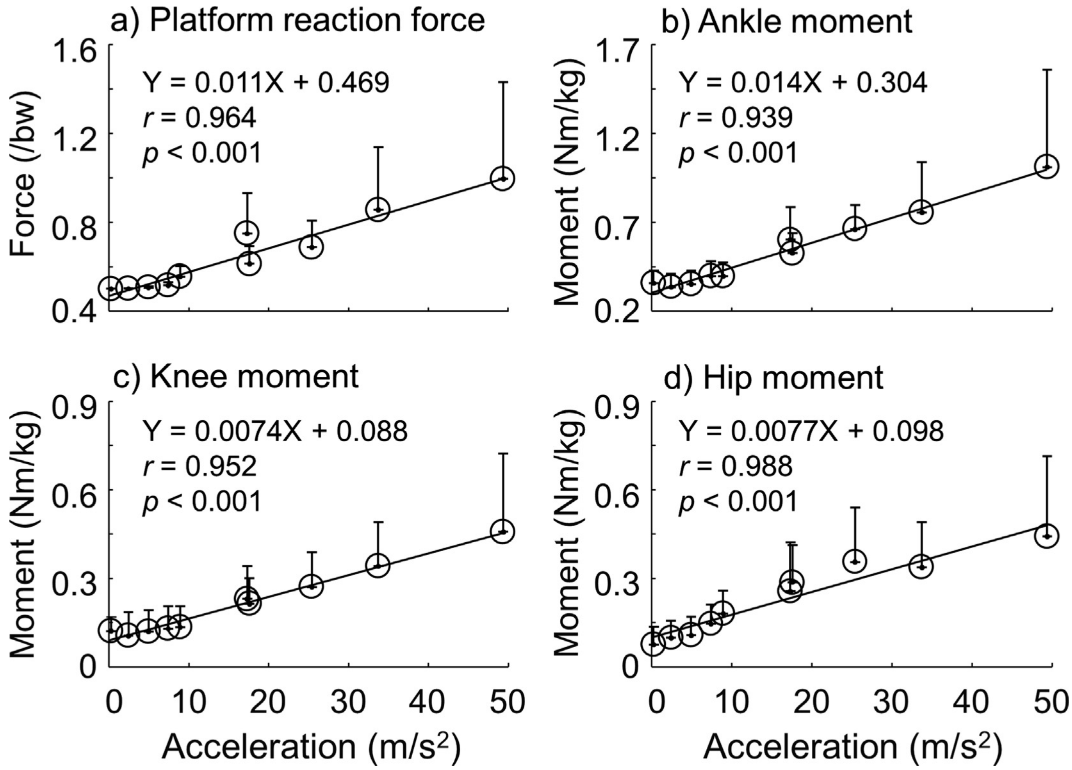

Fig. 2. Scatterplot with line of best fit of the root-mean-square vibration platform acceleration versus the root-mean-square values of (a) the platform reaction force, (b) ankle joint moment, (c) knee joint moment, and (d) hip joint moment under all nine vibration conditions and the standing condition without vibration. The value of the platform acceleration and the four outcome measurements under each condition was the average value across all participants. The platform acceleration is calculated as the second derivative of the platform's vertical displacement with respect to time. The platform's displacement is determined by the position of the marker attached onto the platform during vibration. Also shown are the regression equation ($Y = kX + b$), Pearson's correlation coefficient (r), and the significance level (p) for each linear regression model.

4. Discussion

This study inspected how CWBV intensity affects lower limb joint moments during standing. Our main finding was that increased vibration intensity, by heightening either the frequency or amplitude, significantly increases the lower extremity joint moments among young adults (Fig. 1). The lower extremity joint moments are strongly proportional to the vibration intensity (or the vibration platform acceleration) (Fig. 2).

Our study was the first to analyze the interaction between the vibration intensity and lower limb joint moments. As mentioned before, joint moment contains the contributions from muscle, tendon, and ligaments, and the joint contact forces and vibration could impact all of them. Therefore, joint moment may provide more information than muscle activity alone to reflect the effects of the vibration. Despite such differences between the muscle activity and joint moment, our finding concours with the ones from previous studies where increased muscle activity or acceleration in the leg were reported as the vibration intensity increases. For example, it was concluded that the lower limb muscle activity and acceleration level is enhanced with increases in either vibration frequency or amplitude among both healthy (Di Gimiani et al., 2013; Friesenbichler et al., 2014; Lienhard et al., 2017; Pollock et al., 2010) and diseased populations (Alizadeh-Meghrazi et al., 2014). Although the vibration parameters in terms of the frequency and amplitude are different between the present study and previous ones (0–55 Hz and 0.9–5.5 mm in previous studies vs. 10–30 Hz and 1–3 mm in the present study), the trends are similar, i.e., the increased vibration intensity increases muscle activity and joint moment. Our study extends and deepens the current understanding of the influence of vibration on the human body from the viewpoint of biomechanics.

We hypothesized that the increased vibration frequency, with other vibration parameters held unchanged, would raise the leg joint moments. Our results supported this hypothesis. Specifically, when the frequency increases from 10 to 30 Hz within each amplitude level, the moments at all three leg joints increased. Post-hoc analyses further suggested that almost all measured joint moments were significantly larger for higher frequencies than lower ones (Table 2). A previous study, examining the tonic vibration reflex, reported that the plantar flexor force increases with the increases in frequency during a CWBV protocol (Zaidell et al., 2013). Our finding about the overall frequency-ankle moment relationship confirms the results from this past study.

The only exception is the hip joint moment which is not significantly different between 20 and 30 Hz for all three amplitudes (Table 2). This could indicate that the hip joint moment may have reached its peak value within the frequency range of 20–30 Hz. Results from a prior study illustrated that muscle activity levels were comparable for the rectus femoris and gluteus maximus muscles when the vibration frequency alters from 20 to 25, and then to 30 Hz at the amplitude of 2.5 mm (Pollock et al., 2010). The frequency and amplitude are very similar between our current study and the previous one (Pollock et al., 2010). Since these two muscles are associated with the hip joint moment, our results align with the findings from the previous study (Pollock et al., 2010).

The results also partially supported our second hypothesis, which stated that the lower limb joint moments would elevate as the vibration amplitude is increased with all other parameters being constant (Table 3). Within the frequencies of 20 and 30 Hz, all joint moments significantly increased with increasing the amplitude. Although the main effect of the amplitude on the joint moment for the frequency 10 Hz is significant, post-hoc analyses revealed that the differences in the three joint moments were not significantly different between the amplitudes of 1 and 2 mm. All moments were statistically greater at 3 mm than 2 mm, and at 3 mm than 1 mm within 10 Hz. This could imply that at a lower frequency (like 10 Hz) and smaller amplitudes (like 1 mm), the CWBV stimulation level may not be strong enough to induce significant changes in joint moments. This could be further supported by the observations that all four outcome measures at 10 Hz and 1 mm are very similar to the ones during the non-vibration standing trial (Fig. 1). A previous study reported that the transmissibility of vibration power from the platform to the lower limb joints is small (<1) with lower amplitudes (0.05–1 mm) at 10 Hz while the transmissibility could reach up to 10 when the amplitude is 3 mm at the same frequency (Kiiski et al., 2008). The small power transmissibility at low frequency and amplitude may suggest that the stimulation level on the lower limb is insufficient, elucidating the non-significant results in the joint moments observed in our study.

The third hypothesis that joint moments strongly and positively correlate with the platform acceleration level was supported by our results. The correlation coefficient was high and statistically significant for all four outcome measurements ($r \geq 0.939$, Fig. 2). Based on the regression models, a unit (1 m/s^2) increase in the platform acceleration would heighten the platform reaction force by a factor of 1.1% body weight and the moments by a factor between 0.8 and 1.4% N m/kg (Fig. 2). The regression models deliver another piece of evidence that the CWBV-induced stimulation level is closely correlated with the vibration platform acceleration.

It has been postulated that the force between the vibration platform and the feet increases when the vibration intensity increases. A previous study has used the vertical acceleration of the vibration platform to represent the interaction force between the platform and the human body (Crewther et al., 2004). Although the interaction force is related to the acceleration, the latter is not equivalent to the former, especially given the high complexity, damping effect, and dynamic nature of the human body. Thus, it is questionable to use the acceleration to represent the reaction force. Our study has experimentally verified the postulated proportional relationship between acceleration and platform reaction force. When the vibration intensity, and thus the platform acceleration, increases, the interaction force between the human body and the platform increases (Fig. 2a). The acceleration transmitted to the human body also increases (Abercromby et al., 2007b; Kiiski et al., 2008; Pollock et al., 2010; Tankisheva et al., 2013). Since joint moments are determined by both the kinetics (the platform reaction force) and kinematics (the acceleration of the body), the increases in these two aspects would elevate joint moments.

Excessive exposure to high-intensity vibration has been associated with detrimental effects on the human body (International Organization for Standardization, 1997). The ISO 2631-1 recommends using the vibration dose value that is determined by the vibration acceleration and its exposure duration. However, such a method does not reflect the impact of vibration on the human body structure from the mechanical perspective. A study in mice has found that the excessive exposure to intense vibration could lead to mechanical damages to the animal body (McCann et al., 2015). Given that the human body is a highly complex and nonlinear biodynamic apparatus, the omission of mechanical loading could either overestimate or underestimate the influence of vibration on the human body (Abercromby et al., 2007b), creating potential safety concerns. Therefore, this established ISO standard is not applicable to CWBV applied to the human body (Lienhard et al., 2017; Rittweger, 2010). On the other hand, the approach used in our study is a novel method to evaluate the mechanical effect of vibration on the human body. It possesses the potential to provide more meaningful insight into the assessment of possible risk of body structure injury from CWBV.

Our study has limitations. First, we did not randomize the order of the vibration conditions. This could introduce the order effect to our results. Each 10-second trial was followed by a one-minute rest which was also used as a washout period. So the effect from the preceding trial could have diminished before the start of the following trial. This may reduce the order effect. Second, although our results suggest the linear correlations between the platform acceleration and joint moments (Fig. 2), one needs to take caution when extrapolating our results to the acceleration levels beyond the range examined in the present study. Third, only healthy young adults were included in this study. The body response to vibration stimulation could differ between populations. Lastly, the insoles can only measure the platform reaction force in the vertical direction. This would have induced inaccuracy in the calculation of sagittal-plane joint moments as the anteroposterior reaction force is also needed for this calculation. It is worthwhile to further examine all of these issues.

In conclusion, this study illustrated that increased vibration intensity significantly and proportionally enhances lower limb joint moments among healthy young adults. Our findings revealed the stimulation from vibration onto the human body from another perspective – joint loading. As the mechanical loading is related to body or tissue damages (McCann et al., 2015), our results may supply some preliminary information for further studies investigating the safety and hazard issue of applying CWBV as an intervention in the rehabilitation field.

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Conflict of interest statement

None declared.

References

Abercromby, A.F.J., Amonette, W.E., Layne, C.S., Mcfarlin, B.K., Hinman, M.R., Paloski, W.H., 2007a. Variation in neuromuscular responses during acute whole-body vibration exercise. Med. Sci. Sports Exerc. 39, 1642–1650.

Abercromby, A.F.J., Amonette, W.E., Layne, C.S., Mcfarlin, B.K., Hinman, M.R., Paloski, W.H., 2007b. Vibration exposure and biodynamic responses during whole-body vibration training. Med. Sci. Sports Exerc. 39, 1794–1800.

Alizadeh-Meghrazi, M., Masani, K., Zariffa, J., Sayenko, D.G., Popovic, M.R., Caraven, B.C., 2014. Effect of whole-body vibration on lower-limb EMG activity in subjects with and without spinal cord injury. J. Spinal Cord Med. 37, 525–536.

Crewther, B., Cronin, J., Keogh, J., 2004. Gravitational forces and whole body vibration: implications for prescription of vibratory stimulation. Phys. Thear. Sport 5, 37–43.

de Leva, P., 1996. Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters. J. Biomech. 29, 1223–1230.

Di Gimiani, R., Masedu, F., Tihanyi, J., Scrimaglio, R., Valenti, M., 2013. The interaction between body position and vibration frequency on acute response to whole body vibration. J. Electromyogr. Kinesiol. 23, 245–251.

Fratini, A., La Gatta, A., Bifulco, P., Romano, M., Cesarelli, M., 2009. Muscle motion and EMG activity in vibration treatment. Med. Eng. Phys. 31, 1166–1172.

Friesenbichler, B., Lidnhard, K., Vienneau, J., Nigg, B.M., 2014. Vibration transmission to lower extremity softy tissues. J. Biomech. 47, 2858–2862.

Hazell, T.J., Jakobi, J.M., Kenno, K.A., 2007. The effects of whole-body vibration on upper- and lower-body EMG during static and dynamic contractions. Appl. Physiol., Nutr., Metab. 32, 1156–1163.

International Organization for Standardization, 1997. ISO 2631–1: 1997, Mechanical Vibration and Shock – Evaluation of Human Exposure to Whole-body Vibration, Part 1, General Requirements. International Organization for Standardization, Geneva, Switzerland.

Kiiski, J., Heinonen, A., Jarvinen, T.L., Kannus, P., Sievanen, H., 2008. Transmission of vertical whole body vibration to the human body. J. Bone Miner. Res. 23, 1318–1325.

Krol, P., Piecha, M., Slomka, K., Sobota, G., Polak, A., Grzegorz, J., 2011. The effect of whole-body vibration frequency and amplitude on the myoelectric activity of vastus medialis and vastus lateralis. J. Sports Sci. Med. 10, 169–174.
Lam, F.M.H., Liao, L.-R., Kwok, T.C.Y., Pang, M.Y.C., 2016. The effect of vertical whole-body vibration on lower limb muscle activation in elderly adults: influence of vibration frequency, amplitude and exercise. Maturitas 88, 59–64.
Lienhard, K., Vienneau, J., Nigg, S., Friesenbichler, B., Nigg, B.M., 2017. Older adults show higher increases in lower-limb muscle activity during whole-body vibration exercise. J. Biomech. 50, 55–60.
Lienhard, K., Vienneau, J., Nigg, S., Meste, O., Colson, S.S., Nigg, B.M., 2015. Relationship between lower limb muscel activity and platform acceleration during whole-body vibration exercise. J. Strength. Cond. Res. 29, 2844–2853.
Madou, K.H., Cronin, J.B., 2008. The effects of whole body vibration on physical and physiological capability in special populations. Hong Kong Physiother. J. 26, 24–38.
McCann, M.R., Patel, P., Pest, M.A., Patneswaran, A., Lalli, G., Beaucage, K.L., Backler, G.B., Kamphuis, M.P., Esmail, Z., Lee, J.-M., Barbalinardo, M., Mort, J.S., Holdsworth, D.W., Beier, F., Dixon, S.J., Seguin, C.A., 2015. Repeated exposure to high-frequency low-amplitude vibration induces degeneration of murine intervertebral discs and knee joints. Arthritis Rheumatol. 67, 2164–2175.
Muir, J., Kiel, D.P., Rubin, C.T., 2013. Safety and severity of accelerations delivered from whole body vibration exercise devices to standing adults. J. Sci. Med. Sport 16, 526–531.
Pai, Y.-C., Yang, F., Wening, J.D., Pavol, M.J., 2006. Mechanisms of limb collapse following a slip among young and older adults. J. Biomech. 39, 2194–2204.
Pel, J.J.M., Bagheri, J., van Dam, L.M., van den Berg-Emons, H.J.G., Horemans, H.L.D., Stam, H.J., van der Steen, J., 2009. Platform accelerations of three different whole-body vibration devices and the transmission of vertical vibrations to the lower limbs. Med. Eng. Phys. 31, 937–944.
Pollock, R.D., Woledge, R.C., Mills, K.R., Martin, F.C., Newham, D.J., 2010. Muscle activity and acceleration during whole body vibration: effects of frequency and amplitude. Clin. Biomech. 25, 840–846.
Rittweger, J., 2010. Vibration as an exercise modality: how it may work, and what its potential might be. Eur. J. Appl. Physiol. 108, 877–904.
Ritzmann, R., Gollhofer, A., Kramer, A., 2013. The influence of vibration type, frequency, body position and additional load on the neuromuscular activity during whole body vibration. Eur. J. Appl. Physiol. 113, 1–11.
Rubin, C., Pope, M., Fritton, C., Magnusson, M., Hansson, T., McLeod, K., 2003. Transmissibility of 15-Hertz to 35-Hertz vibrations to the human hip and lumbar spine: determining the physiologic feasibility of delivering low-level anabolic mechanical stimuli to skeletal regions at greatest risk of fracture because of osteoporosis. Spine 28, 2621–2627.
Tankisheva, E., Jonkers, I., Boonen, S., Delecluse, C., van Lenthe, G.H., Druyts, H.L., Spaepen, P., Verschueren, S.M., 2013. Transmission of whole-body vibration and its effect on muscle activation. J. Strength. Cond. Res. 27, 2533–2541.
Winter, D.A., 2009. Biomechanics and Motor Control of Human Movement. Wiley, Hoboken, NJ.
Zago, M., Capodaglio, P., Ferrario, C., Tarabini, M., Galli, M., 2018. Whole-body vibration training in obese subjects: a systematic review. PLoS ONE 13, e0202866.
Zaidell, L.N., Mileva, K.N., Sumners, D.P., Bowtell, J.L., 2013. Experimental evidence of the tonic vibration reflex during whole-body vibration of the loaded and unloaded leg. PLoS ONE 8, e85247.