Chapter 18
A Pilot Study on Pedestrian Comfort Under Vertical Vibrations

Rajesh Govindan, Bintian Lin, Genevieve K. R. Williams, and Stana Živanović

Abstract The pedestrian comfort to footbridge vibration is likely influenced by numerous parameters specific to the structure and the person crossing the bridge. In the current design practice, vibration magnitude is routinely considered when defining vibration serviceability limits. Some design standards, such as BS 5400 (outdated) and ISO 10137 (current), also define frequency-dependent vibration limits, while the exposure time and pedestrian's pacing frequency are routinely neglected.

This pilot study explores the perceptual effects of vertical vibration during walking, with relevance to vibrations experienced on footbridges, using a combination of controlled and randomized test parameters. Unlike previous studies that typically ignored the influence of one or more parameters of interest, this study examined combined effect of vibration magnitude, vibration frequency, pacing frequency, and exposure time.

The findings reveals that vibration magnitude, frequency, and exposure time are the principal determinants of subjective comfort, whereas derived parameters related to gait or its combination with vibration parameters such as pacing frequency, frequency ratio, and frequency deviation did not significantly influence perceived comfort.

Keywords Footbridges · Vibration serviceability · Pedestrian comfort · Vibration perception · Exposure time

Introduction

Pedestrian comfort on footbridges is influenced by both structural and human factors, with vibrations capable of evoking responses ranging from mild discomfort to instability. Current design practice primarily addresses vibration magnitude [1], while some standards BS 5400 (outdated) [2] and ISO 10137 [3], also include frequency-dependent limits. However, important factors such as exposure time and pacing frequency are not explicitly considered, despite their potential influence on perceived comfort.

Most previous research has concentrated on static postures (seated, standing, or supine) or on structural responses under pedestrian loading [4–6]. Studies directly addressing pedestrian comfort during walking are relatively limited. Pioneering investigations [7, 8] and later systematic studies [9–11] demonstrated that walking pedestrians perceive vibrations at much higher levels than standing individuals, and that factors such as pacing rate, age, and gender can influence tolerance. However, the combined effects of vibration magnitude, frequency, pacing frequency, and exposure time on comfort remain underexplored.

This pilot study addresses these gaps by systematically examining the perceptual effects of vertical vibration during walking, with relevance to footbridge vibrations, under controlled laboratory conditions. Unlike previous studies that typically ignored the influence of exposure time, this research explores the combined effect of vibration magnitude, vibration frequency, walking speed, and exposure time to identify key predictors of perceived discomfort. Following this introduction, Section 2 describes the methodology, including test participant, experimental setup, instrumentation, test protocols, and data processing. Section 3 presents the results on the simultaneous influence of these parameters on subjective comfort ratings.

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Methodology

Test Participants

The pilot study was conducted with single voluntary participant (TP: Female, age 50, and body mass index 22.22 kg/m^2) from University of Warwick. Participant signed an informed consent before the beginning the experiment as required by the University's Biomedical and Scientific Research Ethics Committee. The participant was physically active with no history of motion sickness, vibration sensitivity and/or walking locomotion impairments and pregnancy.

Experimental Setup

The vertical vibration applied through octopod motion platform (VSimulators, University of Exeter) equipped with treadmill to allow prolonged walking during the experiments. The 3.7m $\times$ 3.7m motion platform reproduces motion with high fidelity within limits of $\pm$ 21 mm displacement and 2 m/s^2 maximum acceleration over a 0 to 40 Hz frequency range. An Optitrack motion capture system provided real-time full-body kinematic tracking using reflective markers with sampling rate of 100 Hz. Participant wore a wireless noise-cancelling headphones (Sony WH-1000xm4) to mask the sound produced by the motion platform (Fig. 1a).

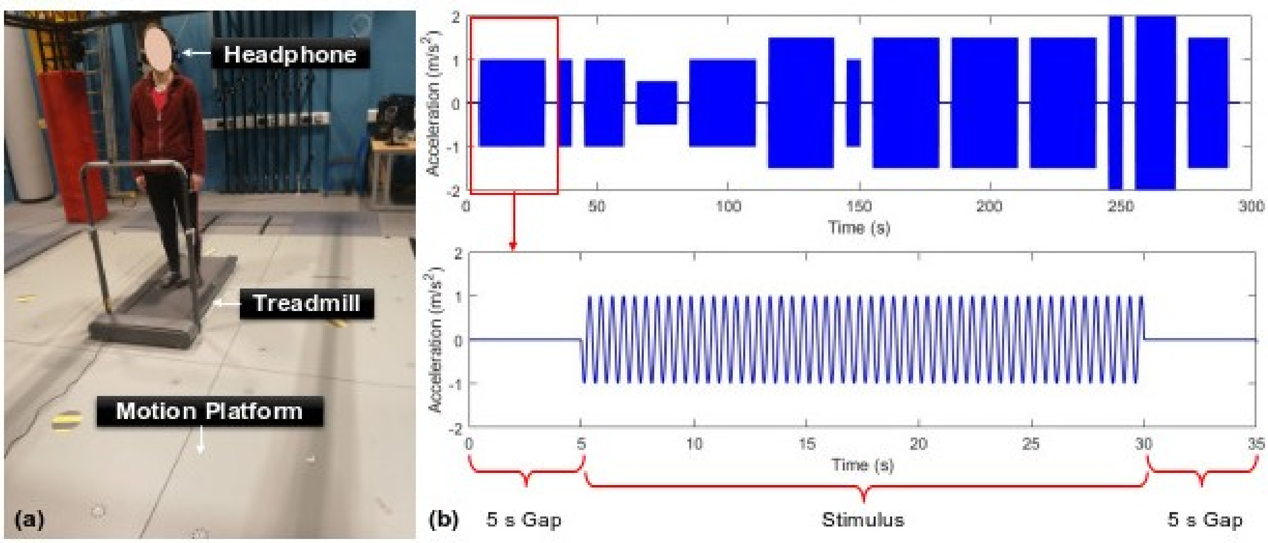

Fig. 1 (a) Test participant on the treadmill placed on the motion platform (b) Top: representative randomized vibration stimuli block; Bottom: representative 25 s exposure time stimulus with 5 s gaps

Test Protocol

The participant was exposed to four vibration magnitudes (0.5, 1.0, 1.5 and 2.0 m/s^2), eight frequencies between 1.587 and 8.0 Hz in 1/3 octave band, and three exposure times (5, 15 and 25 s), approximating the time required to cross the central span of 15 m, 45 m and 75 m bridges, respectively. Walking trials were conducted at three preferred speeds (Slow, Normal and Fast).

Experiments were completed over two sessions on separate days. At the start of first session, preferred walking speeds were established. Participants began walking on the treadmill at 2.5 km/h, with speed adjusted in 0.5 km/h increments to identify "normal" walking speed. Slow and fast speeds were determined by decreasing or increasing from the normal speed in 0.5 km/h increments until noticeably slower or brisk but still comfortable pace was reached. Trials at normal speed were conducted in the first session, while slow and fast speed trials were completed in the second session.

At each speed, participant exposed to 96 randomized vibration stimuli (four amplitudes $\times$ eight frequencies $\times$ three exposure time) including one no-vibration trial per exposure time. The combination of 2 m/s^2 and 1.587 Hz was excluded due to VSimulators performance limitation. To manage participant fatigue due to continuous walking, the 96 stimuli were divided into seven blocks of around five minutes each (including five-seconds gaps between stimuli). An example of the randomized vibration stimuli block and a stimulus with five-seconds gaps is shown in Fig. 1b. Participant walked continuously during each block and rested for 150 s between blocks. Following each stimulus, during the five-second gap, participant rated their vibration comfort on a five-point scale: not perceived, comfortable, slightly uncomfortable, moderately uncomfortable or strongly uncomfortable.

Data Acquisition and Processing

Before the experimental session, two markers were placed on the heels of the participant shoes to detect the heel-strike event. The trajectories of the markers were filtered with 4^{th} order low-pass Butterworth filter with a cut-off frequency of 16 Hz. The heel-strike event was identified as a time instance at which horizontal (fore-aft) velocity of leading leg heel marker changes from positive to negative [12]. The time between two successive heel-strikes of both feet gave the step time. The pacing frequency (f_p) was computed as the reciprocal of step time.

To determine the combined influence of pacing frequency and vibration frequency on subjective comfort, two additional measures were defined: frequency ratio and frequency deviation. The frequency ratio (FR) was computed as the ratio between the harmonic (n) of participant's mean pacing frequency (f_p) and the vibration frequency (f_v). Specifically, for each test i.e. response measured for the given stimulus, the frequency ratio was calculated as:

$$FR = \frac{nf_p}{f_v}, \text{ where } n = 1, 2, 3, 4 \tag{1}$$

The harmonic yielding the FR value closest to unity (i.e., the smallest absolute deviation from 1) was selected, and the corresponding FR was used for further analysis.

The frequency deviation ($|\Delta f|$) quantifies the absolute difference between the harmonics of participant's mean pacing frequency (f_p) and the vibration frequency (f_v). Specifically, for each test, absolute frequency deviation was calculated as:

$$|\Delta f| = |nf_p - f_v|\,, \text{ where } n = 1, 2, 3, 4 \tag{2}$$

The harmonic that minimized this difference was selected, and the corresponding $|\Delta f|$ value was used for subsequent analysis.

Data Analysis

The influence of test parameters (vibration magnitude (a_v), vibration frequency (f_v), exposure time (T_{exp}) and walking speed (w_s)) and derived parameters (pacing frequency (f_p), frequency ratio (FR), and frequency deviation (Δf)) on the subjective comfort of participant under vibration exposure were statistically analysed. Spearman's rank correlation (ρ) was used to assess monotonic relationship among test parameters, derived parameters and subjective comfort ratings. An ordinal regression analysis was applied to examine the simultaneous influence of test and derived parameters on subjective comfort ratings. Descriptive statistics of test and derived parameters is shown in Table 1.

Table 1 Descriptive statistics of test and derived parameters for walking condition on a vibrating surface

	N	Minimum	Maximum	Mean	Std. Deviation	Skewness		Kurtosis	
						Statistic	S.E.	Statistic	S.E.
Walking Speed (km/h)	279	3.860	5.470	4.720	0.663	-0.246	0.146	-1.505	0.291
Exposure Time (s)	279	5.000	25.000	15.000	8.180	0.000	0.146	-1.505	0.291
Vibration Magnitude (m/s^2)	279	0.500	2.000	1.226	0.552	0.051	0.146	-1.325	0.291
Vibration Frequency (Hz)	279	1.587	8.000	4.147	2.082	0.576	0.146	-0.889	0.291
Pacing Frequency (Hz)	279	1.549	1.999	1.776	0.143	-0.260	0.146	-1.459	0.291
Frequency Ratio (-)	279	0.710	1.320	0.995	0.151	0.099	0.146	-0.893	0.291
Frequency Deviation (Hz)	279	0.001	0.608	0.224	0.160	0.614	0.146	-0.335	0.291

N: Number of tests, S.E.: Standard Error

Results and Discussion

An ordinal logistic regression was conducted to assess the combined effects of vibration magnitude (a_v), vibration frequency (f_v), exposure time (T_{exp}), pacing frequency (f_p), frequency ratio (FR), and frequency difference ($|\Delta f|$) on subjective comfort rating (Table 2). All test and derived parameters were standardized using z-scores to place them on a common scale, facilitating comparability and ensuring that differences in measurement units did not bias the regression coefficients. Since strong correlations between test and derived parameters may introduce multicollinearity and affect reliability of regression model, Spearman's rank correlation (ρ) was used to assess the parameter association (Table 2).

Walking speed was found to be highly correlated with pacing frequency ($\rho = 0.941$, $p < 0.01$) and was therefore excluded from the regression analysis. Subjective comfort ratings showed a strong positive correlation with vibration magnitude ($\rho = 0.782$, $p < 0.001$), a weak positive correlation with exposure time ($\rho = 0.195$, $p = 0.001$) and a weak negative correlation with vibration frequency ($\rho = -0.187$, $p = 0.002$).

Table 3 presents ordinal logistic regression model for subjective comfort rating as a function of vibration magnitude (a_v), vibration frequency (f_v), exposure time (T_{exp}), pacing frequency (f_p), frequency ratio (FR), and frequency difference ($|\Delta f|$). The model was statistically significant ($\chi^2(6) = 345.73$, $p < 0.001$) and demonstrated excellent fit, explaining 75% of the variance in subjective comfort ratings (Nagelkerke R^2).

Table 2 Association among the test parameters, derived parameters and subjective comfort rating

Parameter	w_s	T_{exp}	a_v	f_v	f_p	FR	$\|\Delta f\|$	SR
	Spearman correlation coefficient (ρ)							
Walking Speed (w_s)	1	0	0	0	**0.941****	0.041	0.024	0.038
Exposure Time (T_{exp})	0	1	0	0	-0.013	0.021	-0.004	**0.195****
Vibration Magnitude (a_v)	0	0	1	0.068	0.012	-0.073	0.045	**0.782****
Vibration Frequency (f_v)	0	0	0.068	1	0.004	-0.114	**0.366****	**-0.187****
Pacing Frequency (f_p)	**0.941****	-0.013	0.012	0.004	1	0.027	0.002	0.04
Frequency Ratio (FR)	0.041	0.021	-0.073	-0.114	0.027	1	-0.042	0
Frequency Deviation ($\|\Delta f\|$)	0.024	-0.004	0.045	**0.366****	0.002	-0.042	1	-0.055
Subjective Rating (SR)	0.038	**0.195****	**0.782****	**-0.187****	0.04	0	-0.055	1

** Correlation is significant at the 0.01 level (2-tailed).

The estimated thresholds represent the cut-points on the latent comfort scale that separate adjacent subjective ratings. Among the predictors, vibration magnitude (a_v) was the strongest determinant of subjective comfort ($\beta = 3.006$, $p<0.01$), indicating that higher vibration magnitudes substantially increased the odds of reporting greater discomfort. Vibration frequency (f_v) showed a significant negative effect ($\beta = -1.174$, $p<0.01$), suggesting that increasing frequency was associated with lower odds of reporting higher discomfort. Exposure time (T_{exp}) also had a significant positive influence ($\beta = 0.843$, $p<0.01$), meaning longer exposure increased the likelihood of higher discomfort.

In contrast, the derived parameters (pacing frequency (f_p), frequency ratio (FR), and frequency difference ($|\Delta f|$)) were not statistically significant predictors, as their odds ratios were close to 1 and confidence intervals crossed unity, indicating little or no effect on subjective comfort within the tested conditions.

The present study demonstrates that vibration magnitude, frequency, and exposure time are the principal determinants of subjective comfort, whereas derived parameters related gait or its combination with vibration parameters such as pacing frequency, frequency ratio, and frequency deviation did not significantly influence perceived comfort once vibration characteristics were accounted for. The strong effect of vibration magnitude aligns with previous studies reporting that higher acceleration levels consistently intensify discomfort and reduce walking stability on vibrating structures [10, 11]. Similarly, the observed negative association with vibration frequency is consistent with evidence that, under constant acceleration, increasing frequency reduces vibration displacement amplitude, thereby making walking less uncomfortable [10]. The role of exposure time as a significant predictor is particularly noteworthy, as current vibration serviceability standards ISO 10137 and Sétra [1, 3] do not explicitly account for it. This finding is consistent with results from studies of statics postures, where prolonged exposure amplifies the cumulative effect of vibration on perceived discomfort up to certain threshold [13, 14]. Pacing frequency and frequency ratio, often highlighted in pedestrian-structure interaction studies [15] and have been as-

Table 3 Association between subjective comfort ratings and test and derived parameters

	Parameter	β	SE	95% CI for Odds Ratio		
				Lower	Odds Ratio	Upper
Threshold	Not Perceived	-6.438***	0.507	0.001	0.002	0.004
	Comfortable	-1.405***	0.21	0.162	0.245	0.371
	Slightly Uncomfortable	1.138***	0.204	2.09	3.12	4.657
	Moderately Uncomfortable	3.561***	0.301	19.514	35.204	63.508
Predictors	Vibration Magnitude (a_v)	3.006***	0.2309	12.855	20.214	31.785
	Vibration Frequency (f_v)	-1.174***	0.1607	0.226	0.309	0.423
	Exposure Time (T_{exp})	0.843***	0.1373	1.774	2.323	3.04
	Pacing Frequency (f_p)	0.109	0.1278	0.868	1.115	1.432
	Frequency Ratio (FR)	0.038	0.1295	0.806	1.038	1.338
	Frequency Deviation ($\|\Delta f\|$)	0.007	0.1407	0.764	1.007	1.327

β: Regression coefficient. SE: Standard error. CI: Confidence Interval. R^2 = 0.71 (Cox & Snell), 0.75 (Nagelkerke). Model $\chi^2(6) = 345.73$, $p < 0.001$. *** $p < 0.001$

sociated with reduced vibration sensitivity at higher walking speed [9]. The absence of such effects in the present study suggests that vibration sensitivity may be highly individual and influenced by participant-specific factors.

Conclusions

The study highlight the significance of vibration magnitude, frequency, and exposure time in shaping subjective comfort during walking under vertical vibration exposure. These results provide empirical support for existing vibration serviceability guidelines while also emphasizing the need to consider exposure time, which is not explicitly addressed in current standards. Future research involving larger and more diverse participant groups will be essential to validate and generalize these findings, offering a more comprehensive understanding of human comfort under vertical vibrations. Such evidence can contribute to the development of improved vibration design criteria for pedestrian bridges and similar structures.

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