Perceptual Thresholds for Vibration Transmitted to Road Cyclists

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Objectives: In this article, we seek to determine how sensitive road cyclists are to vertical vibration transmitted while riding a road bicycle and to propose metrics for the evaluation of dynamic comfort.

Background: Road cyclists are exposed to random-type excitation due to road roughness. Vibration transmitted affects dynamic comfort. But how sensitive are cyclists to vibration level? What are the best metrics to measure the amount of vibration transmitted to cyclists? Previous studies used sinusoidal excitation with participants on rigid seats and measured acceleration.

Methods: We use a psychophysical estimation of Just Noticeable Differences in Level (JNDL) for vertical vibration transmitted to cyclists on a road simulator. In Experiment 1, we estimate the JNDL for whole-body vibration using vertical excitation on both wheels simultaneously (20 male cyclists). In Experiment 2, we estimate the JNDL at two different points of contact by applying the same signal to only the hands or the buttocks (9 male cyclists).

Results: The JNDLs are expressed in terms of acceleration and power transmitted to the cyclist. We compare the JNDLs expressed with these 2 metrics and measured at different points of contact.

Conclusion: Using these two metrics and at all points of contact, vibration magnitude needs to be reduced by at least 15%, for the change to be detectable by road cyclists.

Application: A road bicycle needs to transmit at least 15% less vibration for male cyclists to detect an improvement in dynamic comfort. Dynamic bicycle comfort can be measured in terms of a new metric: power transmitted to the cyclist.

Keywords: road bicycle, dynamic comfort, vibration, perceptual thresholds, JNDL, transmitted power, acceleration

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INTRODUCTION

The dynamic comfort of road bicycles has become an important design criterion for the cycling industry. Specifically, vibration generated by the road and transmitted to the cyclist has recently garnered increased attention (Giubilato & Petrone, 2012; Hölzel, Höchtl, & Senner, 2012; Olieman, Marin-Perianu, & Marin-Perianu, 2012). Road cyclists are typically exposed to two types of road excitations: random-type excitation mainly related to road roughness and small irregularities, and shock-type excitation caused by potholes and cracks in road surface, or even cobblestones. In this context, road bicycle dynamic comfort (RBDC) is related to the perception of vibration transmitted to the cyclist at the points of contact with the bicycle and must be distinguished from static comfort, which is related to the bicycle's size in relation to the size and shape of the cyclist (Drouet, Guastavino, & Girard, 2016). A wide variety of dynamic tests have been proposed to characterize and compare bicycles (e.g., Lépine, Champoux, & Drouet, 2013, 2014). But to design more comfortable road bicycles, it is essential to know how much vibration attenuation is needed for the improvement to be noticeable by the cyclist. Two recent studies on RBDC have been reported in the literature. Richard, Champoux, Lépine, and Drouet (2015) assessed the Just Noticeable Difference in Level (JNDL) of road bicycle front tire pressure for seven participants using a three-alternative forced-choice (3-AFC) method. Drouet et al. (2016) determined the perceptual threshold in terms of the transmitted energy at the cyclists' hands for the case of two closely spaced impacts at the front wheel of a road bicycle using a two-alternative forced-choice (2-AFC) method. In both studies, shock-type excitation was used. The present study is the first investigation of perceptual thresholds for random-type excitation due to road roughness and irregularities in the context of road cycling.

The amount of vibration transmitted to a cyclist can be evaluated using different mechanical quantities. The most common measure of vibration exposure for both laboratory and outdoor measurements is the acceleration (e.g., International Standardization Organisation, 1997 and previous studies on bicycle comfort cited above). The level of force at the hands and buttocks is also used (Lépine et al., 2014; Lépine, Champoux, & Drouet, 2015; Pelland-Leblanc, Lépine, Champoux, & Drouet, 2014). More recently, the power and energy transmitted at the cyclist's hands and buttocks have been proposed (Drouet et al., 2016; Lépine et al., 2015; Pelland-Leblanc et al., 2014; Richard et al., 2015; Vanwalleghem et al., 2012). Preliminary laboratory and outdoor tests have shown that acceleration and force tend to be more influenced by the cyclist's natural position sway than power and energy (Lépine et al., 2015; Richard et al., 2015). Because it is less affected by the position of the cyclist on the bicycle, the power transmitted to the cyclist should be preferably used to assess comfort for the case of random-type excitation (Drouet et al., 2016). For shock-type excitation, however, the energy transmitted to the cyclist is a more effective measure, since it integrates the magnitude and duration of each impact independently of measurement duration (Drouet et al., 2016).

To our knowledge, there are no studies available about perceptual thresholds for whole-body vibration using transmitted power, especially in the context of road cycling, with the exception of preliminary findings of the present study (Ayachi, Champoux, Drouet, & Guastavino, 2016). JNDLs for whole-body vibration have been reported in the literature in terms of acceleration (e.g., Bellmann, 2002; Forta, Morioka, & Griffin, 2009; Matsumoto, Maeda, & Oji, 2002). Most of the studies measured JNDLs for whole-body vibration using sinusoidal excitation with participants sitting on a car seat or a rigid flat seat. Some studies (Morioka & Griffin, 2000; Pielemeier, Otto, Meier, & Jeyabalan, 1997; Weber, Baumann, Bellmann, & Mellert, 2001) found the JNDLs were independent of vibration frequency.

In this paper, we report two experiments conducted to estimate vibration JNDLs in terms of acceleration and power transmitted to the cyclist's hands and buttocks using random-type excitation at the bicycle wheels. This is the first time random-type excitation has been used for JNDL assessment regarding RBDC. The JNDLs were assessed using the psychophysical method of constant stimuli (Gescheider, 1997).

The present experiments focus on two different aspects of whole-body vibration perceived by experienced male road cyclists. Experiment 1 estimates the JNDLs for whole-body vibrations using vertical excitation on both wheels simultaneously. In this experiment, both hands and buttocks are exposed to vibration. In Experiment 2, we estimate JNDLs at different points of contact by applying the same excitation signal used in Experiment 1 in turn to the front wheel or to the rear wheel. Only the hands are exposed to vibration when the excitation is applied to the front wheel, whereas vibration is transmitted to buttocks only when the excitation is applied to the rear wheel. Experiment 2 aims to determine whether there is a difference in the overall JNDL (whole-body vibration) and the JNDLs at the hands and at the buttocks (measured separately). The design of these experiments is based on the results of a previous online survey on bicycle comfort (Ayachi, Dorey, & Guastavino, 2015) in which cyclists reported being most affected by vibration transmitted through the handlebar and the saddle. Thus, the vibration levels were examined at the hands and at the buttocks. The vibration transmitted through the feet was not considered because the contact force at the pedals is for propulsion and was not found to influence comfort evaluations in Ayachi et al. (2015).

The article is organized as follows. First, we outline the methods used to estimate the JNDLs. Then, we describe the experimental setup for the experiments (Experiment 1: Whole-body vibration; Experiment 2: Isolated points of contact). The results are then presented and discussed. Finally, we conclude and present perspectives for future work.

METHODS

This section describes the experimental setup and signal acquisition material used as well as the participants and procedure. This research complied with the tenets of the Declaration of Helsinki and was approved by the Institutional Review Board at Université de Sherbrooke and McGill University. Informed consent was obtained from each participant.

Psychometric Function (PF)

The raw data resulting from a psychophysical experiment are the proportions of correct responses, y, measured at a number of different stimulus intensities, x. Let K denote the number of block/data points of experimental trials at the same stimulus level, n the number of trials in each block, and N the total number of experimental trials: $N = \sum_{i=1}^{K} n_i$.

The fitting procedure is based on maximum likelihood combined with bootstrap sampling to determine confidence intervals, as suggested by Wichmann and Hill (2001a, 2001b). The psychometric curve was modelled using a binomial mixture as suggested by Wichmann and Hill (2001a, 2001b):

$$\Psi(x,\theta) = \gamma + (1 - \gamma - \lambda) \cdot \Im(x,\theta) \qquad (1)$$

with parameter vector $\theta = \theta$ (α, β, γ, λ), where α denotes the location parameter (threshold), β the slope parameter, γ the lower asymptote determined by the psychometric procedure (50% in a 2-AFC), and λ the upper asymptote (ceiling performance). The fitting procedure estimates the parameter values that best matched the experimental data. We used a maximum likelihood procedure combined with bootstrap sampling to determine the confidence interval, as suggested by Wichmann and Hill (2001a). Four sigmoid functions were tested, and we selected the Weibull function as it best matched our experimental data according to the criterion of deviance, with values for all participants within the 95% confidence interval.

A summary of the fitting method is outlined below (Wichmann & Hill, 2001a, 2001b):

- conduct the experiment to obtain the data set $Y = (y_1, y_2, \rightleftharpoons y_n)$ and calculate the estimate $\hat{\theta}$ from Y.
- B datasets, y_i^*, are generated using the PF resulting from the maximum likelihood estimation.
- For each $\mathrm{I} = (1, 2, \rightleftharpoons B)$ generated datasets for y_i^*, the Deviance, D_i^*, is calculated to get the deviance distribution, D_i, which is the deviance expected from binomially distributed correct responses with probability of success equal to $\psi(\mathrm{x}, \hat{\theta})$.
- Determine the two-sided confidence interval for deviance using the standard percentile method where a two-sided confidence interval can be represented as $[D^{*(0.025)}, D^{*(0.975)}]$.

Observed values of D_{empir}^* outside the 95% confidence interval indicate a poor fit.

Experimental Setup

Road simulator and apparatus. All measurements were carried out in a controlled laboratory environment, using a road excitation simulator developed by VÉLUS Laboratory (University of Sherbrooke) for testing road bike dynamic behavior (Lépine et al., 2013). The same carbon fiber road bicycle was used for all the tests (Cervélo R3—size: 56 cm; Fulcrum 7 wheels—size: 700C; Vittoria Rubino Pro tires—width: 23 mm, pressure: 8 bar). Two Xcite model 1100-7-4-T/C hydraulic shakers were used to impose a vertical displacement under each wheel as shown in Figures 1 and 2. The excitation signals were purely vertical (along the z axis) and were selected to represent the vertical excitation that the bike undergoes when rolling on a granular road at a speed of 26 km/h as measured and described by Lépine et al. (2013).

The bicycle was held in a vertical position with horizontal bungees attached near the seatpost clamp and to a lab fixture. The bungee cords were selected to be compliant enough not to affect the vibration measurement but stiff enough to hold the cyclist riding the bicycle in a vertical position. The cyclist was not asked to pedal. We measured the vibration transmitted to the cyclist at two points of contact—namely, the hands and the buttocks. The force and the acceleration transmitted to the cyclist's hands were respectively measured with a strain gauge instrumented brake hood and a PCB 352C68

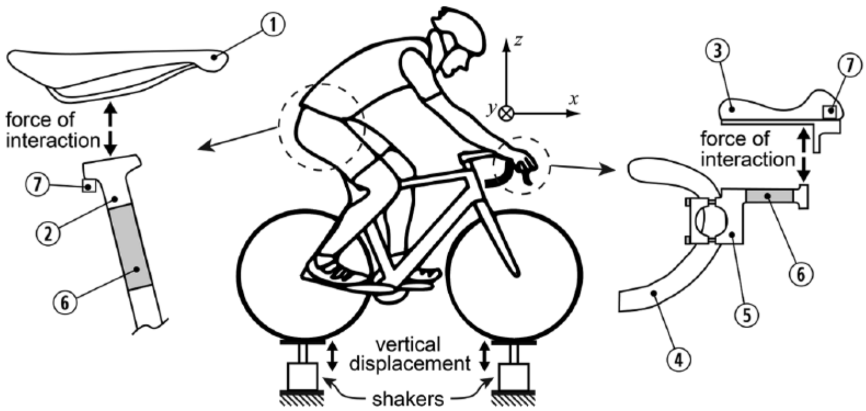

Figure 1. Set-up for Experiment 1: Road simulator was equipped with two shakers for bicycle vibrational transmissibility assessment. The bicycle is equipped with an instrumented seat post and instrumented brake hoods. 1-saddle; 2-seat post; 3-hand rest; 4-handlebar; 5-brake hood body; 6-strain gauges area; 7-accelerometer.

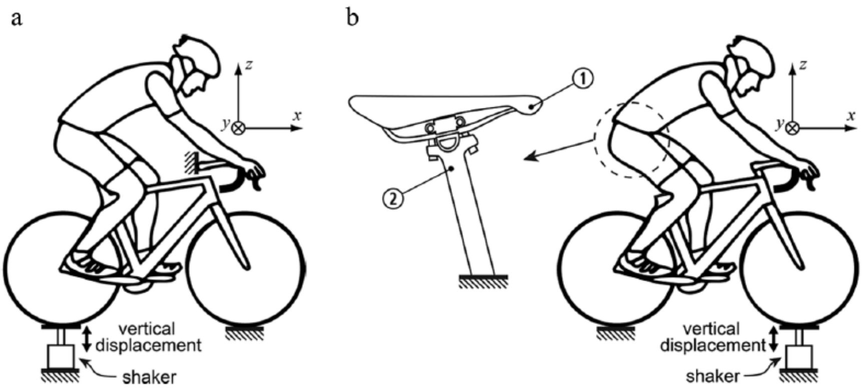

Figure 2. Set-ups for Experiment 2: (a) Case 1: Isolation system for the hands with excitation of the rear wheel only and with the handlebar stem decoupled from the bicycle and attached to an external support. The instrumented seat post is used to measure vibration at the buttocks. (b) Case 2: Isolation system for the buttocks (1-saddle, 2-noninstrumented seat post) with excitation of the front wheel only and with the seat post decoupled from the bicycle and attached to an external support. The instrumented brake hoods are used to measure vibration at the hands. The hatch marks indicate the ground.

accelerometer under the hands (Lépine et al., 2015; Figure 1). Similarly, for the buttocks, we used a PCB 352C68 accelerometer at the saddle–seat post connection and a strain gauge (force measurement) instrumented seat post (Lépine et al., 2015; Figure 2).

An LMS SCADA Recorder, a 24-bit acquisition system (model SCR01-08B), and LMS Testlab software were used to acquire data (sampling frequency: f_s = 8,192 Hz). The mean transmitted power measurement can be computed in either the time or the frequency domain. The mean transmitted power P is the time average over a number of observations N of the instantaneous power $P_i = F_i v_i$ as given by Equation 2, where F_i and v_i (obtained by integrating the

TABLE 1: The Stimulus Levels and Increment Steps According to the Ratio Between the Test and Reference Signals

Stimulus	Ratio (Test-Ref)	Δ-Level (m/s^2) Mean Value	Δ-Level (db) Mean Value
Reference	12.7 (m/s^2)	—	—
1	0.96	0.5	0.25
2	0.93	0.76	0.6
3	0.9	1.25	0.91
4	0.86	1.6	1.1
5	0.84	1.75	1.5
6	0.75	2.6	2.5
7	0.58	5.1	4.8

Note. $N(dB) = 20\log_{10}(a/a_0)$ with $a_0 = 10^{-6} m/s^2$.

acceleration signal) are, respectively, the instantaneous vertical force (force of interaction; Figure 2) and speed:

$$P = \frac{1}{N}\sum_{i=1}^{N} F_i v_i. \qquad (2)$$

Furthermore, the total power transmitted to the cyclist's whole body represents the sum of the power transmitted at the different points of contact—namely, the hands and the buttocks.

The set-up for Experiment 1 (whole-body vibration) is shown in Figure 1. The set-ups for Experiment 2 (isolated contact points) are shown in Figure 2, for which we have two cases:

Case 1—Isolating the hands: We excite only the rear wheel to assess the amount of the vibration transmitted to the cyclist at the buttocks (Figure 2a).

Case 2—Isolating the buttocks: We excite only the front wheel for the measurement of the vibration transmitted to the cyclist at the hands (Figure 2b).

Participants and Procedure—Experiment 1: Whole-Body Vibration

Twenty experienced road cyclists (all male, mean age = 37 ± 14 years, mean height = 183 ± 6.5 cm, mean weight = 77.89±10 kg, more than 2,000 km of cycling experience) were recruited from cycling clubs and tested individually while sitting in a comfortable position on the bike. On each trial, they were presented with two stimuli and asked to indicate which one had the greater intensity. One of two stimuli was the original road signal (referred to as "reference" throughout the article), and the other one was a comparison corresponding to seven different stimulus intensities, which were all less than the reference (see Table 1). The stimuli levels were determined after pilot testing various configurations to ensure that participants would reach a ceiling performance in the easiest condition and chance level on the most difficult condition, as this is needed for the estimation of perceptual thresholds.

An AB comparison task (2-AFC) procedure was used. The experiment was divided into seven experiment blocks. One block contained 40 trials (n = 40). Each trial consisted of a 3-second "reference" stimulus, followed by a 1-second pause, followed by a 3-second "comparison" stimulus. The intensity of the reference stimulus was fixed throughout the experiment; the intensity of the comparison stimulus varied. We counterbalanced the order of presentation within the trial (2 presentation orders for reference/comparison and comparison/reference) and across trials to nullify order effect. In summary, we have 7 stimuli pairs × 2 presentation orders × 20 repetitions for a total of N = 280 trials per participant. The participants took 45 to 60 minutes to complete the experiment.

After each trial, the participant responded to the question, "Which of the two signals has the greater intensity?" The participants indicated verbally either "first" or "second"; the experimenter noted their responses before moving on to the next trial. Additionally, to mask the background noise generated by the road simulator, the participants were presented with pink noise over headphones during the entire duration of the test (bandpass noise 20–20,000 Hz at 70 dB).

Participants and procedure—Experiment 2: Isolated points of contact. Nine cyclists (9 out of the initial 20 participants from Experiment 1) were recruited to estimate the JNDLs at the hands and at the buttocks and compare them with the overall JNDLs for whole-body vibration estimated in Experiment 1. To do so, we used the same procedure as above except for the excitation signal: Here, we stimulated independently the two different contact points with an excitation signal inputted only at the front or the rear wheel. Considering the cross-coupling from the input at the wheel to the contact points through the bike frame, a new input signal was used in Experiment 2. This signal inputted at the rear or front wheel, respectively, was designed to reproduce the acceleration signal measured at the buttocks or hands in the previous whole-body vibration case during Experiment 1. Thus, we have two cases:

1. Isolating the hands: We excite only the rear wheel using this new signal to assess the amount of the vibration transmitted to the cyclist at the buttocks (see Figure 2a).
2. Isolating the buttocks: We excite only the front wheel for the measurement of the vibration transmitted to the cyclist at the hands (see Figure 2b).

RESULTS AND DISCUSSION

The JNDL for vibration is estimated from individual PFs. The PF relates the performance of individual participants to the intensity of the stimuli (Gescheider, 1997). Here we calculated the proportion of times that the reference was judged to have a greater intensity than the comparison, and these proportions were fitted with a Weibull function free to vary in position and slope using the software package psignifit for MATLAB (Wichmann & Hill, 2001a). Examples of a PF and its fit for one participant are shown in Figure 3. The PF curve increases from $P(L)$ = 50% (chance level) to 100% (correct response for all trials). For each participant, the individual JNDL was estimated as the stimulus level corresponding to 75% correct responses based on the fitted curve. The overall JNDLs are obtained by averaging individual JNDLs across participants.

Relative JNDLs, or Weber fractions, were calculated by dividing individual JNDLs by the corresponding reference level, as measured at the particular point of contact (i.e., hands or buttocks) for each participant and reported in Table 2. The Weber fractions were estimated as follows:

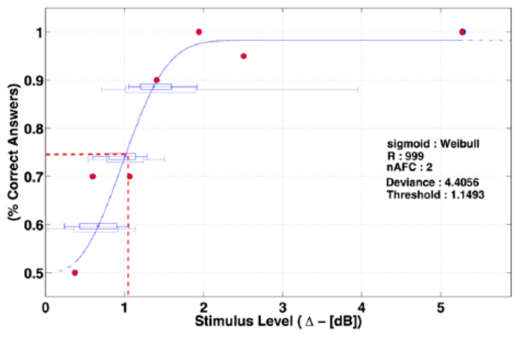

Figure 3. Psychometric curve of a participant estimated using a Weibull function with a 95% confidence interval expressed in dB. The JNDL is estimated as the stimulus level corresponding to 75% correct responses (dotted red line). The error bars represent the estimated variability of parameters, thresholds, and slopes of psychometric functions, obtained from different iteration using bootstrap sampling.

TABLE 2: Average Intensity Values of the Reference Stimulus *I*, Measured Across the 20 Participants

	Experiment 1 (Mean Vibration Level)	
I-Ref Signal	Hands	Buttocks
L_{vib} (m/s^2)	12.7	8.7
L_{vib} (dB)	142	138.8
L_{vib} (W)	1.1	3.2

- For the acceleration and Power metrics, we divided the absolute JNDL of each participant by the measured individual reference stimulus signal.
- For the logarithmic level (dB), we relied on logarithmic level stimulus, $N(dB) = 20\log_{10}(a/a_0)$ with $a_0 = 10^{-6}$m/s^2, instead of the acceleration value in the stimulus-level axis.

Experiment 1: Whole-body vibration—JNDLs in terms of acceleration. In the present study, the JNDLs are measured within a frequency range from 5 Hz to 100 Hz for vertical whole-body vibrations with a reference level of L_{Vib} = 140 dB (corresponds to a = 14 m/s^2 RMS). The mean values and the interindividual standard deviation of

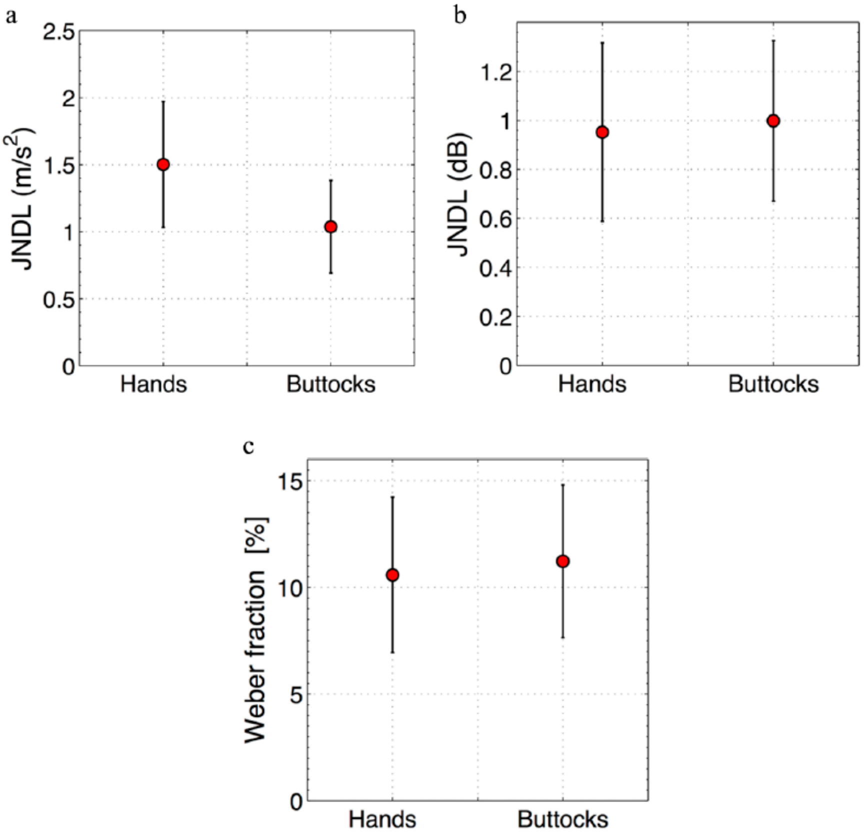

Figure 4. Results of Experiment 1. Mean JNDLs and standard deviations are expressed in terms of acceleration (20 participants). (a) Absolute JNDL expressed in m/s^2, (b) absolute JNDL expressed in dB, and (c) relative JNDL/Weber fraction expressed in percentage.

the JNDLs are presented as a function of different points of contact (hands and buttocks) for the 20 participants in Figure 4. It should be noted that for acceleration measured at the hands, we considered the JNDL measured at the right hand of each participant. The results show a level difference of about 0.95 dB at the hands (mean = 0.95 ± 0.43 dB) and 0.99 dB at the buttocks (mean = 0.99 ± 0.3 dB) (see Figure 4b). There were no significant differences between the measured JNDL at the hands and the buttocks ($p = 0.17$, Friedman test).

These JNDLS are comparable with those obtained by Mansfield and Griffin (2000) using a rigid seat (0.9 to 1 ± 0.57 dB at a reference level of 100 and 114 dB [0.1 and 0.5 m/s^2 RMS]). Studies on vibrations transmitted to a car seat report values in a similar range (Bellmann, 2002: 1.5 ± 0.06 dB; Pielemeier et al., 1997: 0.6 dB to 1.8 dB; Weber et al., 2001: 1.6 dB).

The results in Figure 4a show that the JNDL mean value, for the 20 participants, is about 1.5 m/s^2 RMS with a standard deviation of about 0.46 at the hands (median = 0.9 m/s^2 RMS, interquartile = 0.5) and 1.03 m/s^2 RMS with a standard deviation of about 0.3 at the buttocks (median = 1.025 m/s^2 RMS, interquartile = 0.4). The analysis of data for the absolute JNDL shows a significant difference between the JNDL measured at the hands and the buttocks ($p < 0.05$, Friedman test).

Figure 4c shows the relative JNDL (Weber fractions), expressed as a percentage, for the 20

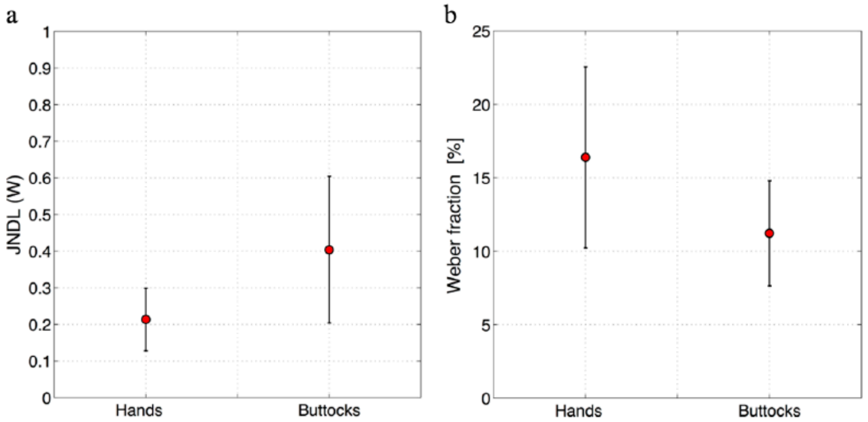

Figure 5. Results of Experiment 1. Average value and standard deviation of the whole-body vibration JNDL using transmitted power (20 participants): (a) absolute JNDL expressed in watts and (b) relative JNDL/Weber fraction expressed in percentages.

participants. The thresholds varied across participants between 8.5% and 18.5% for the buttocks (mean = 11.23 ± 3.5%) and 6% and 19% for the hands (mean = 10.58 ± 3.6%). No significant differences were observed between the JNDL measured at the hands and the buttocks ($p < 0.35$, Friedman test). The Weber fractions determined in this study are in line with those obtained in previous studies with more restricted ranges of vibration magnitude. Indeed, Mansfield and Griffin (2000) reported a Weber fraction around 13% for car seat vibration (broadband noise) independently of the magnitudes (0.2, 0.4, and 0.8 m/s^2 RMS). Bellmann (2002) reported Weber fractions between 15% and 20% for 10, 20, and 40 Hz when using vertical vibration at 0.063 m/s^2 RMS. Forta et al. (2009) reported Weber fractions between 9.5% and 20.3% for vertical whole-body vibration of seated participants with frequencies ranging between 2.5 and 315 Hz.

Experiment 1: Whole-body vibration—JNDLs in terms of transmitted power. In the present study, the JNDL is expressed in terms of transmitted power, as measured in a frequency range from 0.5 Hz to 100 Hz for vertical whole-body vibration with a reference level $L_{\text{Buttocks}} = 3.2 \pm 0.5$ W at the buttocks and $L_{\text{Hands}} = 1.1 \pm 0.18$ W at the hands collapsing over all 20 participants. The absolute difference threshold (JNDL) is shown in Figure 5a. The JNDL at the hands varied between participants over the range 0.17 W and 0.44 W, with a median threshold of 0.19 W (mean = 0.21 ± 0.08 W). The JNDL at the buttocks varied between participants over the range 0.12 W and 0.76 W with median threshold of 0.37 W (mean = 0.41 ± 0.19 W). The JNDLs assessed at the buttocks were significantly greater than the JNDLs at the hands ($p = 0.0003$, Wilcoxon-Mann-Whitney). However, when considering the relative JNDL (Weber fractions; shown in Figure 5b), expressed as a percentage, no significant difference was observed ($p = 0.084$, Wilcoxon-Mann-Whitney) between the buttocks (mean = 13.94% ± 4.5%) and the hands (mean = 16.27% ± 6%). A comparison with the literature is not possible because there are no studies about perceptual thresholds for vertical whole-body vibrations, using transmitted power in the literature or in existing standards.

Experiment 2: Isolated points of contact—JNDLs in terms of transmitted power. Experiment 2 aims to determine whether there is a difference in the overall JNDL (Experiment 1—whole-body vibrations) and the JNDL at the hands and at the buttocks measured separately (Experiment 2). Based on the definition of the power transmitted to the cyclist given by Equation 3, we can quantify the total power transmitted to the cyclist by summing the power transmitted at different points of contact (i.e., in

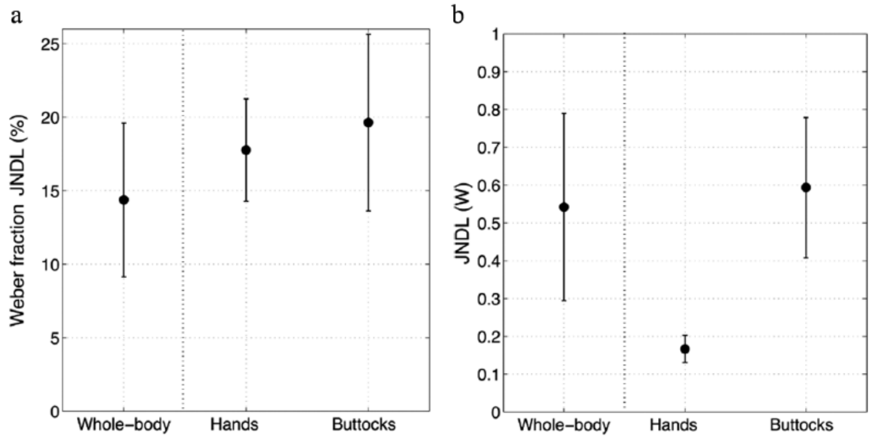

Figure 6. Comparisons between the results of Experiment 1 (whole body) and Experiment 2 (hands, buttocks). Mean value and standard deviation of the whole-body JNDL using transmitted power assessed over 9 common participants. (a) Absolute JNDL expressed in watts and (b) relative JNDL/Weber fraction expressed in percentages. No significant difference between the JNDL (using transmitted power) for vibration transmitted to the whole body and at different contact points separately was observed.

our case at the buttocks and at the hands). Unlike power, summing the acceleration at different points of contact to quantify the total acceleration transmitted to the body has no physical meaning. We will thus hereafter assess the JNDLs only in terms of transmitted power.

In Experiment 2, the JNDLs are measured in a frequency range from 0.5 Hz to 100 Hz for vertical whole-body vibrations with a reference level $L_{\text{Buttocks}} = 3.0 \pm 0.3$ W at the buttocks and $L_{\text{Hands}} = 0.86 \pm 0.19$ W at the hands computed over the nine participants who participated in both Experiment 1 and Experiment 2. The reference ("standard" stimuli) excitation signal for Case 1 (excitation at the rear wheel, top left; Figure 3a) is $L_{\text{Buttocks}} = 3.12$ W and for Case 2 (excitation at the front wheel, bottom left; Figure 3b) is $L_{\text{Hands}} = 0.88$ W.

Comparing the different points of contact (see Figure 6a), JNDLs were higher at the buttocks (0.59 ± 0.18 W) than at the hands (mean = 0.17 ± 0.03 W) and whole body (0.54 ± 0.20 W). There were significant differences between the measured JNDL at the hands and the buttocks ($\chi^2(2,26) = 17.35$, $p = 0.0002$, Kruskal-Wallis).

But when looking at the relative JNDLs (Weber fractions shown in Figure 6a), there is no significant difference between the buttocks and the hands (p value > 0.05, Mann-Whitney), or between the whole body and the isolated points of contact (p value > 0.05, Mann-Whitney). Therefore, it is concluded that JNDLs for vertical vibration are consistent with Weber's Law, which states that the size of a just noticeable difference is a constant proportion of the original stimulus value (here 15% to 20%).

Generally, the results obtained are in line with previous findings, despite methodological differences in terms of experimental setup and stimuli. Indeed, in previous studies, participants were seated on a car seat or a rigid seat and exposed to sinusoidal vibration. Furthermore, a direct comparison with previous studies has to take in consideration differences in terms of the estimation methods used (fixed comparison vs. adaptive methods) and the expertise of our participants who were all male road cyclists with many years of experience. Future research will extend this investigation to female road cyclists as well as other excitation signals to test the generalizability of our findings.

CONCLUSION

We reported a psychophysical laboratory experiment conducted to estimate JNDLs for vertical vibration perception transmitted to male cyclists riding on a road simulator. The results contribute to the establishment of metrics for bicycle comfort and yield new insights on evidence-based design requirements for more comfortable road bicycles. Specifically, we propose to use the power transmitted as a metric to assess dynamic comfort with random-type excitation as it is less affected than other mechanical quantities (acceleration or force) by the position of the cyclist on the bicycle (Pelland-Leblanc et al., 2014). The extent to which acceleration and transmitted power could be used as metrics for other types of excitations, such as impacts, remains to be investigated in future research. On practical grounds, our results indicate that for random-type excitation, using the two metrics, acceleration or the transmitted power, vibration magnitude will need to be reduced by about 15% (Weber fractions), for the change to be detectable by experienced male road cyclists.

APPENDIX

Instructions for Participants

- The aim of this experiment is to determine the difference threshold for vertical sinusoidal whole-body vibration.
- Before the experiment, the acceleration condition will be calibrated. During the calibration, you will sit in the seat.
- After the calibration, the experiment will be started. You will feel two vibration stimuli, then you will be asked: "Which of the two signals has the greater intensity?" Your task is to answer, either "first" or "second."
- Stimuli will be presented several times.
- Please maintain the posture and concentrate on the stimuli during the measurement.
- Seven measurements will be performed; it will take about 10 to 15 minutes for each.

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KEY POINTS

- First study to investigate human sensitivity to vibration in the context of road cycling.
- Estimated JNDLs for vertical vibration perception transmitted to experienced male cyclists on a road simulator estimated for whole-body vibration and at two different points of contacts (hands and buttocks). The JNDLs are expressed in terms of acceleration and power transmitted to the cyclist.
- Using these two metrics, vibration magnitude needs to be reduced by about 15% for the change to be detectable by cyclists.
- These results contribute to the establishment of metrics for bicycle comfort and yield new insights on evidence-based design requirements for more comfortable road bicycles.

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