Validation of Intra-Subject Variation in Biodynamic Responses of Seated Human Exposed to Whole-Body Vibration*

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Abstract
Many studies have been conducted to investigate the change in human response under various experimental conditions. Usually, these experiments were conducted using many subjects and the inter-subject variation was evaluated. However, the intra-subject variation in human response is also necessary for understanding the change in an individual’s physical response to whole-body vibration (WBV). The aim of this study is to investigate the intra-subject variation in biodynamic responses (both apparent mass and seat-to-head transmissibility) of a seated human exposed to vertical whole-body vibration over time. In the experiments, nine male subjects were exposed to vertical random vibration (0.2-0.3 m/s² in r.m.s.) in the 0-30Hz frequency range. The measurement variation was also evaluated, wherein the measurements were repeated five times without any change to form the “baseline” for each subject, and the intra-subject variations were evaluated by comparing their responses with these “baseline.” The intra-subject variation was examined from two different viewpoints: variation “within a day” and that “over several days.” To determine the intra-subject variation “within a day”, the five measurements were obtained at two-hour intervals on the same day. In the intra-subject variation “over several days”, the five measurements were obtained again, but at the same time of the day on five consecutive days. The results show that the intra-subject variations (both “within a day” and “over several days”) in biodynamic responses are larger than the “baseline.” However, when the variation “within a day” in biodynamic responses is compared to that “over several days,” no common trend is observed among subjects. Although the magnitude of intra-subject variation in biodynamic responses depends on each subject, both variations “within a day” and that “over several days” have a similar range of variation.

Key words: Whole-Body Vibration, Seat-to-Head Transmissibility, Apparent Mass, Intra-Subject Variation

1. Introduction

Human body responses to whole-body vibration (WBV) have been studied either from the view of “to-the-body” relationship at the human-seat interface in terms of apparent mass or from the view of “through-the-body” relationship between the input (seat or floor) and the output (head) in terms of transmissibility, e.g., seat-to-head transmissibility (1)(5). The data of human response in these functions can be evaluated by using either an inter-subject variation or an intra-subject variation. In general, the inter-subject variation refers to the
physical difference between subjects, e.g., body mass, age and gender, while the intra-subject variation refers to the change in an individual’s response over time, either from one moment to another or over a much longer period\(^1\). Many studies investigated the change in human responses under various experimental conditions, in which experiments were conducted under various experimental conditions using many subjects and the inter-subject variation was evaluated\(^4\)\(^\text{-}\)\(^\text{13}\). In ISO 5982, the biodynamic responses of a seated human are also based on inter-subject variation when the subjects exposed to WBV at different excitation amplitudes or different postures\(^1\)\(^\text{-}\)\(^\text{7}\).

On the other hand, the research on the intra-subject variation in two types of biodynamic responses (both apparent mass and seat-to-head transmissibility) has rarely been reported\(^3\)\(^\text{-}\)\(^\text{4}\). When the effect of vibration to the human is considered, the intra-subject variation is also necessary to understand the change in human response of a seated human exposed to WBV. For example, from the human fatigue viewpoints, the assessment of intra-subject variation is necessary to understand if the biodynamic responses of a seated human exposed to WBV changed over time. For comparing the different seats, it is also necessary to observe if the biodynamic responses of a seated human differs depending on the seat. A preliminary study was performed to investigate the measurement variations and intra-subject variations in the seat-to-head transmissibility of a seated human exposed to vertical random vibration\(^14\). However, the acquired results of intra-subject variations in a preliminary study need to be validated through the number of participants are increased.

The aim of this study was to investigate the intra-subject variation in the seat-to-head transmissibility of a seated human exposed to WBV over time and the intra-subject variation in apparent mass was also evaluated. Furthermore, the experimental design was also somewhat modified by the intra-subject variation section in a preliminary study. Both the intra-subject variations (“within a day” and “over several days”) were evaluated using the same number of samples: the intra-subject variation “within a day” was measured five times in a day, with two-hour intervals between each measurement on the same day, while the intra-subject variation “over several days” was measured at the same time of the day on five consecutive days.

2. Method

2.1 Experimental design

Nine healthy male subjects aged between 23 and 33 years participated in the experiment. All subjects were students with no history of occupational exposure to whole-body vibration. The body mass of the subjects ranged from 56 to 84 kg (mean body mass of 66.3 kg, SD 7.5 kg) and the body height was between 164 and 182 cm (mean stature of 171.8 cm, SD 6.2 cm). Physical characteristics of the subjects are summarized in Table 1. They sat in a comfortable upright posture with hands lightly resting on the thighs, without backrest, with feet supported, looking straight ahead.

<table>
<thead>
<tr>
<th>N = 9</th>
<th>Age (year)</th>
<th>Mass (kg)</th>
<th>Stature (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>23</td>
<td>84</td>
<td>164</td>
</tr>
<tr>
<td>Maximum</td>
<td>33</td>
<td>56</td>
<td>182</td>
</tr>
<tr>
<td>Mean</td>
<td>25</td>
<td>66.3</td>
<td>171.8</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>4.1</td>
<td>7.5</td>
<td>6.2</td>
</tr>
</tbody>
</table>

An electromagnetic vibrator (Model F-200 BM/A, EMIC Ltd., Japan) was used to generate vertical random vibration at frequency 0-30 Hz, and acceleration data was acquired.
using the Dewtron-3016 (Type Dewtron-3016, Austria). The magnitude of vibration was 0.2-0.3 m/s² in r.m.s. and the duration of the exposure was 60 s, which is within acceptance of ISO13090-1(1998). In order to keep the constant power spectrum density of input vibration at frequency 0 to 30 Hz, the input vibration signal was regenerated by the signal processing system (Labview, NI Ltd, USA) and the input vibration signal and magnitude are determined by referring to the floor vibration during car driving. All experimental procedures were approved by the Research Ethics Committee in Tokyo Metropolitan University. The force plate (Kistler 9286 A, Japan) was mounted on the rigid seat (Figure 1(b)) and the acceleration in the z-direction was measured on the seat surface using an accelerometer (Type 356A32, PCB Piezotronics, USA). The vibration of the head was measured using the head gear and the force at the seat surface was measured by the force plate. The head gear was used to measure tri-axial translations and tri-axial rotations of head motion with respect to the center of the head. They were estimated by using three tri-axial accelerometers (A, B, and C) as shown in Figure 1(a).

![Image](image-url)

Fig. 1 Three tri-axial accelerometers ((A–C)) located on the head gear (a) one on the forehead and one above each ear, and the force plate located on the rigid seat (b).

### 2.2 Experimental procedure

Before the intra-subject variations were obtained, the measurement variation was also evaluated by taking measurements five times in a row without any change, which established the “baseline” for each subject. When considering the change in human response of a subject exposed to WBV, the data acquired from experiments involves the measurement variation, the intra-subject variation and the human response. Without evaluating the measurement variation and the intra-subject variation in the acquired data, it is difficult to judge if the human response changes due to WBV. This study investigates how much human has intra-subject variation within a day or over several days. Therefore, for observation of extent of the intra-subject variations in biodynamic responses (“within a day” and “over several days”), it is necessary to compare the intra-subject variations with the “baseline” (measurement variation). Table 2 indicates the schedule of measurements in the experiments. Table 2 shows that the “baseline” is a common part between variation “within a day” and “over several days”. The “baseline” can be used for comparing two different intra-subject variations. The reason is that if the different baseline is used for evaluation of intra-subject variations, both intra-subject variations can not be evaluated at the same condition. To determine the intra-subject variation “within a day” in biodynamic responses, five measurements were obtained at two-hour intervals on the same day. In the intra-subject variation “over several days” in biodynamic responses, five measurements were also obtained at the same time of the day for consecutive five days. Subjects maintained good reproducibility of posture at measurement. The posture of subject was checked against checklist: check the hip location, knee angle, hands location and check ear location relative to the vibrator using a laser pointer, which was focused on the ear at the first measurement.
and had been fixed. Take a photo from the side at each measurement so that reproducibility of the posture can be checked afterward at each measurement. During experiments, we requested that subjects did not change their respective lifestyles and to avoid extreme exercise, heavy drinking and poor sleep during the experiments. The reason is that the intra-subject variations over time can be affected by human behavior and environmental factors.

Table 2 Schedule of measurements in three conditions

<table>
<thead>
<tr>
<th>Time</th>
<th>Day 1</th>
<th>Day 2</th>
<th>Day 3</th>
<th>Day 4</th>
<th>Day 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>10:00</td>
<td>“baseline”</td>
<td>“over several days”</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12:00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14:00</td>
<td>“within a day”</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16:00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18:00</td>
<td></td>
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</tr>
</tbody>
</table>

2.3 Analysis methods

The vibration stimulus was vertical direction and this study focused on the biodynamic responses in the z-direction. Apparent mass and seat-to-head transmissibility are usually defined by:

\[ M(f) = \frac{F(f)}{a_{\text{seat}}(f)} \]

where \( M(f) \) is apparent mass, \( F(f) \) is force, and \( a_{\text{seat}}(f) \) is acceleration at the seat at frequency, \( f \)

\[ T(f) = \frac{a_{\text{head}}(f)}{a_{\text{seat}}(f)} \]

where \( T(f) \) is the seat-to-head transmissibility, \( a_{\text{seat}}(f) \) is the acceleration at the seat, and \( a_{\text{head}}(f) \) is the acceleration at the head at frequency, \( f \). The time domain data are converted to the frequency domain by Fourier transform. Frequency analysis was carried out at a resolution of 0.1227Hz. Further, the biodynamic responses (seat-to-head transmissibility and apparent mass) are evaluated as a complex ratio of cross spectrum density between the input (vertical seat acceleration) and the output (vertical head acceleration or force), to the power spectrum density of the input:

\[ G(f) = \frac{S_{ab}(f)}{S_{aa}(f)} \]

where, \( G(f) \), \( S_{ab}(f) \), and \( S_{aa}(f) \) are the biodynamic responses, the cross spectrum density between the input (seat : a) and the output (head or force : b), and the power spectrum density of the input (seat : a), respectively. The following procedure was applied for evaluating the variation:

The averaged biodynamic responses (both transmissibility and apparent mass) \( \overline{G(f)} \) were calculated as a complex arithmetic mean, where \( N \) is the number of averages (\( N=5 \)):

\[ \overline{G(f)} = \frac{1}{N} \sum_{i=1}^{N} G_i(f) \]

The standard deviation (\( \sigma \)) was calculated using the modulus (both transmissibility and
apparent mass) at each frequency \( f_k \)

\[
\sigma(f_k) = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} \left( |G_i(f_k)| - |G(f_k)| \right)^2}
\]

(5)

where \( G_i(f_k) \) is a modulus (of transmissibility or apparent mass) at the \( i \)-th measurement. Equation (5) is formulated in order to evaluate the variation of modulus of biodynamic responses. In this study the total value of standard deviation (\( \sigma_{\text{total}} \)) is formulated to assess the variation of transmissibility or apparent mass within the frequency range of interest.

The total value of standard deviation (\( \sigma_{\text{total}} \)) is given by

\[
\sigma_{\text{total}} = \left[ \frac{1}{n} \sum_{k=1}^{n} \sigma_k^2(f_k) \right]^{1/2}
\]

(6)

where \( \sigma_k(f_k) \) is the standard deviation at the particular frequency \( f_k \), and \( n \) is the number of frequency lines within the range of interest.

To observe the distribution of variation within the frequency range of interest, the variation index (\( VI \)) is formulated using those functions (15):

\[
VI(f) = \frac{G(f)}{\sqrt{G(f)^2 + \sigma^2(f)}}
\]

(7)

where \( \sigma(f) \) equals the standard deviation at the frequency. The value of \( VI \) will show values between 0 and 1: a \( VI \) of 0 would indicate large variation at a particular frequency \( f \), whilst, a value of 1 would indicate no variation at a particular frequency \( f \). Therefore, this function can be used like a coherence function.

3. Result

3.1 Intra-subject variations (“within a day” and “over several days”) in seat-to-head transmissibility

Figure 2 shows “within a day” intra-subject variation with a single subject (subject E), evaluated by measurements repeated five times with two-hour intervals within a day, while Figure 3 indicates “over several days” intra-subject variation for the same subject, evaluated by measurements taken at the same time of the day for five days. It shows that when the intra-subject variations (both “within a day” and “over several days”) are compared with the “baseline,” the intra-subject variation shows larger variation at the high-frequency range and this tendency is evident for all subjects. It distinctly reveals that the value of \( VI \) (variation index) at the high-frequency range in the intra-subject variations (both “within a day” and “over several days”) is lower than that of the “baseline”. The total value of the standard deviation of the modulus of seat-to-head transmissibility in the frequency range of interest, the \( \sigma_{\text{total}} \) was evaluated for each subject (Figure 4). It is noted that the \( \sigma_{\text{total}} \) of “within a day” in the intra-subject variation appeared to range from 0.05 to 0.3 (Figure 4 (a)), and that of “over several days” in the intra-subject variation ranged
from 0.08 to 0.25 (Figure 4 (b)). It is clear that the intra-subject variations (both “within a day” and “over several days”) are larger than the “baseline.” However, when the variation “within a day” and that “over several days” between subjects are compared, this common trend is not observed; some subjects show that variations “within a day” are larger than those “over several days,” while other subjects show the opposite trend. For example, when the variation “within a day” and that “over several days” are compared for subject E, variation “within a day” ($\sigma_{\text{total}} = 0.21$) has a larger variation than that “over several days” ($\sigma_{\text{total}} = 0.12$), while subject F shows that variation “within a day” ($\sigma_{\text{total}} = 0.12$) has a smaller variation than that “over several days” ($\sigma_{\text{total}} = 0.22$). However, when comparing the averaged variations for “within a day” ($\bar{\sigma}_{\text{total}} = 0.156$) and those “over several days” ($\bar{\sigma}_{\text{total}} = 0.152$) in all subjects, both variations show no significant difference. Although the magnitude of the intra-subject variations depends on each subject, both variations “within a day” and that “over several days” have a similar range of variation.

Moreover, although subjects have different scatters of variation within the frequency range of interest, the resonant peaks lie in the 4-7 Hz frequency range for all subjects under all conditions. For example, the resonant peak is commonly observed in the intra-subject variations and “baseline” with subject E, as shown in Figure 2 and 3. The peaks of five transmissibilities in “baseline” ranged from 5.1 Hz to 5.3 Hz (mean: $\mu = 5.18$ Hz, SD: $\sigma = 0.083$ Hz), while the peaks of “within a day” and that of “over several days” ranged from 5.0 Hz to 5.4 Hz (“within a day”: $\mu = 5.2$ Hz, $\sigma = 0.158$ Hz, “over several days”: $\mu = 5.16$ Hz, $\sigma = 0.167$ Hz). Though the peak relies on each subject, the distribution of peaks in all subjects is within 1Hz.
Fig. 3 Transmissibilities evaluated by “baseline” (a), and transmissibilities evaluated by measurements performed at the same time of the day for five days. The gray line is the initial transmissibility on the first day. The dotted gray line, the black line, the dotted black line, and the pointed black line indicate transmissibilities on Days 2, 3, 4, and 5, respectively, after the first day (b) (2–20Hz).

Fig. 4 Seat-to-head transmissibility: comparison of the total value of SD (σ_{total}) “within a day” (black) and that of the baseline (white) (a); comparison of the total value of SD (σ_{total}) “over several days” (gray) and that of the baseline (white) (b) (2–20Hz)
3.2 Intra-subject variation (“within a day” and “over several days”) in apparent mass

Figure 5 shows the apparent mass obtained in the “within a day” condition, while Figure 6 shows apparent mass measured in “over several days” condition. It shows that although there is no significant difference between the value of $V_I$ in the intra-subject variations and those in the “baseline”, the intra-subject variation in the vicinity of peak is slightly larger than the “baseline”. The apparent mass is usually normalized with respect to the static seated mass in order to get rid of the body mass effect\(^{(9)}\). The normalization of the apparent mass is necessary to directly compare the data from subjects of different weights, and this was performed by dividing the magnitude of apparent mass from the supported weight. Figure 7 shows the total value ($\sigma_{\text{total}}$) of normalization of the intra-subject variations in the apparent mass evaluated for each subject. In Figure 7 (a), the $\sigma_{\text{total}}$ of “within a day” in intra-subject variation ranged from 0.02 to 0.06, while in Figure 7 (b), the $\sigma_{\text{total}}$ of “over several days” in the intra-subject variation ranged from 0.03 to 0.05. It is also clear that the normalization of the intra-subject variations (both “within a day” and “over several days”) is larger than that of the “baseline.” When the averaged variation of the normalization of “within a day” ($\bar{\sigma}_{\text{total}} = 0.042$) and that of “over several days” ($\bar{\sigma}_{\text{total}} = 0.041$) were calculated for all subjects, both variations show no significant difference.

Moreover, the resonant peaks of apparent mass lie in the 5-7 Hz frequency range for all subjects under the all conditions. For example, the resonant peak is observed in the intra-subject variations and “baseline” with subject E, as shown in Figure 5 and 6. The peaks of five apparent mass in “baseline” ranged from 5.3 Hz to 5.5 Hz (mean: $\mu = 5.4$ Hz, SD: $\sigma = 0.1$ Hz), while the peaks in “within a day” ranged from 5.5 Hz to 5.8 Hz ($\mu = 5.68$ Hz, $\sigma = 0.109$ Hz) and the peaks in “over several days” ranged from 5.1 Hz to 5.3 Hz ($\mu = 5.2$ Hz, $\sigma = 0.1$ Hz). The distribution of peaks under the all conditions for all subjects is within 1Hz.

(a) Variation “baseline” for Subject E   (b) Variation “within a day” for Subject E

Fig. 5 Apparent masses evaluated by “baseline” (a), and apparent masses evaluated by measurements repeated five times at two-hour intervals on the same day. The gray line is the initial apparent mass at the start time. The dotted gray line, the black line, the dotted black line, and the pointed black line indicate apparent masses at 2, 4, 6, and 8 h, respectively, after the start time (b) (2–20 Hz).
Fig. 6 Apparent masses evaluated by “baseline” (a), and apparent masses evaluated by measurements performed at the same time of the day for five days. The gray line is the initial apparent mass on the first day. The dotted gray line, the black line, the dotted black line, and the pointed black line indicate apparent masses on Days 2, 3, 4, and 5, respectively, after the first day (b) (2–20 Hz).

Fig. 7 Normalization of apparent mass of comparison between the total value of SD ($\sigma_{\text{total}}$) “within a day” (black) and that the baseline (white) (a), Comparison of the total value of SD ($\sigma_{\text{total}}$) “over several days” (gray) that of the baseline (white) (b) (2-20 Hz).
4. Discussion

We confirmed that although magnitude of intra-subject variations depends on each subject, both variations (“within a day” and “over several days”) have a similar range of variation. When the effect of vibration to the human response is considered, the intra-subject variations provide to help understanding the change of human response. For example, from the human fatigue viewpoints, the WBV is one of the potential contributors in environmental factors. In order to examine the WBV-human response relationships, the assessment of intra-subject variation is necessary to understand if the biodynamic response of a seated human exposed to WBV changes over time. The reason is that if the change of human response does not exceed the range of intra-subject variation, it is understood that the significant difference is not observed. Moreover, for comparing the different seats, the knowledge of the intra-subject variation is also necessary to judge if the biodynamic response of a seated human differs depending on the seat. Thus, the intra-subject variation will give the base for understanding the change of human response to WBV.

Furthermore, in order to examine the intra-subject variations (“within a day” and “over several days”), the measurements are iterated with intervals in experiments. In addition, before the comparison of the intra-subject variations with the “baseline”, the input signals were evaluated under three experimental conditions. In this study, the magnitude of input singal was 0.25-0.27 m/s² in r.m.s.. Figure 8 shows the power spectrum density of the input signals, where the input signals were measured five times in “baseline” condition and the input signals show some minor variation. The consistency of the input signals were evaluated as the total value of standard deviation, which is introduced in order to assess the variation of the power spectrum density within the frequency range of interest (PSD_ σtotal).

The following procedure was applied for evaluating the variation of PSD.

The averaged power spectrum density of the input (S^a(f))

\[ \bar{S}_{aa}(f) = \frac{1}{N} \sum_{i=1}^{N} S_{aa}^i(f) \] (8)

where \( S_{aa}^i(f) \) is the power spectrum density of the input (floor:a) at the \( i \)-th measurement, \( N \) is the number of averages (\( N=5 \)).

The standard deviation (\( \sigma \)) was calculated using power spectrum density at each frequency (\( f_k \))

\[ \sigma(f_k) = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (S_{aa}^i(f_k) - \bar{S}_{aa}(f_k))^2} \] (9)

In this study, the total value of standard deviation of power spectrum density (PSD_ σtotal) is formulated to assess the variation of power spectrum density within the frequency range of interest and is given by

\[ PSD_{\text{mean}} \sigma_{\text{total}} = \left[ \frac{1}{n} \sum_{k=1}^{n} \sigma^2(f_k) \right]^{1/2} \] (10)

where \( \sigma(f_k) \) is the standard deviation at a particular frequency (\( f_k \)), and \( n \) is the number of frequency lines within the range of interest.

The results indicate that the PSD_ σtotal of “baseline” is \( 1.5 \times 10^{-4} \) [(m/s² )²/s], the
\( PSD_{\sigma_{\text{total}}} \) of “within a day” is \( 1.7 \times 10^{-5} \) [(m/s\(^2\))^2/s], and the \( PSD_{\sigma_{\text{total}}} \) of “over several days” is \( 1.7 \times 10^{-5} \) [(m/s\(^2\))^2/s]. Although the input signals show some minor variation in each experiments, the input signals have no significant differences.

![Fig. 8 Power spectral density of the input signals in “baseline” condition measured five times on the seat surface using an accelerometer](image)

5. Conclusions

The aim of this study was to investigate the intra-subject variation in biodynamic responses (both apparent mass and seat-to-head transmissibility) of a seated human exposed to vertical vibration over time. The intra-subject variations (“within a day” and that “over several days”) were evaluated by comparing with a “baseline” (measurement variation).

Intra-subject variations (both “within a day” and “over several days”) in biodynamic responses for all subjects tended to be larger than those in the “baseline.” However, when variations “within a day” and “over several days” in biodynamic responses were compared for all subjects, the common trend were not observed among subjects: some subjects show that variations “within a day” that are larger than those “over several days,” while, other subjects shown the opposite trend. Although the magnitude of intra-subject variation depends on the each subject, both variations (“within a day” and “over several days”) have a similar range of variation.

Both seat-to-head transmissibility and apparent mass are observed the distribution of variation using \( V_I \) (variation index) within the frequency range of interest. At high frequency range, the intra-subject variations in seat-to-head transmissibility show larger variation than that of the “baseline,” while, the intra-subject variations in apparent mass at the vicinity of resonant peak is slightly larger than that of the “baseline”. Furthermore, although the resonant peak is varied over time, the variation of the peak in all subjects is within 1 Hz.

References