Multi-axis sinusoidal whole-body vibrations: 
Part I - How long should the vibration and rest exposures be for reliable discomfort measures?

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ABSTRACT

Laboratory-based whole-body vibration studies often involve complex experimental designs, dozens of vibration exposures and multiple sessions. Shortening the test vibration duration would increase experimental efficiency by permitting more trials in the same time period. This study evaluated reported discomfort based on different sinusoidal vibration durations and amounts of rest between successive vibrations. Ten subjects were exposed to four blocks of vibration trials (15/20 second vibration and 5/10 second rest durations). Each block of 37 trials included repeated single axis, planar, and 6 degree of freedom multi-axial vibrations. These repeated trials were analysed to evaluate whether discomfort varied between the different blocks. We did not observe any statistically significant differences in discomfort between the different vibration and rest durations. This finding is useful for designing future vibration experiments. Part II of this study evaluates the relationship between discomfort and vibration exposure.

Keywords: whole-body vibration, discomfort, multi-axis vibration, exposure duration

1. INTRODUCTION

Industrial exposure to whole-body vibration is associated with injury and discomfort [1]. Between 4 and 7% of the work force in North America and Europe is exposed to potentially harmful levels of whole-body vibration [2]. Furthermore, epidemiological evidence supporting an increased risk of low back pain, and degenerative changes to the spinal column is well documented [3,4]. Certain industries, notably mining, construction, and forestry, involve high levels of vibration [5-12], including complex 6 degree of freedom (df) vibration. Field studies of 6 df vibration can not independently evaluate different modes of vibration [9]; field studies often note that the vertical vibration dominates the response making it impossible to evaluate the independent contribution of different modes of vibration. Accordingly, laboratory-based studies of vibration are essential for controlled and systematic evaluation of the human responses to vibration [13]. Various research
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studies have used different vibration exposure durations (between 4 [14,15], 20 [16] seconds, extending up to 5 [9] and 10 [17] minutes) and experiment lengths (between 15 [16] and 60 [17] minutes). Studies have employed complex experimental designs and dozens of vibration conditions applied during several experimental sessions [18]. If the duration of the individual vibrations could be shortened (even for a couple of seconds) without compromising the measurements, then the subjects would be exposed to a lower vibration dose and the experimental efficiency would increase by permitting more trials in a given period of time. It is necessary to specifically evaluate whether the duration of the vibration exposure, the amount of rest between vibrations, and the experiment duration significantly influence the subjective ratings of discomfort during laboratory-based studies of vibration. This is important since current reviews suggest that future studies of whole-body vibration will involve laboratory-based studies of complex vibrations [19], and must balance the competing influences of maximizing the vibration conditions to gain the most information while minimizing the vibration dose to the subjects.

The purpose of this study was to evaluate whether the duration of the vibration exposure (15 or 20 seconds), and rest between vibration exposure periods (5 or 10 seconds), significantly influence the subjective ratings of discomfort during laboratory-based studies of vibration.

2. METHODS:
2.1 Subjects

Ten adult subjects participated in this experiment. The 5 female and 5 male subjects were either graduate or senior undergraduate students at the University of Guelph (age 26.4 ± 5.3 years, height 170 ± 14.5 cm, mass 66.8 ± 11.7 kg). After familiarisation with all of the procedures associated with the experiment, each subject provided informed consent. All subjects completed the entire experimental paradigm and no subjects complained of pain during or after the experiment. Following their participation in the study, participants were debriefed. The cumulative vibration dose, experienced by the volunteer subjects, was calculated based on platform motions, and was below the health guidance caution zone limits set out in ISO 2631-1 [20]. The experimental procedures were approved by the University of Guelph Research Ethics Board.

2.2 Vibration System and Test Conditions

The robotic system was developed using a commercial parallel robot (R2000; Parallel Robotics Corporation, South Hampton, New Hampshire, USA). An automobile seat and foot rest were mounted to the robotic platform (Figure 1). The robot performed 16 specific sinusoidal vibration exposures at 1.6, 3.15, 6.3 or 8 Hz in either the Z direction, XY plane (Tx, Ty and Rz), XZ plane (Tx, Tz and Ry) or 6 df (Tx, Ty, Tz, Rx, Ry, Rz) (Table I). The amplitudes of the translational vibrations were defined at 0.55, 1.75 or 2.25 m/s² r.m.s for linear accelerations, and 0.63, 1.64 or 3.86 rad/s² r.m.s for angular accelerations. These acceleration levels are similar to previous studies [21-23]. Specific vibration exposures were selected which fell into specific bands of Vibration Total Value (0.25, 0.6, 1.1, 1.8 and 2.5 m/s²). The individual vibration conditions were either presented one (9 vibrations), three (6 vibrations) or ten times (one vibration) to yield a total of 37 vibration exposure conditions per block. This report will focus exclusively on the seven specific vibration conditions that were repeated three or ten times per block (Table I), in order to evaluate whether there were systematic changes in the subjective reports of discomfort between different vibration block presentation, vibration exposure duration periods or rest times allowed between each vibration exposure. The order of presentation of the trials was randomized between subjects. Custom-written Matlab code automated the testing sequence by organizing the random testing order, and defined vibration and rest duration for each block.
Figure 1. Automobile seat mounted to the robotic platform; the six legs and actuators around the base ring are visible. The platform motion has been programmed to perform specific 6 degree of freedom sinusoidal vibrations.

Table I. Matrix of 16 tests based on Vibration Total Value (VTV) range and mode of vibration. The digit in parentheses indicates the number of repetitions of that particular vibration per block. The individual vibration profiles were generated by combinations of low (0.55 m/s², 0.63 rad/s² r.m.s.), medium (1.75 m/s², 1.64 rad/s² r.m.s.) and high (2.25 m/s², 3.86 rad/s² r.m.s.) amplitude vibrations on each axis.

<table>
<thead>
<tr>
<th>VTV (m/s²)</th>
<th>Z axis</th>
<th>XY plane</th>
<th>XZ plane</th>
<th>6 df</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25</td>
<td>(1) 1.6 Hz@low</td>
<td>(1) 6.3 Hz@low</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.6</td>
<td>(10) 1.6 Hz@low</td>
<td>(3) 8 Hz@med</td>
<td>(3) 8 Hz@low</td>
<td></td>
</tr>
<tr>
<td>1.1</td>
<td>(3) 1.6 Hz@high</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.8</td>
<td>(3) 8 Hz@med</td>
<td>(3) 1.35 Hz@med</td>
<td>(3) 8 Hz@med</td>
<td></td>
</tr>
<tr>
<td>2.5</td>
<td>(3) 8 Hz@high</td>
<td>(1) 1.6 Hz@med</td>
<td>(1) 6.3 Hz@high</td>
<td>(1) 1.6 Hz@high</td>
</tr>
</tbody>
</table>
2.3 Experimental Design
The experiment consisted of four blocks of vibration exposures; either 15 or 20 seconds in duration (1 df: Z axis, 3 df: XY plane, 3 df: XZ plane, or 6 df: Tx, Ty, Tz, Rx, Ry, Rz) alternating with either 5 or 10 seconds of rest between vibration exposures. The order of presentation of the four blocks was randomized. Each of the blocks was composed of 37 individual sinusoidal vibration exposures in randomized sequence. The subjects were exposed to 43 minutes of vibration within the 62 minute experiment in order to complete all vibration exposure conditions.

2.4 Subjective Discomfort Measures
Subjective feelings of discomfort were verbally reported following each vibration exposure (during the rest period). This testing approach, rather than an intensity matching scheme, was used since it is thought to be more appropriate for obtaining measurements of subjective discomfort to combined dimensions (vibration in more than one axis) [24]. The discomfort scale was modeled after a previously published 9 point continuous discomfort scale which has been found to provide the greatest reliability and discrimination between different vibration intensities among 14 scales [25], but was modified to enable verbal reports of the discomfort. The scale was anchored at zero with the words “zero discomfort” and at 9 with the words “max. discomfort”. The subjects were informed that they could report decimal values rather than merely integers. This scale, and verbal report approach, is similar to previous investigations [16]. Although this particular scale has not been directly validated, studies have shown that subjective reports of discomfort are strongly related to objective measures of pressure distribution [26].

2.5 Procedures
Prior to initiating the experiment, subjects were exposed to two sample vibration conditions in order to help them define the discomfort scale. They were exposed to a relatively low dose vibration (Z axis 1.6 Hz 2.25 m/s²) and told that “this is rated by most subjects as a low number, usually zero” and a relatively high dose vibration (XZ plane 3.15 Hz 1.75 m/s²) and told that “most subjects would report this as a high number, usually a 9”. A similar approach, using sample vibrations before the experiment, has been used by previous researchers [25,27]. The order of presentation of the individual vibration trials was randomized between subjects and then the subjects were exposed to the four blocks of vibration, in random order of presentation. The subjects were given the option of standing up and stretching their legs between blocks. Following the experiment, the discomfort ratings for the repeated trials within each block were extracted for further analysis.

2.6 Statistical Analysis
The raw discomfort scale values for the repeated vibration trials in each of the four blocks were analyzed using two-way ANOVAs (vibration duration 15 or 20 seconds x rest duration 5 or 10 seconds measured either 3 or 10 times) using SAS (version 9.1.3, SAS Institute Inc, Cary NC, USA). Each of the seven vibrations (4 Tz, 1 XY plane, 1 XZ plane and 1 6df) were analyzed in separate ANOVAs.

3. RESULTS
As reported in previous studies [16], we observed a considerable degree of variability in discomfort ratings between subjects; Figure 2 illustrates the variability in the vertical vibration that was repeated ten times per block (Tz 6.3 Hz 0.55 m/s² r.m.s.). Individual subjects, such as subjects 8 and 10, appeared to be less sensitive to vibration as their discomfort ratings were lower than the other subjects. Although subject sex and experience with occupational exposure may contribute to these inter subject differences, they do not fully explain the differences; subject 10 (male), who reported the lowest ratings of discomfort, has had 6 years of occupational vibration exposure while subject 8, female, who reported the second lowest ratings of discomfort, has no previous exposure to occupational vibration; this finding held for
all vibrations (not only Tz 6.3 Hz 0.55 m/s² r.m.s.). The statistical results were similar for all of the seven repeated vibrations. The statistical analysis did not reveal any significant interactions in the ANOVAs (i.e. p > 0.05). The discomfort ratings did not vary significantly within the blocks of vibration (means for each subject for the vertical vibration that was repeated ten times per block are shown in Figure 3; Tz 6.3 Hz x 0.55 m/s² r.m.s.). One of the subjects, Subject 1, responded differently to the repeated vibrations compared to the other subjects. This subject reported increased
discomfort for the final six vibration exposures compared to the initial four exposures. This effect was not merely a change over time since it occurred in each of the four vibration exposure blocks. The main effects of vibration duration (15 or 20 seconds) and rest of duration (five or 10 seconds) were not statistically significant (Figure 4).

4. DISCUSSION

We did not observe any statistically significant differences in discomfort between the 15 or 20 second vibration exposures, or the 5 vs 10 second rest durations for any of the vertical, planar or 6 df vibration exposures. In addition, the discomfort ratings did not vary systematically within the blocks of vibration. It appears that the one hour experiment duration did not result in systematic changes in reported discomfort, and that testing sessions involving either 15 or 20 seconds of vibration interspersed with 5 or 10 seconds of rest are appropriate for evaluating discomfort associated with vertical, planar or 6 df vibration profiles.

This project evaluated repeated vibration exposures during an hour-long testing session. Although the ISO 2631-1 standard, and previous research [28], does not acknowledge that discomfort changes as a function of exposure length [20], other research has shown that subjective reports of comfort decrease continuously throughout hour-long testing sessions [29]. We did not observe statistically significant changes in discomfort ratings between the different blocks throughout the hour-long testing session.

Previous research reports that the strength of the correlation between normalized ratings of subjective comfort and specific methods of vibration assessment (for example vibration dose value-VDV, maximum transient vibration value-MTVV, and absorbed power) depend on the type of vibration (e.g., random versus equally spaced shocks) [16]. Accordingly, the results from this study may not be generalizable to non-sinusoidal vibrations. However, the results of the current study do suggest that, at least for a range of vertical, planar or 6 df sinusoidal vibration profiles, we could...
use either 15 or 20 second vibration exposures interspersed with 5 or 10 second rest for periods up to one hour. Many subjects commented that they preferred the 5 second rests; this shorter rest period was adequate for collecting the subjective discomfort measures, but was short enough to reduce boredom.

This study has shown that verbal reports of discomfort on a previously validated 9 point scale [25] are appropriate for quantifying subjective reports of discomfort during vibration trials. We modified this scale to permit the subjects to report decimal values yielding a virtual continuous scale for the subjective measures of discomfort. This is a verbal analog to the written scale whereby subjects place a mark along a line with the left-hand side corresponding to “little discomfort” and the right-hand side to “much discomfort”, as employed in many previous studies [9,17,25,27] and is in contrast to categorical judgment method which is limited to integer values [30]. In addition to laboratory-based studies, this experimental paradigm is likely to be suitable for field studies of vibration; this would permit collection of discomfort data at intervals throughout ongoing trials rather than previous studies which have collected discomfort measures at the end of field trials [9,17]. This approach will yield a greater density of discomfort data as opposed to one discomfort measure per 5 minutes [9] or 10 minutes [17]. Previous research has observed that discomfort measures during long trials (140-300 seconds) are not affected by crest factors [9]; this may be due to the subjects failing to appreciate transient changes in discomfort when asked to report discomfort at the end of prolonged trials.

Although this study included both male and female subjects, we did not formally evaluate differences in reported discomfort between males and females due to the limited sample size. Previous research has demonstrated that males consistently rated the vibration exposures as less severe than females [16]. This factor may be responsible for some aspects of the inter-subject variability that we observed. It is quite likely that differences in context also resulted in inter-subject variability. While most of the subjects were naïve to whole-body vibration, one subject had 6 years of previous occupational experience (subject 10 in Figures 2 and 3); this subject tended to rate all of the vibrations low on the discomfort scale and made comments like “this is nothing compared to industrial exposures”. Previous experiments have also observed that specific subsets of subjects responded differently to vibration [9]; they determined that physically fit individuals with experience driving under off-road conditions (soldiers in this particular case) report significantly lower discomfort compared to the other subjects (test personnel, students, secretaries and managers in this case).

The current study produced planar (3 df) and 6 df vibration profiles by combining the motion along the various axes with zero phase shift. Previous studies have shown that there is a complex effect of phase [32]; apparently phase angle, in combination with frequency, plays a significant role for X-plus-Z vibrations, but not for Y-plus-Z vibrations.

The results from this study, based on zero phase shift between modes of vibration, may not be relevant to studies using sinusoidal vibrations with different phase shifts. In addition, this study was limited by the choice of using an automobile seat rather than an industrial heavy-machinery seat. This seat modulated the platform vibrations via its transfer function. Accordingly, we might expect different discomfort ratings at specific frequencies if we had used an industrial seat; however, since the same seat was used throughout the experiment, the repeated measurements in the current study have internal validity.

In conclusion, we did not observe any statistically significant differences in discomfort between the 15 or 20 second vibration exposures, or the 5 vs 10 second rest durations, for hour-long experiments of single axis, planar, and 6 df vibrations. This finding is particularly relevant for laboratory and field-based studies of
discomfort during whole-body vibration, and can be used for designing future laboratory-based vibration experiments. In addition, the verbal discomfort scale used in this study may be helpful in field-based studies.

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