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Subjective response of standing persons exposed to fore-aft, lateral and vertical whole-body vibration

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ABSTRACT

The aims of this study were to propose multiply scale factors for evaluation of discomfort of standing persons and to investigate whether there exist differences between multiplying factors used for evaluation of discomfort of standing persons and those of seated persons exposed to WBV. Twelve male subjects were exposed to twenty-seven stimuli that comprise three acceleration magnitudes (0.2, 0.4, and 0.8 m/s^2 r.m.s.) along fore-aft (x), lateral (y) or vertical (z) direction. The subjects with seated or standing posture on the platform of the vibration test rig rated the subjective discomfort for each stimulus that has frequency contents ranging from 1.0 Hz to 20 Hz with a constant power spectrum density. The order of presentation of the test stimuli was fully randomized and each stimulus was repeated three times. The subjective scale for discomfort was calculated by using the category judgment method. The best combinations of multiplying factors were determined by calculating correlation coefficients of regression curves in-between subjective ratings and vibration magnitudes. In all the directions, body posture significantly influenced on subjective discomfort scales. Particularly in the fore-aft and lateral direction, the upper limit of all the categories for the standing posture resulted in higher vibration acceleration magnitudes than those for the seated posture. In contrast, in the vertical direction, only the upper limit of category "1: Not uncomfortable" for standing posture was observed to be higher than that for seated posture. The best agreement for ISO-weighted vibration acceleration occurred at x factor of 1.8 and y factor of 1.8 in the standing posture and x factor of 2.8 and y factor of 1.8 in the seated posture. The results suggest that seated people respond more sensitively and severely in perception of discomfort to fore-aft and lateral vibration than standing people do while standing people respond more sensitively and severely to vertical vibration than seated people do. Thus the effects of body postures on multiplying factors should be considered in evaluation of discomfort caused by whole-body vibration.
Relevance to industry: This study reports differences in subjective response of standing persons to fore-aft, lateral and vertical whole-body vibration. The results obtained in this study propose the fundamental data on the sensitivity to whole-body vibration exposed with standing posture.

1. Introduction

Passengers in public transportation such as city bus, tram, and commuter train are often exposed to whole-body vibration (WBV) with standing posture. Standing passengers as well as seated ones spend their travel time to perform various activities: writing, reading, working with computers, and operating mobile communicating devices (Mansfield, 2005). This lifestyle partly because of time-pressure has made the passengers in public transport systems more sensitive to discomfort in standing posture (Baker and Mansfield, 2010). According to a previous study, around 50% of healthy subjects perceived low back discomfort after 2 h of prolonged unconstrained standing (Gregory and Callaghan, 2008). The passengers empirically know that acceptable values of vibration magnitude for comfort are affected by body postures. Thus in public transportation those who feel difficulty in performing their activities because of the insufficient ride comfort with standing posture usually try to change their foot posture or try to find vacant seats to obtain comfort enough to accomplish their activities.

The international standard ISO 2631-1(International Organization for Standardization, 1997), widely used to evaluate discomfort caused by exposure to WBV, provides a subjective scale

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of discomfort that connects the vibration total value of the frequency-weighted acceleration magnitude to likely discomfort reaction to vibration in public transportation. According to this standard, the vibration total value is obtained by the use of frequency weightings and multiplying factors, which is known as a root sum-of-squares technique (Griffin, 1990). However, the standard does not take into account the effects of body posture on subjective responses to vibration. In this standard, the multiplying factors and ISO-frequency weightings used to calculate the vibration total value for standing persons are assumed to be the same as those for seated ones, which suggests that discomfort reaction of standing people under exposure to WBV with a certain acceleration results in the same discomfort reaction of seated people regardless of the body postures. Thus the current evaluation criterion specified in ISO 2631-1 does not support our daily experience of posture-related discomfort reactions caused by exposure to WBV in any form of transport system.

Previous studies on ride discomfort caused by exposure to WBV have focused on seated occupants. A few studies have reported that discomfort caused by exposure to seated multi-axis WBV was well predicted by the square root of sum of the squares of the magnitudes of the weighted acceleration in each axis (Griffin and Whitham, 1977; Mistrot et al., 1990). Thus the square root of sum of the squares of the magnitudes of the weighted acceleration multiplied by a factor in each axis has become a main prediction method of discomfort caused by exposure to multi-axis WBV. Cross-modal matching analysis performed to determine the relative contribution of translational and rotational vibration to discomfort for seated subjects reported multiplying factors of 2.7, 1.8, and 1.0 in the fore-aft (x), lateral (y), and vertical (z) direction, respectively (Marjanen and Mansfield, 2010). Another study on subjective ratings for seated subjects exposed to multi-axis WBV has shown that the best agreement between subjective ratings and objective vibration acceleration measurements occurred with multiplying factors of 2.2 (x), 2.4 (y), and 1.0 (z) (Mansfield and Maeda, 2011). The multiplying factors for evaluation of discomfort reported in the previous studies are quite different from those specified in ISO 2631-1.

A few studies have reported subjective response scales or frequency-weightings used for evaluation of discomfort in standing posture. Recently subjective response scales of standing people to fore-aft, lateral, and vertical random vibration have been constructed from a laboratory experiment (Shibata et al., 2012). Equivalent discomfort contours of standing persons exposed to fore-aft, lateral, and vertical vibration have been reported (Thuong and Griffin, 2011, 2012) and concluded that frequency-weightings obtained from the equivalent comfort contours differed from those specified in the current standard ISO 2631-1. However no study has been reported on multiplying factors for evaluation of vibration discomfort for standing people.

The aims of this study were to propose multiply scale factors for evaluation of discomfort of standing persons and to investigate whether there exist differences between multiplying factors used for evaluation of discomfort of standing persons and those of seated persons exposed to WBV. Subjective ratings of discomfort were determined for male subjects exposed to fore-aft, lateral, or vertical WBV with standing and seated posture.

2. Subjects and methods

2.1. Subjects

Twelve healthy male subjects with a mean age of 24.5 (SD:±0.79) years old, a mean height of 170.7 (SD:±5.87) cm, and a mean body weight of 61.9 (SD:±8.34) kg participated in this study. A screening questionnaire was collected from subjects on their previous experience of exposure to WBV and history of musculoskeletal back disorders. None of the subjects have been exposed to high levels or long periods of WBV occupationally or in their leisure time activities. Thus the subjects had no prior history of low back pain or related musculoskeletal disorders.

All the subjects underwent an explanation of the test procedure and gave their written informed consent to participate in this study. Prior to the study, the experiment protocol was approved by the Research Ethics Board of National Institute of Occupational Safety and Health, Japan.

2.2. Test facility

The vibration test rig used in this study consists of a highly rigid platform of 250 kg weight, which was actuated by seven electro dynamic shakers (Fig. 1). Among these seven shakers, four shakers powered along the vertical direction, two along the lateral direction and one along the fore-aft direction, combinations of which can generate roll, pitch, and yaw vibration. The weight capacity of this test rig is 200 kg, which covers a total weight of an experimental chair and each subject participated in this experiment. The test bench can afford to vibrate in the frequency range of 0.15–150 Hz along each basicentric axis. The peak vibration magnitude available is up to 3.5 m/s^2 in the fore-aft and lateral direction and 5.0 m/s^2 in the vertical direction.

Seven accelerometers (JA-24MA; Japan Aviation Electronics Industry Ltd., Tokyo, Japan) were mounted on the platform to control the seven shakers by using a system controller (SA110A; IMV Corporation, Osaka, Japan). The control software running in a personal computer gathered signals emitting from the accelerometers through a signal-processing unit. Then corrected driving signals calculated for the next step were feed-backed to the shakers through a power amplifier (SA1-304; IMV Corporation, Osaka, Japan).

The resonance frequencies of the platform and the test chair were higher than the frequency range of interest (1–20 Hz) in this study. Cross-axis vibration measured along axes orthogonal to the vibration axis, which includes cross-talk response of the accelerometer, misalignment errors of the accelerometer, and background noise of transverse motion itself, was maintained less than 5% at all frequencies of interest (Shibata et al., 2012). Also rotational vibrations around the axes were negligible.

2.3. Preparation of vibration stimuli

A vibration signal was designed in the frequency range of 1–20 Hz to form a vibration signal segment in such that the power spectrum density (PSD) is constant in this frequency range. This vibration signal segment was then reconstructed to generate three rescaled signal segments so that the unweighted r.m.s. acceleration magnitudes were exactly 0.2, 0.4, and 0.8 m/s^2.

As shown in Fig. 2, twenty-seven vibration signal segments, which consist of three vibration magnitudes (0.2, 0.4 and 0.8 m/s^2) by three vibration directions (fore-aft, lateral, and vertical) with three trials for each, were sequentially connected to construct a series of test stimuli. The duration time of each vibration signal segment was 7 s, which was followed by a 2-s interval. The signal sequence was designed to provide a series of stimuli that remained within human short-term memory, thus which could be judged without reliance upon the long-term storage of stimuli information by the test subject (Atkinson and Shiffrin, 1968). Also all the signal segments were randomly connected to each other so that the subjects cannot predict the magnitude or direction of vibration of the forthcoming stimulus.