Applied Ergonomics 44 (2013) 423–434

Contents lists available at SciVerse ScienceDirect

Applied Ergonomics

journal homepage: www.elsevier.com/locate/apergo

Predicting discomfort from whole-body vertical vibration when sitting with an inclined backrest

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ARTICLE INFO

Article history:
Received 10 November 2011
Accepted 8 October 2012

Keywords:
Backrest angle
Whole-body vibration
Ride comfort
Prediction model

ABSTRACT

Current methods for evaluating seat vibration to predict vibration discomfort assume the same frequency weightings and axis multiplying factors can be used at the seat surface and the backrest irrespective of the backrest inclination. This experimental study investigated the discomfort arising from whole-body vertical vibration when sitting on a rigid seat with no backrest and with a backrest inclined at 0° (upright), 30°, 60°, and 90° (recumbent). Within each of these five postures, 12 subjects judged the discomfort caused by vertical sinusoidal whole-body vibration (at frequencies from 1 to 20 Hz at magnitudes from 0.2 to 2.0 m s^{-2} r.m.s.) relative to the discomfort produced by a reference vibration (8 Hz at 0.4 m s^{-2} r.m.s.). With 8-Hz vertical vibration, the subjects also judged vibration discomfort with each backrest condition relative to the vibration discomfort with no backrest. The locations in the body where discomfort was experienced were determined for each frequency at two vibration magnitudes. Equivalent comfort contours were determined for the five conditions of the backrest and show how discomfort depends on the frequency of vibration, the presence of the backrest, and the backrest inclination. At frequencies greater than about 8 Hz, the backrest increased vibration discomfort, especially when inclined to 30°, 60°, or 90°, and there was greater discomfort at the head or neck. At frequencies around 5 and 6.3 Hz there was less vibration discomfort when sitting with an inclined backrest.

1. Introduction

The inclination of a seat backrest influences sitting comfort. In some limousines, aircraft, and ships, seats with backrests that incline from the vertical to the horizontal may be associated with luxury. However, in a transport environment, the inclination of the backrest will also influence the vibration transmitted to the body and the vibration discomfort experienced by passengers and by drivers. Procedures for predicting the discomfort associated with different backrest inclinations and different characteristics of vibration are needed so that seats can be optimised for comfort.

Vertical vibration is often dominant in transport. Studies of the discomfort caused by the whole-body vertical vibration of people seated with no backrests have shown a strong dependence on the frequency of the vibration (e.g. Miwa, 1967; Jones and Saunders, 1972; Dupuis et al., 1972; Griffin et al., 1982; Morioka and Griffin, 2006). Studies of physical responses (e.g. apparent mass, mechanical impedance, transmissibility) to whole-body vertical vibration when sitting with no backrest also show a strong dependence on the frequency of the vibration (e.g. Fairley and Griffin, 1989; Paddan and Griffin, 1988). Some similarities in the frequency-dependence of subjective and physical responses suggest vibration discomfort is associated with physical responses of the body. For example, the seated body tends to be most sensitive to whole-body vertical acceleration around 5 Hz, consistent with an apparent mass resonance around 5 Hz (e.g. Fairley and Griffin, 1989).

Studies of subjective responses to whole-body vertical vibration suggest the presence of an upright backrest increases discomfort at frequencies greater than the frequencies at which the body is most sensitive (e.g. Shoenberger and Harris, 1971; Oborne and Boarer, 1982). A similar influence of a backrest can be seen in the physical responses of the body. With a vertical backrest, a general trend for increased resonance frequencies and increased apparent mass at frequencies greater than the resonance has been reported, probably due to changes in the dynamic responses of the body arising from differences in the vibration transmission paths to the body and the body posture (Fairley and Griffin, 1989). The transmission of vertical seat vibration to the head is also changed by the addition of a backrest: fore-and-aft head motion has been reported to increase at frequencies up to 25 Hz, with almost a doubling at the

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0003-6870/$ – see front matter
http://dx.doi.org/10.1016/j.apergo.2012.10.006

frequency of greatest transmissibility around 7 Hz; vertical head motion showed a more distinct peak around 6 Hz, and pitch head motion was increased at frequencies greater than principal resonance around 4 Hz (Paddan and Griffin, 1988).

With increasing inclination of a backrest, there is a systematic increase in the resonance frequency of the vertical apparent mass of seated people: from 5 Hz with a vertical backrest to 6.4 or 7.5 Hz with 30° backrest inclination (e.g. Shibata and Maeda, 2009; Toward and Griffin, 2009), and to 7.0 or 9.4 Hz with maximum contact of the semi-supine body with a horizontal backrest (Huang and Griffin, 2008).

Studies of the subjective responses of seated people exposed to vertical vibration have been limited to upright backrests. Although there have been studies of the influence of backrest inclination on the discomfort caused by fore-and-aft vibration (Kato and Hanai, 1998; Basri and Griffin, 2011), current understanding is not sufficient to predict how the discomfort caused by whole-body vertical vibration depends on backrest inclination.

Current standards (BS 6841, 1987; ISO 2631-1, 1997) suggest the overall vibration discomfort of seated people can be predicted from an appropriate summation of the discomfort expected from vibration evaluated separately at the seat, the back, and the feet (i.e., multiple-input vibration). Frequency weightings and axis multiplying factors have been developed to reflect sensitivity to different frequencies and different directions of vibration at these locations. The 'weighted' accelerations are then combined, using the square-root of the sums-of-squares (r.s.s.) of the individual values, to predict the overall discomfort. This procedure was based on the assumption that the discomfort from multiple-input vibration could be predicted the same way that the discomfort of multiple-axis vibration can be predicted: using the r.s.s. method as opposed to using linear summation of all values, the greatest value (e.g. Griffin and Whitham, 1977; Shoenberger, 1988; Mistrot et al., 1990), or masking methods (Fothergill and Griffin, 1977). The method of summation ignores the influence of phase between inputs, although phase differences can contribute to discomfort (Jang and Griffin, 1999, 2000).

There is no clear provision in the standards for any adjustment of either the frequency weightings or the axis multiplying factors to allow for variations in the inclination of backrests. However, it has been reported that backrest inclination changes frequency sensitivity to *x*-axis vibration of backrests (Kato and Hanai, 1998; Basri and Griffin, 2011) and sensitivity to vertical seat vibration (Basri and Griffin, 2012). The frequency weighting W_c, recommended in the standards for evaluating the *x*-axis vibration of the back, was based on the equivalent comfort contours of 12 male subjects exposed to fore-and-aft vibration of an upright backrest while sitting on a stationary seat pan with a stationary footrest (Parsons et al., 1982). Application of the W_c weighting when evaluating the *x*-axis vibration of inclined backrests tends to overestimate vibration discomfort at low frequencies (less than 8 Hz) and underestimate vibration discomfort at high frequencies (Kato and Hanai, 1998; Basri and Griffin, 2011). Recently, equivalent comfort contours have been determined for 12 male subjects exposed to vertical vibration of a seat pan while sitting with stationary inclined backrests (0°, 30°, 60° and 90° from vertical) and a stationary footrest (Basri and Griffin, 2012). With increasing inclination of the backrest, the proportion of body weight supported by the vibrating seat pan decreased and vibration discomfort reduced at all frequencies. The reduction in discomfort was more prominent (by about 6 dB) with greater inclinations of the backrest (60° and 90°) and at frequencies less than 8 Hz. The findings imply that the axis multiplying factor for vertical seat vibration (1.0 in the current standards) should reduce as backrest inclination increases.

The study reported here investigated the influence of backrest inclination on the discomfort of seated people exposed to whole-body vertical vibration (i.e., vertical vibration at the seat, the back, and the feet). This made it possible to examine the suitability of current procedures for evaluating vibration with respect to the discomfort caused by multiple-input vibration. It was hypothesised that, with increasing backrest inclination, there would be a change in the frequency-dependence of discomfort caused by backrest vibration, and a change in the relative sensitivity to seat vibration. Consequently, the frequency-dependence of the discomfort of seated people arising from whole-body vertical vibration would change with backrest inclination. It was also hypothesised that the r.s.s. procedure would predict the difference in vibration discomfort experienced when sitting upright with or without a backrest. It was expected that current frequency weightings and axis multiplying factors for seat vibration and back vibration would not provide optimum predictions of variations in vibration discomfort when sitting with different inclinations of the backrest.

2. Method

2.1. Test rig

An aluminium frame supporting a wooden seat pan, backrest, footrest and, where appropriate, support for the lower leg, was constructed and mounted securely to the platform of a vertical vibrator (Fig. 1). The backrest was adjustable to inclinations of 0°, 30°, 60°, or 90° (fully recumbent). The footrest was inclined 30° from horizontal. The dimensions of the apparatus were determined based on a comfortable sitting posture for a 50th percentile British male aged 19–45 years (Pheasant, 1990). The positions were achieved using an H-point manikin with knee and ankle angles set to 120° and 100°, respectively (Rebiffé, 1969). With the backrest inclined at 90°, subjects lay flat on their backs with their calves supported. A rigid headrest was provided, except when there was no backrest and when the backrest was upright. The supports for the pelvic area (buttocks and thighs), back, head, and calves were covered with 1-mm thick neoprene rubber to provide some friction between the supports and the body.

2.2. Signal generation and acquisition

The vibration stimuli were produced using a hydraulic vibrator capable of 1-m peak-to-peak displacement in the vertical direction. The stimuli were generated and sampled using *HVLab* Signal Processing Toolbox in Matlab (version R2009) and output via a digital-to-analogue converter (NI 6211) at 512 samples s^{-1}.

The acceleration of the platform was monitored using single-axis piezo-resistive accelerometers (Entran Model EGCSY-240D-10) attached to the platform. Signals from the accelerometers were low-pass filtered at 50 Hz and then sampled at 512 samples s^{-1}.

2.3. Vibration stimuli

All vibration stimuli were 5-s sinusoids with 1-s cosine-tapering at the start and end.

The subjects were requested to judge 'vibration discomfort' (i.e., their feelings about the vibration alone; Griffin, 1990). In Part 1, subjects judged the discomfort caused by various frequencies and magnitudes of vertical whole-body vibration within the same sitting condition: they compared the discomfort caused by 'test' vibrations relative to a 'reference' vibration (i.e., 8 Hz at 0.4 m s^{-2} r.m.s.). The 'test' vibrations were from an array of 14 frequencies (the preferred one-third octave centre frequencies from 1 to 20 Hz)