Vibrotactile Perception and Effects of Short-Term Exposure to Hand-Arm Vibration

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This study clarifies whether the established frequency weighting procedure for evaluating exposure to hand-transmitted vibration can effectively evaluate the temporary changes in vibrotactile perception thresholds due to pre-exposure to vibration. In addition, this study investigates the relationship between changes of the vibrotactile perception thresholds and the normalized energy-equivalent frequency-weighted acceleration. The fingers of 10 healthy subjects, five male and five female, were exposed to vibration under 16 conditions with a combination of different frequencies, intensities, and exposure times. The vibration frequencies were 31.5 and 125 Hz and exposure lasted between 2 and 16 min. According to International Organization for Standardization (ISO) 5349-1, the energy-equivalent frequency-weighted acceleration for the experimental time of 16 min is 2.5 or 5.0 m s⁻² root-mean-square, corresponding to a 8-h equivalent acceleration, A(8), of ~0.5 and 0.9 m s⁻², respectively. A measure of the vibrotactile perception thresholds was conducted before the different exposures to vibration. Immediately after the vibration exposure, the acute effect was measured continuously on the exposed index finger for the first 75 s, followed by 30 s of measures every minute for a maximum of 10 min. If the subject’s thresholds had not recovered, the measures continued for a maximum of 30 min with measurements taken every 5 min. Pre-exposure to vibration significantly influenced vibrotactile thresholds. This study concludes that the influence on the thresholds depends on the frequency of the vibration stimuli. Increased equivalent frequency-weighted acceleration resulted in a significant change in threshold, but the thresholds were unaffected when changes in the vibration magnitude were expressed as the frequency-weighted acceleration or the unweighted acceleration. Moreover, the frequency of the pre-vibration exposure significantly influenced (up to 25 min after exposure) recovery time of the vibrotactile thresholds. This study shows that the frequency weighting procedure in ISO 5349-1 is unable to predict the produced acute changes in the vibrotactile perception. Moreover, the results imply that the calculation of the ‘energy-equivalent’ frequency-weighted acceleration does not reflect the acute changes of the vibration perception thresholds due to pre-exposure to vibration. Furthermore, when testing for the vibrotactile thresholds, exposure to vibration on the day of a test might influence the results. Until further knowledge is obtained, the previous practice of 3 h avoidance of vibration exposure before assessment is recommended.

Keywords: perception; QST; threshold; vibration; vibrotactile

INTRODUCTION

Four populations of mechanoreceptors mediate the sense of touch in the hands, the slowly adapting Type I and II receptors (SAI and SAII) and the rapidly adapting Type I and II receptors (FAI and FAII). The SAI receptors are involved in the detection of surface topography and the SAII receptors respond primarily to skin stretch. The role of the FAI receptors is mainly to provide the sensory input necessary to grip and hold objects and the FAII receptors are very sensitive to vibration. The different receptors are associated with distinct anatomical structures in the glabrous skin of the hand: Merkel disks (SAI), Meissner corpuscles (FAI), Pacinian corpuscles (FAII), and Ruffini endings.
Prolonged occupational exposure to hand-arm vibration arising from the operation of hand-held power tools is associated with a greater occurrence of deterioration of finger tactile perception than in control groups not exposed to hand-transmitted vibration (e.g. Lindsell and Griffin, 1999; Palmer et al., 2000; Bovenzi, 2005). The awareness of the importance of sensory neuropathy has resulted in an interest in quantitative sensory testing (QST) for screening and diagnosis of vibration-induced neuropathy (Lundström, 2002). Compared to normal values, changes in the vibrotactile perception thresholds are often used as an objective test to detect neurological effects (e.g. Lundborg et al., 1987; Letz and Gerr, 1994; Lundström et al., 1999).

Psychophysical techniques for determining the vibrotactile sensitivity have also been defined in the international standards [International Organization for Standardization (ISO 13091-1), 2001; ISO 13091-2, 2003]. Separate responses from the different receptors can be determined using vibrotactile stimulation at different frequencies (Lindsell and Griffin, 1999).

Several investigators have demonstrated that acute threshold shifts and temporary changes in hand function can occur due to short-term hand vibration exposure (e.g. Nishiyama et al., 1996; Thonnard et al., 1999; Yonekawa et al., 1999). These studies examine the effects of variables, such as the magnitude of the vibration pre-exposure, vibration frequency, the exposure time, and the grip force.

The two international standards, ISO 5349-1 (2001) and ISO 5349-2 (2001), define how to measure and evaluate hand-transmitted vibration. The measured vibration acceleration is frequency weighted on the assumption that the harmful effects of acceleration are independent of frequencies between 6.3 and 16 Hz, but progressively decrease with higher frequencies. Since the detrimental effects of vibration exposure depend on the daily exposure time, the assessment of exposure is based on the calculation of the daily energy-equivalent exposure value normalized to an 8-h reference period A(8) of the frequency-weighted acceleration values. However, the relationship between the frequency weighting procedure (prescribed in ISO 5349-1) as well as the energy-equivalent evaluation of the vibration exposure and the measures of the vibrotactile perception thresholds has not been sufficiently described.

This study aims to clarify whether prior exposure to hand-transmitted vibration on the day of the test influence the results obtained from the objective QST diagnostic tests. In addition, this study investigates the relationship between changes of the vibrotactile perception thresholds and different aspects of the vibration exposure, i.e. vibration magnitude, frequency, and duration. The findings will be used to establish an improved definition of test conditions, especially the length of time required between the last occupational exposure to tool vibration and the start of objective testing.

METHODS

Subjects

Ten healthy subjects, five male and five female, with no prior history of regular use of hand-held vibrating tools in occupational or leisure activities participated in the study. All 10 subjects were non-smokers and reported no cardiovascular or neurological disorders in their hands. The subjects’ mean age was 23.3 years (range 21–25), mean height 173.1 cm (range 160–183), and mean weight 66 kg (range 51–80). The Regional Board of Ethical Vetting for medical research in Umeå, Sweden, approved the study.

Experimental procedure

The experiments were performed in a room with an ambient temperature of 22°C (±2°C) and with airflow <0.2 m s⁻¹. The subjects were asked to avoid alcohol 12 h before testing and to avoid nicotine and caffeine consumption 1 h before testing. During the experiments, the subjects were dressed in light indoor clothing and they wore hearing protections during the entire test. After an acclimatisation period of 15 min, finger temperature was measured using a thermocouple attached to the distal phalanx of the examined index finger. The finger skin temperature was never <28°C when testing began. When the fingers were at lower baseline temperatures, the subjects used hand warmers to increase the temperature.

A computer-based system was used to measure vibrotactile thresholds (thresholds at 31.5 and 125 Hz) at the stimulus frequencies via the von Békésy method (up-and-down method) in a manner compliant with the methods in ISO 13091-1. The system consists of a laptop with a specially developed programme in LabView, a DAQ-card (National Instrument 6221M, Austin, TX, USA), and a vibration exciter (Bruel & Kjaer 4809, Nærum, Denmark) with an external amplifier (Sentec PA9, Kopparberg, Sweden). Thresholds were measured on the distal phalanx of the index finger of the dominant hand. Subjects placed their finger such that the centre of the finger print whorl was situated over the centre of the probe of the applicator. The subjects were seated in a chair with a backrest in front of the instrumentation set-up and instructed to apply a downward (push) force of 0.5 N (±0.25 N) during the tests. Using a pointer instrument, the applied force could be controlled by the research leader. During the test, the subject’s wrist supported the hand, Fig. 1. Subjects were instructed to press and hold the response button down as soon as they perceived a vibration.
sensation and to release the response button as soon as they did not perceive the vibration.

**Experimental conditions**

Before the experiments, the subjects were familiarized with the testing procedures and were allowed to practice. A measure of the vibrotactile perception was conducted before the different exposures to vibration. After completing the pretest, the subjects were instructed to place their index, middle finger, and their ring finger on a horizontal wooden platform (70 × 70 mm) mounted on a vibrator (Ling Altec Model 40; Oklahoma City, OK, USA). Their elbows rested at a comfortable angle on an adjustable supported platform. The exposed area of the fingers ranged from the fingertip to the second phalanx. The vibration, a sinusoidal vibration at a frequency of 31.5 and 125 Hz, was generated by an IBM computer-based system. The chosen frequency was used because previous experimental studies have shown that these frequencies induce greater changes in finger tactile perception thresholds than some lower or higher frequencies do (Harada and Griffin, 1991; Bovenzi et al., 1997; Malchaire et al., 1998). The vibration was sent via an amplifier (Sentec PA9) to the vibrator, producing motions in the vertical direction. The subjects were instructed to apply a downward force of 5 N during the entire exposure time. Both the subjects and the research leader monitored the force.

Each subject was exposed to vibration under 16 conditions (Table 1) with a combination of different frequency, intensity, and exposure time. The subjects were only allowed to conduct one test per day, and the test order was distributed with a balanced repeated measures design (Girden, 1992). The frequency-weighted vibration intensity ranged from 2.5 to 14.2 m s$^{-2}$, corresponding to an unweighted acceleration magnitude between 4.8 and 111.4 m s$^{-2}$. According to ISO 5349-1, the calculated energy-equivalent frequency-weighted acceleration magnitude for the whole experimental time of 16 min was either 2.5 or 5.0 m s$^{-2}$ (Table 1).

Immediately after the vibration exposure, the vibrotactile threshold perception assessments were conducted on the exposed index finger. The acute effect was measured continuously for the first 75 s, followed by 30 s of measures every minute up to 10 min. The data from the last measurement were compared with the results from the pretest. If the deviation was

![Fig. 1. The subject's hand-arm posture with the wrist support during the measurement of the vibrotactile thresholds.](http://annhyg.oxfordjournals.org/)

### Table 1. Conditions of exposure used in this study (the root-mean-square acceleration magnitude of vibration and the energy-equivalent frequency-weighted acceleration magnitude for the whole experimental time, 16 min)

<table>
<thead>
<tr>
<th>Experimental conditions (number)</th>
<th>Vibration frequency (Hz)</th>
<th>Frequency-weighted acceleration magnitude (m s$^{-2}$)</th>
<th>Unweighted acceleration magnitude (m s$^{-2}$)</th>
<th>Exposure duration (min)</th>
<th>Equivalent acceleration magnitude (m s$^{-2}$)</th>
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<tr>
<td>1</td>
<td>31.5</td>
<td>7.07</td>
<td>13.62</td>
<td>2</td>
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</tr>
<tr>
<td>2</td>
<td>31.5</td>
<td>5.00</td>
<td>9.63</td>
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<td>2.5</td>
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<td>19.27</td>
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<td>31.5</td>
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<tr>
<td>16</td>
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<td>5.00</td>
<td>39.37</td>
<td>16</td>
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</table>
>2 dB (decibels relative 10^{-6} m s^{-2}) compared with the pretest, then further tests were carried out every 5 min until the deviation was <2 dB. The measurements continued up to 30 min. In between the measurements, the subjects continuously rested their finger on the probe without applying force.

**Statistical analyses**

Computer software SAS (Cary, NC, USA) was used for the statistical analysis. The thresholds were taken as the mean of the measured positive and negative peaks expressed in decibels (ISO 13091-1, 2001). For the first 75 s, the analysis was divided into two time intervals (15–45 and 45–75 s). In the analysis, the measured vibrotactile thresholds for each subject and condition were compared with the corresponding measured thresholds before the exposure to vibration (the pretest). The difference was used as an indication of response on the perception sensation. For the statistical analysis, repeated measures analysis of variance with mixed model was used to test the hypothesis of ‘no difference’ in the responses for the different exposure conditions. The test–retest correlation was calculated as the intraclass correlation coefficient. To describe the reliability of single threshold measures, the intraclass correlation coefficient was calculated for the 16 pretest measurements.

**RESULTS**

**Pretest**

The mean vibrotactile perception thresholds at the index finger calculated for all 16 pretest were 122.5 dB (SD 3.7 dB) at 31.5 Hz and 98.2 dB (SD 4.5 dB) at 125 Hz. Female subjects had higher thresholds at both frequencies (31.5 Hz: 114.1 versus 110.8 dB; 125 Hz: 99.2 versus 97.3 dB). Analysis showed that there is a significant difference (P < 0.001) due to gender for the thresholds at 31.5 Hz, but not at 125 Hz (P = 0.065). No significant day-to-day effect was found (P = 0.336). The intraclass correlation coefficient between the different pretests was found to be 0.49 at 31.5 Hz and 0.61 at 125 Hz. The female subjects had a better correlation than the male subjects (0.58 versus 0.27 at 31.5 Hz; 0.65 versus 0.56 at 125 Hz).

Table 2 shows the results from the conducted experiments presented as the mean changes in the vibrotactile thresholds compared to the pretest for the different experimental conditions (Table 1) and as function of time after the exposure.

**Acute effects**

Pre-exposure to vibration had a significant (P < 0.001) acute influence on the vibrotactile thresholds, 30 s after the exposure. The mean change was 6.9 dB (SD 3.7 dB) at 31.5 Hz and 19.9 dB (SD 4.4 dB) at 125 Hz. The influence on the thresholds was significant (P < 0.001) and depended on the frequency of the vibration stimuli (31.5 or 125 Hz). No differences were observed due to gender (P = 0.252 and P = 0.117, respectively).

A doubling of the acceleration, expressed as energy-equivalent frequency weighted, resulted in a mean change of the thresholds with ~1.3 dB (SD 4.9 dB) at 31.5 Hz and 2.9 dB (SD 4.5 dB) at 125 Hz. The changes of the thresholds were significant (P < 0.001) for the vibration stimuli of 125 Hz but not for the vibration stimuli of 31.5 Hz (P = 0.095). The changes in the thresholds due to changes in the accelerations were not influenced by gender (0.164 < P < 0.341). Figure 2 illustrates the relationship between the acute changes of the mean vibrotactile perception thresholds (decibels), compared to the pretest, and the vibration magnitude expressed as the frequency-weighted acceleration for the two frequencies of the vibration stimuli, 31.5 and 125 Hz.

The changes in the 30 s after the exposure were ~7 dB at 31.5 Hz and ~20 dB at 125 Hz. The changes due to increased frequency-weighted acceleration were not significant (0.284 < P < 0.479). The same insignificant results were found for changes in the unweighted acceleration (0.464 < P < 0.667).

An increase of the exposure time (from 2 to 8 min or from 4 to 16 min) for the same acceleration, expressed as energy-equivalent frequency weighted, changed the thresholds with 0.6 dB (SD 4.4 dB) at 31.5 Hz and 5.1 dB (SD 4.4 dB) at 125 Hz. The changes of the thresholds were significant (P < 0.001) for the vibration stimuli of 125 Hz but not for 31.5 Hz (P < 0.537). The changes in the exposure time were not related to gender (0.104 < P < 0.875).

**Recovery**

Ten minutes after the vibration exposure, 41% of the tests had a larger deviation than 2 dB compared with the pretest. Therefore, the measurement was continued. After 15 min, 14% of the tests still had an effect and 4% of the experiments, the measurements had to be continued for 30 min. The noticed prolonged recovery time was not subject specific.

Figure 3 shows the relationship between the changes of the mean vibrotactile perception thresholds (decibels) (compared to the pretest) as a function of time after the exposure. Figure 3 shows the recovery after exposure to the two frequencies of the vibration stimuli, 31.5 and 125 Hz, and for the two energy-equivalent frequency-weighted accelerations of 2.5 or 5.0 m s^{-2}. The influence on the thresholds due to pre-exposure to vibration declines over time. Moreover, there is a difference both due to frequency and magnitude of the vibration stimuli.

The frequency of the vibration stimuli (31.5 or 125 Hz) had significant (P < 0.001) influence on the recovery of the vibrotactile thresholds. The influence was significant for the first 10 min for a vibration...
<table>
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<th>Time (s)</th>
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<tr>
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<td>8</td>
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</tr>
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<td>16</td>
<td>21.44 (6.03)</td>
</tr>
</tbody>
</table>

The results are presented for the 30 min (1800 s) after the vibration exposure. The standard deviation is given in parenthesis.
stimulus of 31.5 Hz and 25 min for the vibration frequency of 125 Hz. The influence was not different due to gender ($P = 0.226$).

The energy-equivalent frequency-weighted acceleration (2.5 or 5.0 m s$^{-2}$) did not affect the recovery time for the vibration stimuli of 31.5 Hz ($P = 0.482$). For the vibration stimuli of 125 Hz, there was a significant increase ($P = 0.001$) of the recovery time from 15 to 25 min. The influence was independent of gender and individual factors. A doubling of the vibration magnitude, expressed as the frequency-weighted acceleration or the unweighted acceleration, indicated the same significant influence.

An increase of the exposure time (from 2 to 8 or from 4 to 16 min) for the same energy-equivalent frequency-weighted acceleration produced a significantly ($0.001 < P < 0.030$) higher change of thresholds for the vibration frequency of 125 Hz during the first 2 min. For the vibration stimuli of 31.5 Hz, no differences could be found. The changes in the exposure time were not influenced by gender.

**DISCUSSION**

QST provides useful diagnostic information in peripheral neuropathy. However, standardized methods and protocols for measuring vibrotactile perception thresholds are required to obtain meaningful results and to compare results obtained using different apparatuses (ISO 13091-1, 2001; Lundström, 2002). Without standardization, the thresholds obtained by different measurement methods may differ substantially, and often unpredictably. This means that they cannot be compared. Moreover, the measurement must be highly reliable to be useful. Measurement repeatability of the vibrotactile perception thresholds may be quantitatively expressed using dispersion characteristics—i.e. standard deviation, coefficient of variation, and the range of values (Harazin et al., 2003). These measurements have been quantified in many studies (e.g. Maeda and Griffin, 1993; De Neeling et al., 1994; Rosecrance et al., 1994). In this study, the intraclass correlation coefficient was used to measure test–retest reliability for all 16 pretest measures of the thresholds by comparing the variability of different measures of the same subject. The intraclass correlation coefficient is an index of the reliability of the results for a typical single measure and was found to be between 0.5 and 0.6. This is a relatively low correlation coefficient. The international standard ISO 13091-2 suggests an alternative way to measure the test–retest variability in thresholds for a given stimuli frequency. The variability in the results should be estimated for each threshold expressed in decibels as 1 SD from the mean value from at least 10 separate occasions on 10 different days. In this study, the standard deviations of thresholds values ranged from 3.7 dB at 31.5 Hz to 4.5 dB at 125 Hz, values that agree with other studies (Maeda and Griffin, 1993; Harazin et al., 2003).

In this study, the measured mean vibrotactile perception thresholds at the index finger agree with the median thresholds for healthy persons presented in the ISO 13091-2 and agree with other studies (Lindsell and Griffin, 2003; Daud et al., 2004). Moreover, the result that female subjects have higher thresholds (more sensitive) than male subjects agrees with the standard.

The vibrotactile perception thresholds were measured before and after vibration exposure in order to investigate the acute effects on the vibrotactile perception as well as the recovery of finger tactile perception. This study confirms the well-established
consensus that exposure to hand-transmitted vibration can produce a temporary change in vibrotactile sensitivity (Griffin, 1990). Moreover, the measured changes of the vibrotactile perception agree with those reported by Harada and Griffin (1991) and Maeda and Griffin (1994). The influence of the pre-exposure to vibration strongly depends on the exposure frequency of the vibration stimuli. An exposure to vibration at 31.5 Hz introduces a significantly much lower temporary change of the thresholds compared to a vibration stimulus of 125 Hz. The difference is almost three times, a result that agrees with other studies (e.g. Harada and Griffin, 1991; Maeda et al., 1995). A possible reason for the difference could be the sensitivity of the mechanoreceptors, Meissner corpuscles (FAI receptor) at 31.5 Hz, and the Pacinian corpuscles (FAII receptor) at 125 Hz (Lundström and Johansson, 1986; Brammer and Piercy, 2000; Brammer et al., 2007).

Threshold recovery measures show that the shifts of the vibrotactile temporary thresholds decrease exponentially with time after exposure, a finding that agrees with earlier studies (Hirosawa et al., 1992; Morioka and Griffin, 2002). In addition, this study shows that the frequency of the pre-vibration exposure had a significant influence on time for recovery of the vibrotactile thresholds. This agrees with other published results (Harada, 1978a; Maeda and Griffin, 1994; Maeda et al., 1995). The temporary threshold shift was significant for the first 10 min for a vibration stimulus of 31.5 Hz and 25 min for the vibration frequency of 125 Hz. Increased acceleration magnitudes produce a longer recovery time for a vibration pre-exposure with the higher frequency of the vibration stimuli but not for the lower frequency. The results also indicate only a small influence of the exposure time. However, the exposure time did not exceed 16 min and the corresponding 8-h equivalent acceleration, A(8), according to ISO 5349-1 is 0.5 and 0.9 m s \(^{-2}\), respectively. These accelerations are well below the action level (2.5 m s \(^{-2}\)) established in the European vibration directive (European Council, 2002). Nevertheless, the results indicate that it is important to recognize that prior exposure to vibration on the day of a test is likely to influence the results obtained for determining the vibrotactile thresholds. The test person should be given a vibration-free period before testing. The length of the vibration-free period, however, could not be derived from this study. The international standard ISO 13091-1 recommends that subjects should avoid hand-transmitted vibration exposure for at least 3 h before measuring perception thresholds. According to this study’s results, this recommendation seems to be a sufficient time considering the low used 8-h equivalent acceleration.

Several studies show that the temporary threshold shifts at the same vibration frequency depend on the acceleration level (Harada, 1978b; Maeda et al., 1995; Morioka and Griffin, 2002). However, the risk assessment for hand-transmitted vibration is based on the frequency-weighted vibration acceleration where the frequency weighting of the vibration magnitude reflects the assumed importance of different frequencies that injure the hand. For constant frequency-weighted vibration acceleration, the effects on the vibrotactile perception should remain constant if the weighting procedure is effective to describe neurological effects (Maeda and Kume, 1989). However, the results from this study, where the same frequency-weighted acceleration was used for the two frequencies tested, indicate that the current standard is inappropriate for prediction in the produced acute changes in the vibrotactile perception. Moreover, the results show that an increase of the frequency-weighted acceleration did not significantly change the vibrotactile perception.

The assessment of hand-transmitted vibration, according to ISO 5349-1, is based on daily exposure to vibration expressed as 8-h ‘energy-equivalent’ frequency-weighted acceleration, A(8). The energy-equivalent frequency-weighted acceleration takes into account that a worker is exposed to vibration intermittently during the day. These calculations define a time dependency in which the vibration magnitude may be doubled if the exposure time is reduced by a factor of 4. The results in this study show that a doubling of the energy-equivalent frequency-weighted acceleration resulted in a significant change of the thresholds for the vibration stimuli of 125 Hz, but not for vibration stimuli of 31.5 Hz. The results imply that the calculation of the energy-equivalent frequency-weighted acceleration does not reflect the acute changes of the vibration perception thresholds due to pre-exposure to vibration.

This study may be subject to several sources of bias due to individual factors, exposure conditions, and methodology. The subjects in the study were young and healthy with no previous history of regular use of hand-held vibrating tools in occupational or leisure activities. The subjects were also recruited using a test–retest procedure for selecting subjects with low variation in their thresholds and high ability in cooperation and concentration. Therefore, when generalizing the results for the elderly who are exposed to vibration or unhealthy subjects, caution should be taken. Furthermore, the relation between measurements of the temporary thresholds shifts produced by vibration and permanent threshold shift among vibration-exposed workers is not fully known (Malinskaya et al., 1964).

Moreover, it is well known that different methods for measuring the vibration thresholds (Thonnard et al., 1997; Malchaire et al., 1998; ISO 13091-1, 2001) could affect the results, such as the probe contact force, use of surroundings, etc. However, in this
study, the same methods were used to compare the effects on the thresholds before and after the exposure to vibration. This design of the study has reduced the errors due to the instrumentation set-up and the subject day-to-day variation. However, the design of the exposure conditions could have affected the results since not all combinations of acceleration and exposure time were used. Another limitation in this study could be the absence of measurement of the influence on the thresholds without exposure to vibration. However, Malchaire et al. (1998) showed that no influence on the thresholds could be found. Moreover, the influences on the acute changes of the vibration perception thresholds were only tested on the same frequency as for the vibration stimuli. Some results (Maeda et al., 1995) show an influence on the vibration perception at other frequencies than the stimuli frequency. Therefore, the overall influence on vibration perception is larger than what was found in this study.

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