Effects of gender differences on the subjective perceived intensity of steering wheel rotational vibration based on a multivariate regression model

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Abstract

The aims of this study were to determine equal sensation curves for hand-arm steering wheel rotational vibration and to investigate the effect of gender on the subjective perceived intensity of steering wheel hand-arm vibration. Psychophysical response tests of 40 participants (20 males and 20 females) were performed using a steering wheel rotational vibration simulator using the category ratio Borg CR10 scale procedure for direct estimation of perceived intensity. The test stimuli were sinusoidal vibrations at 22 third octave band centre frequencies in the range from 3 to 400 Hz, with acceleration amplitudes in the range from 0.04 to 27 m/s^2 r.m.s.. Multivariate regression procedures were applied to the experimentally acquired data in order to establish a regression model expressing the Borg CR 10 perceived intensity values as a function of the two independent parameters of the frequency and amplitude of vibration. The equal sensation curves suggested a nonlinear dependency of the subjective perceived intensity on both frequency and amplitude. Females were found to provide higher Borg CR10 perceived intensity values than males ($p<0.05$), particularly at the higher intensity levels above approximately 1.0 m/s^2 r.m.s and at the higher frequencies above approximately 20 Hz.

Relevance to industry: For the manufacturers of steering systems and of other automobile components this study provides vibration perception curves and identifies the possible importance of gender towards the perception of vibration which arrives at the steering wheel.

Keywords: Perception; Sensation; Hand; Gender; Vibration; Steering; Automobile

1. Introduction

The human subjective response to hand-arm vibration has been investigated in several studies which have established equal sensation curves which indicate the combination of sinusoidal frequency and amplitude that produce a similar sensation of perceived intensity. Miwa (1967) established equal sensation curves for 10 male participants who held their palm flat against a plate which was vibrated sinusoidally in either the vertical or horizontal direction at acceleration amplitudes of either 0.31, 3.1 or 31.1 m/s^2 r.m.s. over the frequency range from 2 to 300 Hz. Human subjective response to hand-arm vibration was found to decrease almost monotonically as a function of frequency. Reynolds et al. (1977) established equal sensation curves for 8 male participants who gripped with one hand a handle which was vibrated sinusoidally in either the vertical, axial or horizontal directions at acceleration amplitudes of either 1.0, 10.0 or 50.0 m/s^2 r.m.s. over the frequency range from 16 to 1000 Hz. The three curves suggested a nonlinear acceleration dependency of the perceived intensity of hand-arm vibration, and a general trend of reduced sensitivity with increasing frequency. Morioka and Griffin (2006) established a family of equal sensation curves for 12 male participants who gripped with one hand a cylindrical handle which was vibrated sinusoidally in either the vertical, axial or horizontal directions over the frequency range from 8 to 400 Hz. At acceleration magnitudes greater than about 2.0 m/s^2 r.m.s. the equal sensation curves suggested a decreased sensitivity to hand-arm vibration with increasing frequency, while at lower acceleration magnitudes the curves suggested an increased sensitivity to hand-arm vibration with increasing frequency from 20 to 100 Hz. At all vibration magnitudes, the curves suggested decreased sensitivity with increasing frequency from 8 to 16 Hz.

With respect to automotive steering vibration Giacomin et al. (2004) established equal sensation curves for 15 participants (10 males and 5 females) who held a rigid sinusoidally rotating steering wheel with both hands at two acceleration amplitudes of 1.0 and 1.5 m/s^2 r.m.s. over the frequency range from 3 to 315 Hz. A constant acceleration dependency was noted from 3 to 5 Hz, and a decrease in the human sensitivity to hand-arm rotational vibration was found with increasing frequency from 5 to 315 Hz. Amman et al. (2005) established equal sensation curves for 28 participants (gender was not reported) who held an automotive steering wheel with both hands. The study investigated the human subjective response to 1.0 m/s^2 r.m.s. amplitude sinusoidal vibration applied along either the longitudinal, lateral or vertical over the frequency range from 8 to 64 Hz. The study also investigated the subjective response to vibration along the rotational direction by means of sinusoidal stimuli with acceleration amplitudes of 0.8 and 1.6 m/s^2 r.m.s. over the frequency range from 8 to 20 Hz. Amman et al.'s equal sensation curves suggested a general trend of decreasing sensitivity to vibration with increasing frequency over the frequency range investigated.

The equal sensation curves established in most of the studies performed to date represent the average responses of small groups of 8 to 15 people. In addition, the human subjective response to hand-arm vibration stimuli is based mainly upon responses from male participants despite the fact that since the 1970s the percentage of female drivers has increased in most countries. In the UK, for example, the number of female drivers has increased from 29 to 63 percent while that of men has only increased from 69 to 81 percent (National Travel Survey, 2005).

The primary objective of the present study was to establish a family of equal sensation curves for perceived intensity of steering wheel rotational vibration using the most commonly applied regression models, namely, least squares regression, all possible regression, backward elimination regression and stepwise regression procedure. The secondary objective was to investigate the effect of gender differences on the shape of the equal sensation curves for hand-arm steering wheel rotational vibration.

2. Experiment

2.1 Test Facility

Figure 1 presents a schematic representation of the steering wheel rotational vibration test facility used in this study and of the associated signal conditioning and data acquisition systems. The main geometric dimensions of the test rig, which were based on average data taken from a small European automobile, are presented in Table 1. The rotational steering system consisted of a 350 mm diameter aluminum wheel attached to a steel shaft which was in turn mounted to two low friction bearings which were encased in a square steel casing. The steering wheel consisted of a 5 mm thick central plate with two cylindrical handles of 25 mm diameter and 3 mm thickness welded at the extremities. The steering wheel was made of aluminum in order to obtain a first natural frequency greater than 350 Hz. Rotational vibration was applied by means of a G&W V20 electrodynamic shaker, which was connected to the shaft by means of a steel stinger rod, and amplified by PA100 amplifier (Gearing and Watson Electronics Limited, 1995) using an Leuven Measurement Systems (LMS) Cada-X 3.5 E software and a 12-channel Difa Systems Scadas III front-end unit (LMS International, 2002). The acceleration obtained at the steering wheel was measured using an Entran MSC6 signal-conditioning unit (Entran Devices Inc, 1991). The acceleration was measured in the tangential direction. The car seat was fully adjustable in terms of horizontal position and back-rest inclination as in the original vehicle. The safety features of the test rig, and the acceleration levels used, conform to the health and safety recommendations outlined by British Standard 7085 (1989).

[Insert here Figure 1]

[Insert here Table 1]

2.2 Test stimuli

Sinusoidal test stimuli were used. The frequencies were chosen to be 1/3 octave band center frequencies in the range from 3 to 400 Hz which span the frequency range (Ajovalasit and Giacomin, 2003; Fujikawa, 1998; Giacomin et al., 2004) over which road vehicles present significant levels of steering wheel vibration. The maximum stroke of the test rig shaker unit (±10 mm) limited the maximum achievable acceleration at the steering wheel which, in turn, limited the minimum test frequency to 3 Hz. For frequencies lower than approximately 3 Hz accurate sinusoidal acceleration signals could not be achieved at the rigid wheel. The acceleration magnitudes were chosen to be in the range from 0.04 to 27 m/s^2 r.m.s.. A total of 86 steering wheel rotational sinusoidal vibration stimuli were used as listed in Table 2.

[Insert here Table 2]

In order to ensure satisfactory signal reproduction accuracy a calibration procedure was performed in order to determine the drive voltage for use with each individual test participant. The accuracy of the signal reproduction was quantified by measuring the maximum r.m.s. error between the actuated stimulus at the wheel and the target drive stimuli. The maximum error was found to be below 5.0%, which compared favorable with the just-noticeable-difference value for human perception of hand-arm vibration of 15 to 18% determined by Morioka (1999).

2.3 Test subjects and test protocol

A total of 40 university students and staff participated in this study, of which 20 were male and 20 were female. A consent form and a short questionnaire were presented to each participant prior to testing, and information was gathered regarding their anthropometry, health and history of previous vibration exposures. Table 3 presents a basic summary of the physical characteristics of the group of test participants. The mean values and the standard deviation of the height and weight of the test participants presented in Table 3 were close to the 50 percentile values for the U.K. population (Pheasant and Haslegrave, 2005). A statistical t-test performed for the test groups suggested significant differences in height and weight between the males and the females ($p<0.05$), while no significant differences were found in age between the males and the females. All subjects declared themselves to be in good physical and mental health.

Before commencing testing each subject was required to remove any heavy clothes such as coats, and to remove any watches or jewelry that they were wearing. They were then asked to adjust the seat position and backrest angle so as to simulate a driving posture as realistically as possible. Since grip type and grip strength (Reynolds and Keith, 1977) are known to effect the transmission of vibration to the hand-arm system, the subjects were asked to maintain a constant palm grip on the steering wheel using both hands. In addition, they were asked to maintain the grip strength which they felt they would use when driving on a winding country road. The subjects were also asked to wear ear protectors so as to avoid auditory cues. Room temperature was maintained within the range from 20 to 25℃ so as to avoid significant environmental effects on the skin sensitivity (ISO 13091-1, 2001).

[Insert here Table 3]

A Borg CR10 category-ratio scale (Borg, 1998), shown in Figure 2, was used to provide direct estimation of the perceived intensity of vibration. The Borg CR10 scale has been found to be reliable in quantifying the human perception of hand-arm vibration, with reliability coefficients ranging from 0.841 to 0.986 (Wos et al., 1988). The information describing the experiment was presented to the test participant by the experimenter using the instructions provided by Borg (Borg, 1998) for the scale’s administration. The test subjects were further asked to focus their eyes on a board which was placed about 1 meter ahead at eye level, which presented the Borg rating scale. Before starting the experiment two trial runs were performed so as to familiarize the participants with the test procedure.

[Insert here Figure 2]

In order to assess the individual’s ability to rate the stimuli, all 86 stimuli were repeated three times in three single blocks, for a total of 258 assessment trials for each participant. The mean Borg CR10 values of the three repetitions, and the SD values, were thus calculated for each stimulus. In order to minimize any possible bias resulting from learning or fatigue effects, the order of presentation of the test signals was randomized for each subject and for each block. A break of 1 minute after the presentation of each block was used to reduce annoyance effects. A 7 second stimulus duration was used so as to provide a vibrotactile stimulus which remained within human short-term memory (Sinclair and Burton 1996), thus a stimulus which could be judged without reliance upon the long-term storage of stimuli information by the test participant. A complete test required approximately 60 minutes to complete with one participant.

3. Multivariate regression methods

A statistical regression analysis was performed using both MATLAB (Mathworks Inc., 2002) and the SPSS software (SPSS Inc., 2004). The objective was to establish a mathematical model to express the Borg CR10 subjective intensity as a function of the two independent parameters of frequency and magnitude. A linear fitting procedure was chosen since nonlinear fitting methods often suffer from convergence problems and since the deviation from linear forms in the current application were not so dramatic as to produce extensive local minima or widely differing multiple solutions. Four different approaches to regression modeling were attempted which differed in the statistical selection criteria used for deciding which variables to maintain in the regression expression. The four methods were least-square regression, all possible regressions, backward elimination and the stepwise regression procedure (Draper and Smith, 1998). Based on the results from a previous study (Ajovalasit and Giacomin, 2007) all the regression models were expressed in logarithmic polynomial form up to either 4th, 5th or 6th order. The use of a logarithmic transformation and of polynomial regression terms from 4th to 6th order for both the frequency and the acceleration values was found in the previous study to provide the most accurate description of the physical phenomena contained in the dataset.

The selection criteria for choosing an optimal model were taken in this study to be the following (a) the fitted model should produce the highest goodness-of fit as defined by the highest adjusted coefficient of determination (R_a^2) and by the smallest residual mean-square error (MSE) (Hocking, 1976), (b) the equal sensation curves which can be determined using the regression model should present similar frequency dependency characteristics to those found in previous studies on the physiology of vibrotactile perception, and (c) the fitted mathematical equation should be as simple as possible in light of possible practical application.

4. Results

Table 4 presents the mean and one standard deviation values obtained for each frequency and each amplitude tested for the 40 test participants. For each test amplitude the mean Borg CR10 subjective values can be seen to generally decrease with increasing test frequency, suggesting a lower perceived intensity at higher frequencies as expected from psychophysical theory (Gescheider, 1997) and from previous research (Miwa, 1967; Reynolds et al., 1977; Giacomin et al., 2004; Amman et al., 2005; Morioka and Griffin, 2006). Another feature that can be observed is that the standard deviation was found to generally increase with increasing test amplitude, suggesting a greater difficulty on the part of the test participants to distinguish high amplitude stimuli.

[Insert here Table 4]

4.1 Effect of the multivariate regression approach

In order to identify an optimal model with which to represent the equal sensation curves the goodness-of-fit statistics were evaluated for each polynomial regression expression determined by means of each multivariate regression procedure. Table 5 presents the goodness-of-fit statistics for the overall test dataset (n = 40) obtained using the four multivariate regression analysis procedures at polynomial orders up to the 6th order. As can be seen from Table 5, although the differences in mean square error MSE and adjusted coefficient of determination R_a^2 were small among the different approaches used, the best result was achieved by means of the stepwise regression procedure using terms up to 6th order, which obtained the lowest MSE value (0.084) and the highest R_a^2 value (0.983).

[Insert here Table 5]

[Insert here Figure 3]

Figure 3 presents the equal sensation curves which achieved the lowest MSE and the highest R_a^2 for each of the different multivariate regression procedures. The curves obtained by means of the stepwise regression procedure suggested a decreased sensitivity with increasing frequency from 6.3 to 400 Hz, a constant sensitivity from 3 to 6.3 Hz, and a dip behavior in the vicinity of 100 Hz similar to the well known response of the Pacinian mechanoreceptors (Verrillo, 1966; Reynolds et al., 1977). In addition, the 6th order stepwise regression procedure produced a regression model with only 12 coefficients which was

$$\boldsymbol{S} = 3.4268 + 0.7638\log(\boldsymbol{f}) + 2.3058\log(\boldsymbol{a}) + 0.5289\log(\boldsymbol{a})^2 - 0.2506\log(\boldsymbol{f})^3 + \\ - 0.0978\log(\boldsymbol{f})^2\log(\boldsymbol{a}) - 0.0881\log(\boldsymbol{f})\log(\boldsymbol{a})^2 + 0.0396\log(\boldsymbol{a})^3 + 0.0523\log(\boldsymbol{f})^4 + \\ - 0.0004\log(\boldsymbol{f})^6 + 0.0003\log(\boldsymbol{f})^5\log(\boldsymbol{a}) - 0.0003\log(\boldsymbol{f})^3\log(\boldsymbol{a})^3 \quad (1)$$

where ***S*** is the Borg CR10 subjective intensity value which is determined by the fitted model, ***f*** is the frequency in units of Hertz and ***a*** is the r.m.s. acceleration magnitude in units of meters per second squared.

4.2 Effect of gender

Table 6 presents the goodness-of-fit statistics obtained for the regression models which were fit separately to the data of only the male test participants (n = 20) and of only the female test participants (n = 20) using the multivariate procedures. For each of the regression methods, the model order which provided the best results for the complete dataset was applied also to the data obtained for each individual gender group. As can be seen in Table 6, the stepwise regression procedure was found to provide the best model for both the male and the female test groups. The procedure provided a MSE value of 0.064 and a value of 0.985 for R_a^2 for the males while it produced a MSE value of 0.168 and a value of 0.973 for R_a^2 for the females.

Figure 4 presents the equal sensation curves obtained for the male and the female sample groups obtained by means of the stepwise regression procedure. From the results of Figure 4 it can be seen that the females provided higher perceived intensity values than the males for the same physical stimulus at most frequencies. At frequencies above approximately 20 Hz the equal sensation curves for the female test group are characterized by a flatter shape than those obtained for the male test group, whereas at frequencies below approximately 20 Hz similar shape was found for both groups. Gender differences were more marked at acceleration amplitudes above approximately 1.0 m/s^2 r.m.s.. For example, it can be seen in Figure 4 that the subjective response of the females for the stimulus with amplitude of 2 m/s^2 r.m.s. and frequency of 30 Hz was approximately 4.0 on the Borg CR-10 scale, while that of males for the same stimulus was approximately 3.0 on the Borg CR-10 scale.

[Insert here Figure 4]

[Insert here Table 6]

5. Discussion

The results of this study suggest that the stepwise regression procedure provided the best equation for modelling the hand-arm equal sensation curves. The best fit equation provided the lowest MSE of 0.084

and the highest adjusted coefficient of determination R_a^2 of 0.983 using only 12 coefficients. Compared to the other regression procedures used in this study, the equal sensation curves obtained by means of stepwise regression suggested small variations in the shape of the curves at low vibration amplitudes and more uniform shape at high vibration amplitudes, resembling the curves defined by previous researchers (Reynolds et al., 1977; Gescheider et al., 2004). A possible explanation of the effectiveness for the stepwise regression procedure may be that only a small number of coefficients were included in the model. Direct support for this can be found in the study of Barrett and Gray (1994) who applied the stepwise regression procedure for constructing a multivariate regression model. They found that the stepwise regression procedure provided a better model using a rather small number of variables as opposed to the all possible subsets approach. In addition, the general efficiency of stepwise regression was noted by Wallace (1964), who suggested that the stepwise regression procedure provided a better model because of the reduced bias of the coefficients selection procedure.

The results of this study also suggest that the equal sensation curves for steering wheel rotational vibration differed between males and females. These differences are most obvious at intensity levels above approximately 1.0 m/s^2 and at frequencies above approximately 20 Hz. This difference is partially supported by the results of Verrillo (1979) who found that vibratory stimuli at suprathreshold levels are felt more intensely by females than by males, and by those of Neely and Burström (2006) which suggest that females report higher levels of physical intensity and discomfort than males. Similar indications can also be found in the study of steering wheel vibration induced fatigue performed by Giacomin and Abrahams (2000), which found that females reported greater arm region discomfort than males, and by the questionnaire-based investigation of Giacomin and Screti (2005) which found that female drivers reported higher discomfort responses than male drivers for the hand-arm region.

While substantial differences in the perception of hand-arm vibration between males and females appear to be present in the research literature, the exact cause has yet to be clarified. While gender itself may be a dominant factor, particularly in the trends identified by Verrillo, the actual mechanical mass of the hand-arm system may be the primary cause of variance in several research investigations, including this current study. For example, Burström and Lundström (1994) have suggested that the size and mass of the subject's hand and arm greatly affect energy absorption. Further research is therefore required so as to establish whether these differences are sensory differences or, instead, biomechanical in nature.

[Insert here Figure 5]

Figure 5 presents the best fit equal sensation curves determined in this study, the results of Miwa (1967) for hand-arm vibration in the vertical direction, the results of Reynolds et al. (1977) for hand-arm axial direction vibration, the results of Giacomin et al. (2004) and those of Amman et al. (2005) for steering wheel hand-arm rotational vibration. Each of the equal sensation curves shown in Figure 5 represents a curve of equal subjective perceived intensity. The equal sensation curves of the current research study are interpolations of the Borg values provided by the test subjects. The curves shown in Figure 5 are for the Borg values 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 4.0, 5.0, 6.0, 7.0 and 8.0. The equal sensation curves from the previous research studies are, instead, interpolations of the acceleration data points obtained using magnitude estimation test protocols in the case of Reynolds et al., Giacomin et al. and Amman et al. and a paired-comparison method in the case of Miwa. All the curves suggest a decreased sensitivity of hand-arm vibration with increasing frequency for frequencies above about 6.3 Hz. For frequencies below 6.3 Hz, the curves obtained in this study suggest a constant sensitivity as also found in the results of Miwa and of Giacomin et al.. The reduction in sensitivity was found, however, to be greater in the curves of Miwa than in either those of Reynolds et al. or those of the current study. While difficult to demonstrate without replication of each of the previous studies, a possible explanation for the differences may in part be the use of different psychophysical test methods in the various investigations and the use of only male test participants. As can be seen from Figure 4, females were found to provide higher perceived intensity values than males resulting in a lower equal sensation curve.

It is also evident from Figure 5 that at low perceived intensities from 0.5 (just noticeable) to 1.0 (very weak) of the Borg CR-10 scale the equal sensation curves determined in the current study show similarities in shape to the well-known vibrotactile perception threshold curves of the human hand. As the perceived intensity increases towards the maximum value of 8.0 found in the current study the equal sensation curves assume a more uniform shape, however, resembling the annoyance threshold for the hand-arm system defined by Reynolds et al. (1977). Comparison of the results of Figure 5 suggests that while the curves of Miwa and of Amman et al. suggest relatively small dependencies on the vibration amplitude, the equal sensation curves of the current study and those of Reynolds et al. suggest a significant nonlinear response. A possible explanation of these differences may be the use of relatively low reference stimuli amplitudes in the studies of Miwa and of Amman et al. The use of a low reference frequency has been found to affect the shape of equal sensation curves, especially at frequencies above approximately 50 Hz (Giacomin et al., 2004).

6. Conclusion

Psychophysical response tests of 40 participants (20 males and 20 females) were performed in a steering wheel rotational vibration simulator using the category-ratio Borg CR10 scale procedure for direct estimation of perceived vibration intensity. The equal sensation curves for steering wheel hand-arm rotational vibration were established using multivariate regression analysis procedures. The best fit regression model to describe the equal sensation curves was found to be a 6^{th} order polynomial model having 12 terms, which was obtained by means of a stepwise regression procedure. The results suggest a nonlinear dependency of the subjective perceived intensity on both frequency and amplitude. The equal sensation curves were found to be characterized by a decreased sensitivity to hand-arm vibration with increasing frequency from 6.3 to 400 Hz, but a constant sensitivity from 3 to 6.3 Hz. The best fit regression models determined for the male test participants and for the female test participants suggest important differences in the frequency range from 20 to 400 Hz, while both curves suggest similar sensitivity at frequencies below 20 Hz. Females were found to be more sensitive to steering wheel rotational vibration than males, particularly at intensity levels above approximately 1.0 m/s^2 r.m.s. and at frequencies above approximately 20 Hz ($p < 0.05$).

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[Table 1] Geometric dimensions of the steering wheel rotational vibration test rig.

[Table 2] Frequency and amplitude of the 86 sinusoidal rotational steering wheel vibration stimuli.

[Table 3] Mean and standard deviation summary statistics for the test participants.

[Table 4] Summary of the subjective responses obtained by means of Borg CR-10 scale.

[Table 5] Goodness of fit statistics obtained for overall data set (n = 40).

[Table 6] Goodness of fit statistics obtained separately for the male test participants data set (n = 20) and for the female test participants data set (n = 20).

[Figure 1] Steering wheel vibration test rig and associated electronics.

[Figure 2] Borg's category ratio CR-10 scale (adapted from Borg 1998).

[Figure 3] Equal sensation curves obtained for Borg subjective perceived intensity values from 0.5 to 8.0 using the four regression procedures considered in this study.

(a) Least-square regression procedure,

(b) All possible regressions procedure,

(c) Backward elimination regression procedure,

(d) Stepwise regression procedure.

[Figure 4] Equal sensation curves obtained separately for the male test participants and for the female test participants, obtained by means of the stepwise regression procedure.

[Figure 5] Equal sensation curves obtained in the current study and those obtained in previous studies of hand-arm translational or rotational vibration.

[Table 1] Geometric dimensions of the steering wheel rotational vibration test rig.

Geometric Parameter	**Value**
Steering column angle (H18)	23
Steering wheel hub centre height above floor (H17)	710 mm
Seat H point height from floor (H30)	275 mm
Horizontal distance adjustable from H point to steering wheel hub centre (d = L11=L51)	390-550 mm
Steering wheel handle diameter	25 mm
Steering wheel diameter	350 mm

[Table 2] Frequency and amplitude of the 86 sinusoidal rotational steering wheel vibration stimuli.

Frequency (Hz)	Acceleration amplitude (r.m.s. m/s^2)
3	0.080, 0.165, 0.486, 1.000
4	0.318, 0.127, 0.503, 1.263
5	0.080, 0.225, 1.065, 3.000
6.3	0.143, 0.454, 0.810, 2.579
8	0.080, 0.275, 1.748, 6.000
10	0.153, 0.560, 1.071, 3.921
12.5	0.080, 0.298, 2.146, 8.000
16	0.159, 0.634, 1.263, 5.017
20	0.080, 0.335, 2.867, 12.000
25	0.167, 0.732, 1.530, 6.694
31.5	0.080, 0.364, 3.521, 16.000
40	0.172, 0.795, 1.710, 7.906
50	0.080, 0.382, 3.981, 19.000
63	0.176, 0.853, 1.876, 9.088
80	0.070, 0.362, 4.255, 22.000
100	0.060, 0.782, 1.841, 10.197
125	0.060, 0.336, 4.461, 25.000
160	0.040, 0.642, 1.620, 10.307
200	0.060, 0.344, 4.713, 27.000
250	0.150, 1.411, 2.977, 13.265
315	0.400, 1.360, 8.529
400	0.800, 3.782, 6.347

[Table 3] Mean and standard deviation summary statistics for the test participants.

Test Group	Age (years)	Height (m)	Weight (kg)
Males (n=20)	33.9 (6.2)	1.81 (0.08)	84.2 (14.0)
Females (n=20)	34.3 (6.6)	1.61 (0.06)	56.5 (7.1)
Total (N=40)	34.1 (6.4)	1.71 (0.12)	70.3 (17.8)

[Table 4] Summary of the subjective responses obtained by means of Borg CR-10 scale.

Frequency (Hz)	Acceleration (m/s^2)	Subjective response	SD
3	0.08	0.695	0.544
	0.165	1.525	0.758
	0.486	2.658	1.006
	1	4.131	1.211
4	0.127	0.837	0.724
	0.318	1.645	0.826
	0.503	2.408	0.864
	1.263	4.100	1.305
5	0.08	0.578	0.527
	0.225	1.612	0.800
	1.065	4.687	1.748
	3	6.188	1.748
6.3	0.143	1.433	0.796
	0.454	2.425	0.936
	0.81	3.968	1.792
	2.579	6.538	1.663
8	0.08	0.412	0.467
	0.275	2.198	0.891
	1.748	4.805	1.252
	6	8.651	2.709
10	0.153	0.986	0.693
	0.56	2.216	0.963
	1.071	3.509	1.369
	3.921	6.272	1.311
12.5	0.08	0.460	0.358
	0.298	1.361	0.641
	2.146	5.389	2.155
	8	8.383	1.804
16	0.159	0.729	0.428
	0.634	2.523	1.101
	1.263	3.231	0.813
	5.017	6.845	2.399
20	0.08	0.213	0.221
	0.335	1.652	0.791
	2.867	4.619	1.180
	12	8.574	2.769
25	0.167	0.650	0.507
	0.732	1.948	1.032
	1.53	4.082	2.076
	6.694	6.206	1.676
31.5	0.08	0.228	0.329
	0.364	1.123	0.677
	3.521	4.489	1.979
	16	8.148	1.942

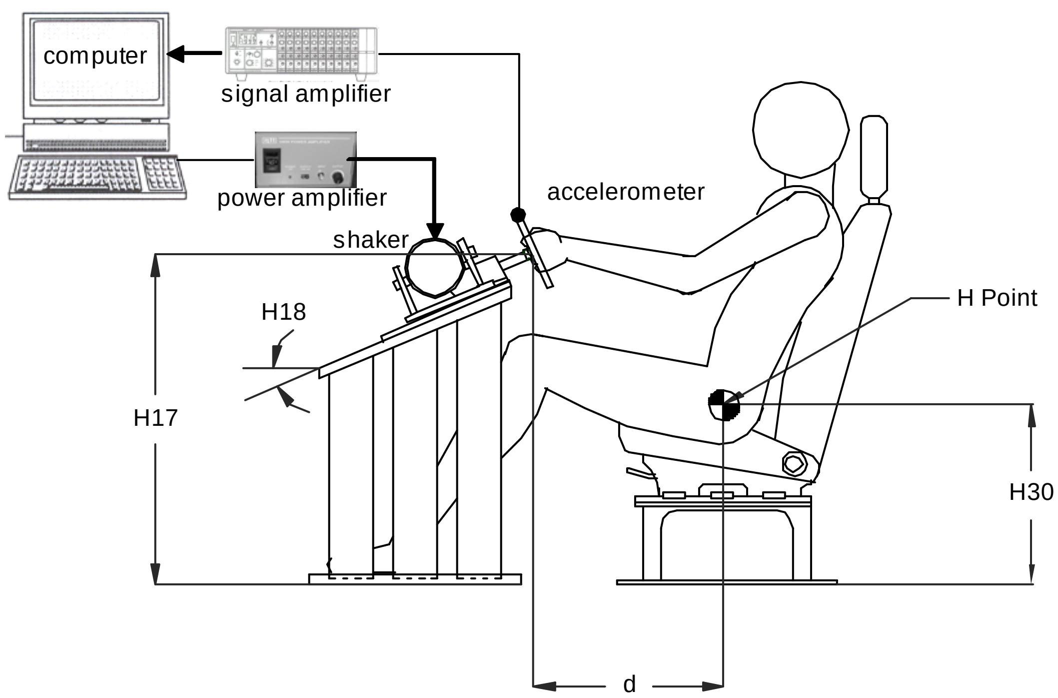
Frequency (Hz)	Acceleration (m/s^2)	Subjective response	SD
40	0.172	0.701	0.558
	0.795	2.094	1.090
	1.71	2.333	0.903
	7.906	6.335	2.683
50	0.08	0.194	0.198
	0.382	1.231	0.692
	3.981	3.910	1.432
	19	7.610	2.953
63	0.176	0.833	0.612
	0.853	1.509	0.771
	1.876	2.716	1.430
	9.088	4.407	1.720
80	0.07	0.198	0.218
	0.362	1.107	0.633
	4.255	3.599	1.599
	22	6.459	1.946
100	0.06	0.092	0.180
	0.782	1.780	1.167
	1.841	1.800	0.822
	10.197	4.619	2.074
125	0.06	0.134	0.223
	0.336	1.271	0.769
	4.461	2.723	1.190
	25	5.483	2.648
160	0.04	0.043	0.127
	0.642	1.321	0.743
	1.62	2.394	1.138
	10.307	3.967	1.678
200	0.06	0.098	0.183
	0.344	0.880	0.730
	4.713	2.686	1.268
	27	4.429	2.423
250	0.15	0.238	0.414
	1.411	1.457	0.841
	2.977	2.271	1.292
	13.265	3.354	1.648
315	0.4	0.495	0.609
	1.36	1.303	0.947
	8.529	3.036	1.809
400	0.8	0.709	0.769
	3.782	2.224	1.690
	6.347	2.305	1.487

[Table 5] Goodness of fit statistics obtained for overall data set (n = 40).

Parameters / Methods	Polynomial order	Interaction terms	Mean square error (MSE)	Adjusted coefficient of determination (R_a^2)	Number of regression coefficients
Least-squares procedure	4th	3rd	0.107	0.979	12
		4th	0.088	0.982	15
	5th	3rd	0.108	0.978	14
		4th	0.093	0.981	17
		5th	0.093	0.980	21
	6th	3rd	0.108	0.978	16
		4th	0.091	0.981	19
		5th	0.092	0.980	23
		6th	0.098	0.975	28
Stepwise procedure	4th	-	0.106	0.979	9
	5th	-	0.085	0.983	13
	6th	**-**	**0.084**	**0.983**	**12**
Backward elimination procedure	4th	-	0.101	0.980	11
	5th	-	0.099	0.980	11
	6th	-	0.099	0.981	10
All possible procedure	4th	-	0.100	0.980	13
	5th	-	0.106	0.980	17
	6th	-	0.109	0.979	19

[Table 6] Goodness of fit statistics obtained separately for the male test participants data set (n = 20) and for the female test participants data set (n = 20).

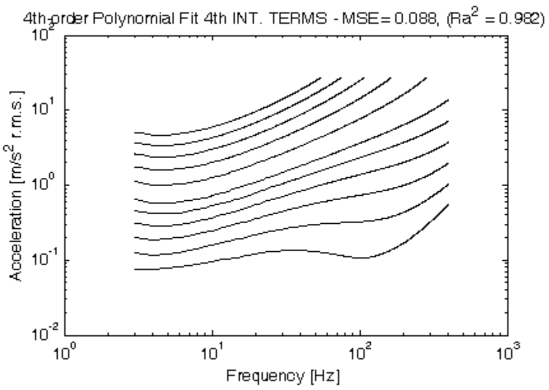
Parameters / Methods	Gender	Polynomial order	Interaction terms	Mean square error (MSE)	Adjusted coefficient of determination (R_a^2)	Number of regression coefficients
Least-squares procedure	M	4^{th}	4^{th}	0.07	0.983	15
	F			0.174	0.970	15
Stepwise procedure	**M**	**6^{th}**	-	**0.064**	**0.985**	**12**
	F			**0.168**	**0.973**	**12**
Backward elimination procedure	M	6^{th}	-	0.08	0.982	11
	F			0.181	0.971	11
All possible procedure	M	4^{th}	-	0.083	0.981	13
	F			0.194	0.969	13



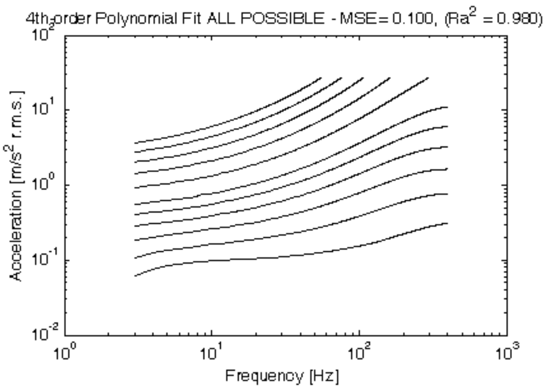
[Figure 1] Steering wheel vibration test rig and associated electronics.

0	Nothing at all	"No P"
0.3		
0.5	Extremely weak	Just noticeable
1	Very weak	
1.5		
2	Weak	Light
2.5		
3	Moderate	
4		
5	Strong	Heavy
6		
7	Very strong	
8		
9		
10	**Extremely strong "Max P"**	
11		
⺃		
●	Absolute maximum	Highest possible

[Figure 2] Borg's category ratio CR-10 scale (adapted from Borg 1998).



(a)



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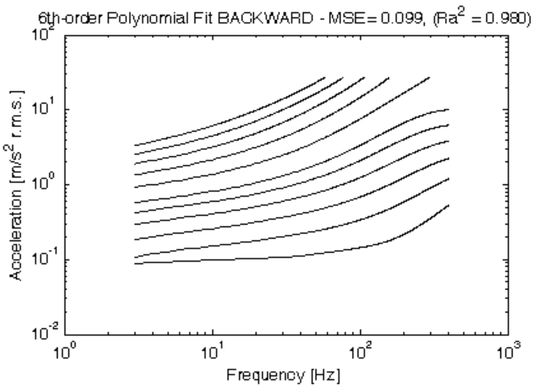

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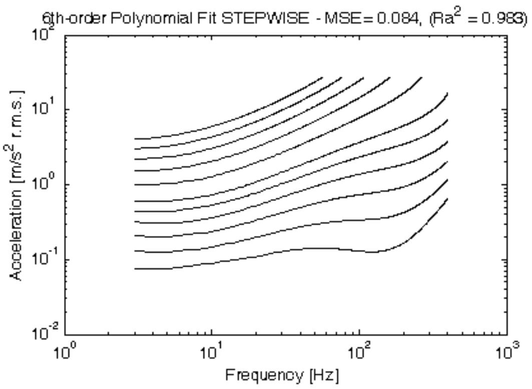


(d)

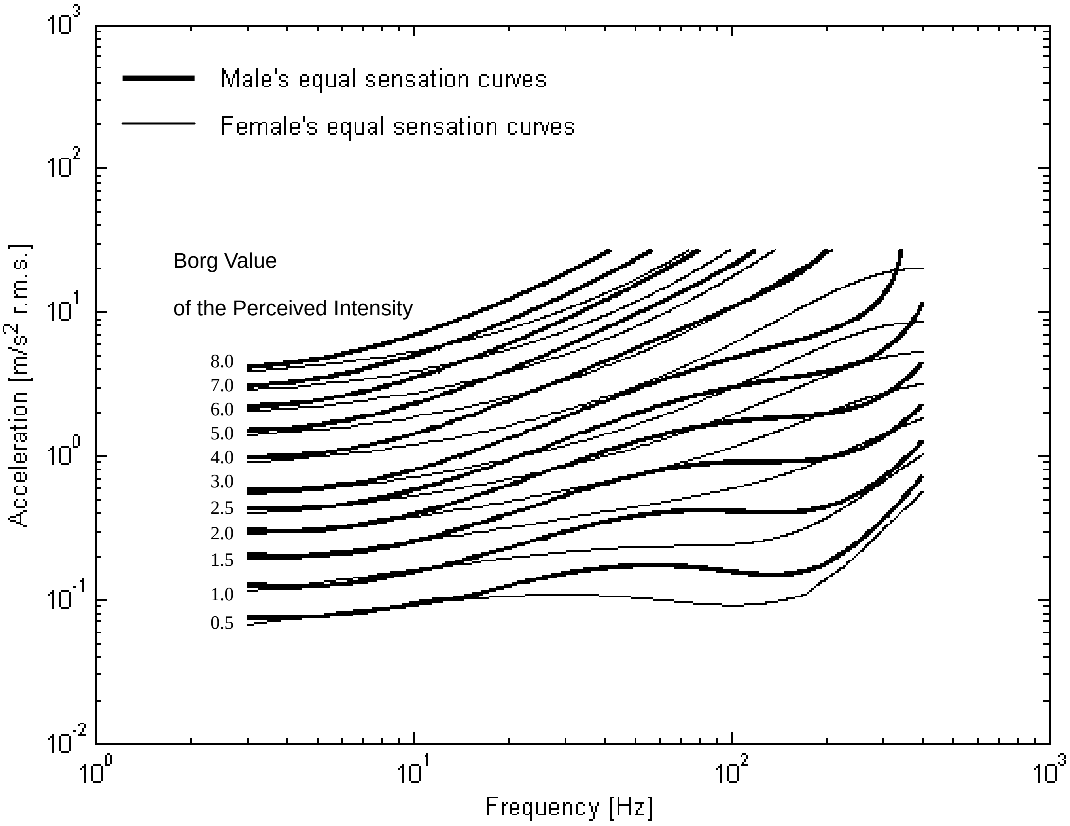
[Figure 3] Equal sensation curves obtained for Borg subjective perceived intensity values from 0.5 to 8.0 using the four regression procedures considered in this study.

(a) Least-square regression procedure,

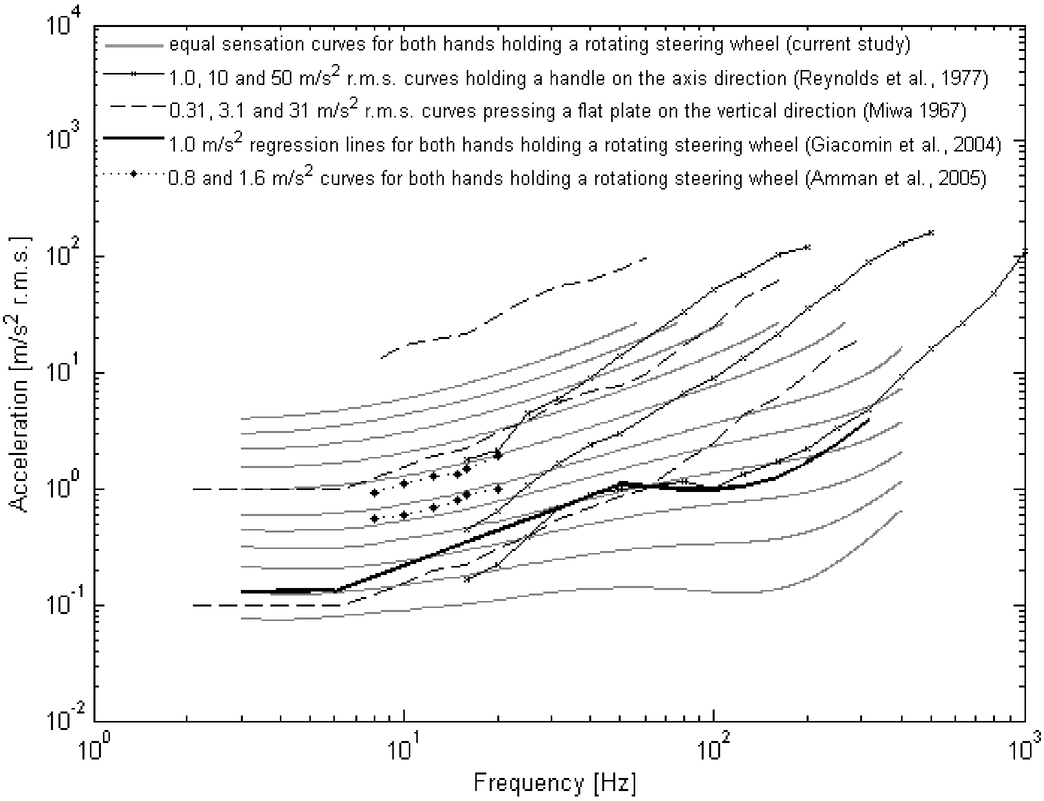
(b) All possible regressions procedure,

(c) Backward elimination regression procedure,

(d) Stepwise regression procedure.



[Figure 4] Equal sensation curves obtained separately for the male test participants and for the female test participants, obtained by means of the stepwise regression procedure.



[Figure 5] Equal sensation curves obtained in the current study and those obtained in previous studies of hand-arm translational or rotational vibration.