Effects of physical body mass on the subjective perceived intensity of steering wheel rotational vibration

Marco Ajovalasit*, Byung-Ho Jeon, Joseph Giacomin
Human Centred Design Institute (HCDI)
School of Engineering and Design, Brunel University
Uxbridge, Middlesex, UB8 3PH, United Kingdom
Email: marco.ajovalasit@brunel.ac.uk*, byung-ho.jeon@brunel.ac.uk, joseph.giacomin@brunel.ac.uk

Abstract

The work presented in this study investigates the effect of physical body mass on the subjective perceived intensity of steering wheel hand-arm vibration. Psychophysical tests of 40 participants (20 light and 20 heavy participants) were performed using using the category-ratio Borg CR10 scale procedure. Equal sensation curves were established using sinusoidal vibrations at 22 third octave band centre frequencies from 3 to 400 Hz, with acceleration amplitudes from 0.04 to 27 m/s2 r.m.s. The equal sensation curves obtained from this experiment for the light participants were found generally higher than those of the heavy participants, suggesting that the equal sensation curves of the light test participants resemble those of the female subjects, while the equal sensation curves of the heavy test participants resemble those of the male subjects. Significant differences were found in Borg CR10 values at frequencies from 6.3 to 100 Hz between the light and heavy participants at a 5 % confidence level ($p<0.05$). From the results of this experiment it can be suggested that the equal sensation curves for steering wheel rotational vibration differ mainly due to differences in body size rather than differences of gender, and that the lighter individuals suffer greater subjective intensity for the same physical intensity of steering wheel vibration.

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 physical body mass towards the perception of vibration which arrives at the steering wheel.

Keywords: Perception; Sensation; Hand; body mass; Vibration; Steering; Automobile

1. Introduction

Previous research studies (Ajovalasit and Giacomin, 2009) have developed a family of equal sensation curves for hand-arm steering wheel rotational vibration and investigated the effect of gender (Jeon et al., 2009) on the human subjective perceived intensity of steering wheel vibration. In these studies it was noted that male subjects were less sensitive than female subjects in terms of their subjective response to steering wheel hand-arm vibration. However, it was not possible from those tests to establish whether the differences are sensory or, instead, biomechanical in nature, because the male test participants also differed from the female participants in terms of their body mass ($p<0.05$). In fact, body mass is one of the principle determinants for the energy absorptions in both whole-body vibration (Wei and Griffin, 2000; Wang et al., 2006) and hand-arm vibration (Burström and Lundström, 1994). In case of the whole body vibration, Parsons and Griffin (1982) established equal sensation curves in order to investigate the effect of subject size on the subjective response with 36 participants (18 males and 18 females) who exposed vertical seat vibration. The vibration stimuli consisted of third octave centre frequencies from 1 to 31.5 Hz at acceleration amplitude of 0.8 m/s^2 r.m.s.. The results suggested that the significant correlations were found between subject size and the discomfort at most frequencies.

Due to the lack of scientific literature concerning the effect of physical body mass on the human perception of hand-arm vibration, this study therefore describes an experiment which investigated the effect of physical body mass on the subjective response of steering wheel hand-arm vibration. A psychophysical experimental was performed in which the test participants were separated into two groups: one consisting of individuals with small overall body mass and one consisting of individuals of large overall body mass.

The primary objective of the present study was to establish a family of equal sensation curves for perceived intensity of steering wheel rotational vibration so as to obtain a mathematical model to express the human subjective perceived intensity as a function of the two independent parameters of vibration frequency and vibration magnitude. The secondary objective was to investigate the effect of physical body mass 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

Eighty-six 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. Table 2 lists the frequency and amplitude of the 86 sinusoidal rotational steering wheel vibration stimuli used in this study.
[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 favorably 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, 20 light participants and 20 heavy participants, were randomly selected to participate in the experiment. Those of less than 65 kg of body mass were classified into the light body mass group, while the other participants who were more than 65kg were assigned to the heavy body mass group. The value of 65 kg was used because it was the median value of the subjects who participated in the experiment. Each group consisted of 10 males and 10 females in order to avoid the possible effect of gender.

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 test participants in terms of the mean value and the standard deviation of the age, height and mass. A statistical t-test performed for the test groups suggested significant differences in height and mass between the light and the heavy test participants ($p<0.05$), while no significant differences were found in age. All subjects declared themselves to be in good physical and mental health.
[Insert here Table 3]

For each test subject, a strict test protocol was adhered to in which a predetermined sequence of events, each of fixed time duration, was performed. Upon arriving in the laboratory, each subject was issued an information and consent form, and was provided an explanation of the experimental methods and of the laboratory safety features.

Before commencing testing each subject was required to remove any heavy clothes such as coats, and to remove any watches or jewellery that they were wearing. In order to reduce the statistical variance in the test results the driving posture was controlled for each test participant since the body posture is known to effect subjective response (Griffin, 1990). Four postural angles were controlled which were the wrist, elbow, shoulder and back angles (Norkin and White, 2003) as shown in Table 4. For the wrist angle the range from 177 to 190 was chosen while for the elbow, shoulder and back angles the range from 102 to 126, from 23 to 39 and from 95 to 105 were chosen, respectively, based on the range of comfortable postures suggested by the literature (Andreoni et al., 2002; Babbs, 1979; Hanson et al., 2006; Henry Dreyfuss Associates, 2002; Park et al., 1999; Porter and Gyi, 1998; Rebiffé, 1969; Seidl, 1994; Shayaa, 2004; Tilley, 1994; Wisner and Rebiffé, 1963). The chosen data of the ranges for each postural angle were the median values of the data presented in Table 4.
[Insert here Table 4]

Since grip type and grip strength (Reynolds and Keith, 1977) are also 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 an automobile 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).

A Borg CR10 category-ratio scale (Borg, 1998), shown in Figure 2, was used to estimate the subjectively perceived intensity of the steering wheel rotational vibration. 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 a trial run involving three stimuli was performed so as to familiarize the participants with the test procedure.
[Insert here Figure 2]

The 86 test 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 standard deviation values, were 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 randomised for each subject 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 session required approximately 60 minutes to complete with one participant.

3. Multivariate regression method

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 vibration frequency and vibration 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 was not so dramatic as to produce extensive local minima or widely differing multiple solutions. The stepwise regression procedure was employed to develop sensation curves using the data from the band-limited random vibration tests because it had provided the best fit regression model among other regression procedures presented in the previous study (Jeon et al., 2009). Based on the results from previous research studies (Ajovalasit and Giacomin, 2007; Jeon et al., 2009) all the regression models were expressed in logarithmic polynomial form up to 6th order. The use of a logarithmic transformation and of polynomial regression terms 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 5 presents the mean and one standard deviation values obtained for each frequency and each amplitude tested for the complete 40 participants. The results obtained from this experiment were not significantly different from those obtained in the previous study (Jeon et al., 2009) for the effect of gender. A t-test performed at a 5% confidence level ($p>0.05$) found no statistically significant difference, at any frequency or amplitude, between the mean value of the new data set and the results from the previous study.

[Insert here Table 5]

Table 6 presents the goodness of fit statistics obtained for the regression model by means of the stepwise regression procedure implemented by Matlab software (Mathworks Inc., 2002). The same selection criteria as those described in the previous study (Jeon et al., 2009) were adopted to rate the quality of the fit of the correlation equation. The stepwise regression procedure provided a residual mean square (*MSE*) value of 0.073 and an adjusted coefficient of determination (R_a^2) value of 0.985.

[Insert here Table 6]

For the complete group of 40 test participants the stepwise regression procedure produced a 6th order polynomial regression model with 12 regression coefficients. The best fit model was

$$\boldsymbol{S} = 3.8812 - 0.4091\log(\boldsymbol{f}) + 2.3672\log(\boldsymbol{a}) + 0.544\log(\boldsymbol{a})^2 - 0.218\log(\boldsymbol{f})^3 + \\ - 0.1063\log(\boldsymbol{f})^2\log(\boldsymbol{a}) - 0.09\log(\boldsymbol{f})\log(\boldsymbol{a})^2 + 0.0436\log(\boldsymbol{a})^3 + 0.0469\log(\boldsymbol{f})^4 + \\ - 0.0004\log(\boldsymbol{f})^6 + 0.0003\log(\boldsymbol{f})^5\log(\boldsymbol{a}) - 0.0003\log(\boldsymbol{f})^3\log(\boldsymbol{a})^3 \quad (1)$$

where ***S*** is the Borg CR10 subjective perceived 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.

Figure 3 presents the family of the equal sensation curves defined by equation 1, which was determined using sinusoidal vibration obtained data and the stepwise regression procedure. The equal sensation curves obtained for the complete group of 40 participants were not significantly different from those obtained in the previous experiment for the effect of gender which was described in the previous study (Jeon et al., 2009).

[Insert here Figure 3]

4.1 Results for the physical body mass test groups

Table 7 presents the mean and one standard deviation values obtained for each frequency and each amplitude for the light and heavy body mass groups consisting of 20 test participants respectively. The subjective response values of the light participants were generally higher than those of the heavy participants. Significant differences were found in Borg CR10 values at frequencies from 6.3 to 100 Hz obtained between the subjective responses of the light and heavy participants at a 5 % confidence level ($p<0.05$).

[Insert here Table 7]

Table 8 presents the goodness-of-fit statistics obtained for the regression models which were fit separately to the data of only the light participants (n = 20) and of only the heavy participants (n = 20) by means of the stepwise regression procedure. The model order which provided the best results for the complete dataset was applied also to the data obtained for each individual body mass group. The stepwise regression procedure provided an *MSE* value of 0.147 and a value of 0.975 for R_a^2 for the light test participants, while it produced an *MSE* value of 0.06 and a value of 0.986 for R_a^2 for the heavy test participants.

[Insert here Table 8]

For the light group of 20 test participants the stepwise regression procedure produced a 6^{th} order polynomial regression model with 12 regression coefficients. The best fit model was

$$\boldsymbol{S} = 3.7106 + 0.5765\log(\boldsymbol{f}) + 2.3673\log(\boldsymbol{a}) + 0.5571\log(\boldsymbol{a})^2 - 0.2137\log(\boldsymbol{f})^3 + \\ - 0.1007\log(\boldsymbol{f})^2\log(\boldsymbol{a}) - 0.0883\log(\boldsymbol{f})\log(\boldsymbol{a})^2 + 0.0537\log(\boldsymbol{a})^3 + 0.0442\log(\boldsymbol{f})^4 + \\ - 0.0004\log(\boldsymbol{f})^6 + 0.0003\log(\boldsymbol{f})^5\log(\boldsymbol{a}) - 0.0003\log(\boldsymbol{f})^3\log(\boldsymbol{a})^3 \quad (2)$$

For the heavy group of 20 test participants the stepwise regression procedure also produced a 6^{th} order polynomial regression model with 12 regression coefficients. The best fit model was

$$\boldsymbol{S} = 4.0526 + 0.2414\log(\boldsymbol{f}) + 2.3672\log(\boldsymbol{a}) + 0.53091\log(\boldsymbol{a})^2 - 0.2222\log(\boldsymbol{f})^3 + \\ - 0.1119\log(\boldsymbol{f})^2\log(\boldsymbol{a}) - 0.0918\log(\boldsymbol{f})\log(\boldsymbol{a})^2 + 0.0336\log(\boldsymbol{a})^3 + 0.0496\log(\boldsymbol{f})^4 + \\ - 0.0005\log(\boldsymbol{f})^6 + 0.0003\log(\boldsymbol{f})^5\log(\boldsymbol{a}) - 0.0002\log(\boldsymbol{f})^3\log(\boldsymbol{a})^3 \quad (3)$$

Figure 4 compares the two families of equal sensation curves obtained for the light test participants (n = 20) and the heavy test participants (n = 20). The light participants rated the subjective intensity generally higher than the heavy participants for the same vibration stimulus, especially in the frequency range from 6.3 to 100 Hz.
[Insert here Figure 4]

The differences were found to be similar to the previous results (Jeon et al., 2009) obtained using the sinusoidal vibration. The equal sensation curves of the light participants resemble those of the female test participants, while those of heavy participants resemble those of the male test participants. In all three data sets the female or the light participants produced higher subjective response values than the male or the heavy participants, at frequencies above approximately 6.3 Hz.

5. Discussion

Comparing the shapes of the equal sensation curves of Figure 4 obtained in the current study to those of Figure 5 which presents the equal sensation curves obtained for the male and the female sample groups from the previous study (Jeon et al., 2009), it can be observed that the curves of the light test participants resemble those of the female subjects, while the curves of the heavy test participants resemble those of the male subjects. As previously noted in the previous study (Jeon et al., 2009), these differences were most obvious at frequencies in the range from approximately

6.3 to 100 Hz. For example, the subjective response of the light participants for the stimulus with amplitude of 1.0 m/s^2 r.m.s. and frequency of 30 Hz was approximately 2.5 on the Borg CR10 scale, while that of heavy participants for the same stimulus was approximately 2.0 on the Borg CR10 scale as shown in Figure 4.
[Insert here Figure 5]

The differences between the light participants and the heavy participants are partially supported by the previous results of Giacomin and Abrahams (2000), who suggested that the light test subjects perceived greater discomfort than the heavy test subjects in their arms for the 4 and 8 Hz test frequencies. Another similar indication supporting the current result is that the size and mass of the subject's hand and arm greatly affect energy absorption (Burström and Lundström, 1994). From the results of this experiment it can therefore be suggested that the equal sensation curves for steering wheel rotational vibration differ mainly due to differences in body size, rather than differences of gender.

6. Conclusion

Psychophysical response tests of 40 test participants (20 light participants and 20 heavy participants) 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 sinusoidal vibration stimuli by means of a stepwise regression procedure.

The results obtained from this experiment were not significantly different at a 5% confidence level ($p>0.05$) from those obtained in the previous study (Jeon et al., 2009) for the effect of gender. The subjective response values of the light participants were generally higher than those of the heavy participants, suggesting that the equal sensation curves of the light test participants resemble those of the female subjects, while the equal sensation curves of the heavy test participants resemble those of the male subjects.

Significant differences were found in Borg CR10 values at frequencies from 6.3 to 100 Hz between the light and heavy participants at a 5 % confidence level ($p<0.05$). For example, the subjective response of the light participants for the stimulus with amplitude of 1.0 m/s^2 r.m.s. and frequency of 30 Hz was approximately 2.5 on the Borg CR10 scale, while that of heavy participants for the same stimulus was approximately 2.0 on the Borg CR10 scale. From the results of this experiment it can therefore be suggested that the equal sensation curves for steering wheel rotational vibration differ mainly due to differences in body size rather than differences of gender, and that the lighter individuals suffer greater subjective intensity for the same physical intensity of steering wheel vibration.

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

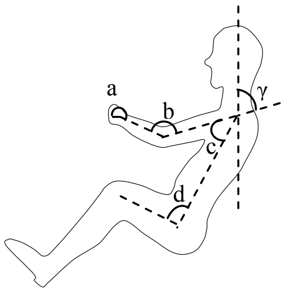
Geometric Parameter	Value
Steering column angle (H18)	23
Steering wheel hub centre height above floor (H17)	710 mm
Seat H point height from floor (H30)	275 mm
Horizontal distance adjustable from H point to steering wheel hub centre (d = L11=L51)	390-550 mm
Steering wheel handle diameter	25 mm
Steering 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	0.08, 0.17, 0.49, 1.0
4	0.13, 0.32, 0.5, 1.26
5	0.08, 0.23, 1.07, 3.0
6.3	0.14, 0.45, 0.81, 2.58
8	0.08, 0.28, 1.75, 6.0
10	0.15, 0.56, 1.07, 3.92
12.5	0.08, 0.3, 2.15, 8.0
16	0.16, 0.63, 1.26, 5.02
20	0.08, 0.34, 2.87, 12.0
25	0.17, 0.73, 1.53, 6.69
31.5	0.08, 0.36, 3.52, 16.0
40	0.17, 0.8, 1.71, 7.91
50	0.08, 0.38, 3.98, 19.0
63	0.18, 0.85, 1.88, 9.09
80	0.07, 0.36, 4.26, 22.0
100	0.06, 0.78, 1.84, 10.2
125	0.06, 0.34, 4.46, 25.0
160	0.04, 0.64, 1.62, 10.31
200	0.06, 0.34, 4.71, 27.0
250	0.15, 1.41, 2.98, 13.27
315	0.4, 1.36, 8.53
400	0.8, 3.78, 6.35

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

Test Group	Age [years]	Height [m]	Mass [kg]
Lighter (n=20)	30.6 (7.2)	1.66 (0.08)	57.4 (5.2)
Heavier (n=20)	33.4 (7.1)	1.75 (0.11)	78.5 (12.0)
Total (N=40)	32.0 (7.2)	1.71 (0.10)	68.0 (14.1)



[unit : degree]

Research	a	b	c	d
Wisner-Rebiffé (1963)	-	80 ~ 90	15 ~ 35	85 ~ 100
Rebiffé (1969)	170 ~ 190	80 ~ 120	10 ~ 45 *	95 ~ 120
Babbs (1979)	170 ~ 190	80 ~ 110	15 ~ 35 *	85 ~ 115
Seidl (1994)	187	126	33	97.9
Tilley (1994)	-	80 ~ 165	0 ~ 35	95 ~ 100
Porter and Gyi (1998)	-	121 ± 18	45.1 ± 2.6	100 ± 5.6
Park et al. (1999)	-	112 ± 11	19.2 ± 5.6	116 ± 6.5
Andreoni et al. (2002)	-	115 ± 10	32 ± 10	93 ± 6
Shayaa (2004)	214 ± 6.1	139 ± 18.9	38 ± 7	108 ± 7.8
Hanson et al. (2006)	187 ± 10	128 ± 16	39 ± 15	100 ± 4.4

[Table 4] Minimum and maximum angles of the (a) wrist, (b) elbow, (c) shoulder and (d) back which were found to guarantee postural comfort.
* The angle is from shoulder to the vertical (γ).

[Table 5] Summary of the subjective response of the complete group of 40 test subjects to sinusoidal steering wheel vibration, obtained by means of Borg CR10 scale.

Freq. [Hz]	Acceleration [r.m.s. m/s^2]	Subjective response	Standard deviation
3	0.08	0.6	0.4
	0.17	1.51	0.65
	0.49	2.67	1.03
	1	4.43	1.3
4	0.13	0.7	0.55
	0.32	1.58	0.78
	0.5	2.5	0.72
	1.26	4.06	1.48
5	0.08	0.46	0.51
	0.23	1.49	0.8
	1.07	4.55	1.25
	3	6.32	1.69
6.3	0.14	1.35	0.71
	0.45	2.24	0.77
	0.81	3.95	1.26
	2.58	6.67	1.65
8	0.08	0.35	0.27
	0.28	2.21	0.81
	1.75	4.78	1.18
	6	8.78	2.03
10	0.15	0.84	0.57
	0.56	2.01	0.67
	1.07	3.62	1.38
	3.92	6.31	1.41
12.5	0.08	0.34	0.26
	0.3	1.35	0.61
	2.15	5.17	1.59
	8	8.07	1.93
16	0.16	0.69	0.37
	0.63	2.26	0.64
	1.26	3.17	0.76
	5.02	6.86	2.25
20	0.08	0.15	0.17
	0.34	1.5	0.72
	2.87	4.46	1.3
	12	8.44	2.3
25	0.17	0.52	0.35
	0.73	1.75	0.89
	1.53	3.35	1.16
	6.69	6.1	1.9
31.5	0.08	0.19	0.21
	0.36	1.06	0.56
	3.52	4.12	1.68
	16	8.15	2.04

Freq. [Hz]	Acceleration [r.m.s. m/s^2]	Subjective response	Standard deviation
40	0.17	0.72	0.51
	0.8	1.95	0.81
	1.71	2.47	1.03
	7.91	6.23	2.69
50	0.08	0.17	0.18
	0.38	1.11	0.63
	3.98	3.68	1.3
	19	7.46	2.9
63	0.18	0.8	0.58
	0.85	1.61	0.87
	1.88	2.52	1.09
	9.09	4.42	1.84
80	0.07	0.18	0.2
	0.36	1.16	0.74
	4.26	3.35	1.36
	22	6.62	2.09
100	0.06	0.08	0.16
	0.78	1.52	0.67
	1.84	1.85	0.9
	10.2	4.35	2.12
125	0.06	0.12	0.18
	0.34	1.15	0.7
	4.46	2.61	1.26
	25	5.25	2.65
160	0.04	0.05	0.11
	0.64	1.22	0.72
	1.62	2.18	1.05
	10.31	3.88	1.73
200	0.06	0.1	0.18
	0.34	0.78	0.63
	4.71	2.51	1.19
	27	4.19	2.35
250	0.15	0.2	0.27
	1.41	1.4	0.9
	2.98	1.99	1.24
	13.27	3.24	1.55
315	0.4	0.4	0.45
	1.36	1.18	0.93
	8.53	2.73	1.7
400	0.8	0.65	0.61
	3.78	1.92	1.62
	6.35	2.19	1.31

[Table 6] Goodness of fit statistics obtained for overall data set (n = 40).

Regression method	Polynomial order	Residual mean square (MSE)	Adjusted coefficient of determination (R_a^2)	Number of regression coefficients
Stepwise procedure	6th	0.073	0.985	12

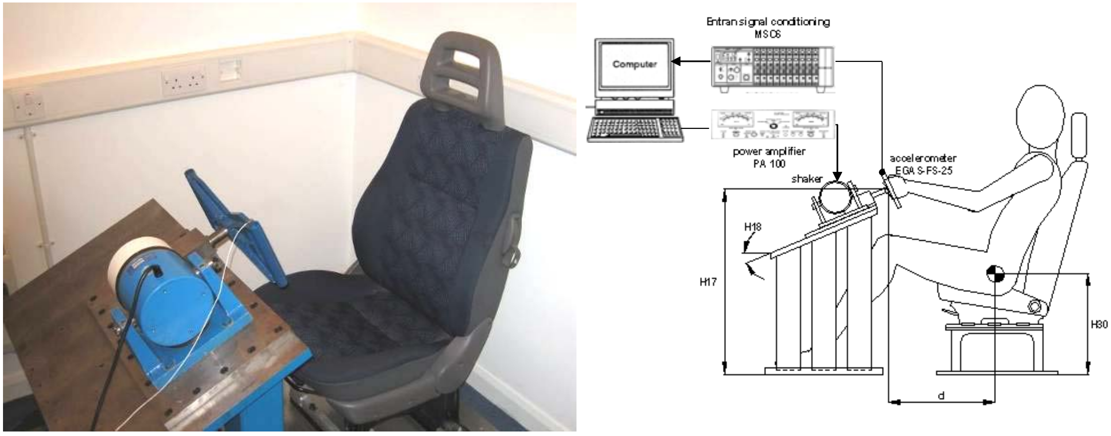
[Table 7] Summary of the subjective response obtained separately for the light test participants data set (n = 20) and for the heavy test participants data set (n = 20) by means of Borg CR10 scale.

Freq.	Acceleration	Lighter		Heavier	
[Hz]	[r.m.s. m/s^2]	Borg	SD	Borg	SD
3	0.08	0.61	0.35	0.59	0.46
	0.17	1.72	0.68	1.3	0.56
	0.49	2.57	0.81	2.77	1.23
	1	4.54	1.24	4.32	1.37
4	0.13	0.66	0.59	0.73	0.52
	0.32	1.45	0.59	1.72	0.92
	0.5	2.53	0.74	2.47	0.72
	1.26	3.8	1.18	4.33	1.72
5	0.08	0.48	0.65	0.44	0.33
	0.23	1.33	0.7	1.65	0.88
	1.07	4.68	1.31	4.42	1.22
	3	6.41	1.75	6.23	1.67
6.3	0.14	1.64	0.73	1.07	0.57
	0.45	2.4	0.63	2.08	0.88
	0.81	4.44	1.17	3.46	1.17
	2.58	6.79	1.74	6.59	1.59
8	0.08	0.45	0.29	0.25	0.21
	0.28	2.56	0.8	1.86	0.67
	1.75	4.77	1.18	4.78	1.22
	6	9.42	2.19	8.14	1.68
10	0.15	0.9	0.61	0.78	0.53
	0.56	2.1	0.6	1.91	0.75
	1.07	4.17	1.46	3.08	1.09
	3.92	6.57	1.54	6.06	1.27
12.5	0.08	0.36	0.32	0.33	0.2
	0.3	1.6	0.63	1.1	0.48
	2.15	5.56	1.72	4.79	1.39
	8	8.2	2.14	7.95	1.75
16	0.16	0.79	0.42	0.59	0.29
	0.63	2.41	0.67	2.12	0.6
	1.26	3.28	0.82	3.06	0.7
	5.02	7.35	2.53	6.37	1.86
20	0.08	0.15	0.17	0.16	0.16
	0.34	1.73	0.77	1.26	0.59
	2.87	4.63	1.49	4.29	1.1
	12	9.18	2.56	7.7	1.77
25	0.17	0.72	0.35	0.31	0.2
	0.73	2.06	0.9	1.44	0.78
	1.53	3.53	1.26	3.18	1.06
	6.69	6.43	2.03	5.77	1.75
31.5	0.08	0.22	0.24	0.16	0.17
	0.36	1.22	0.62	0.91	0.46
	3.52	4.62	1.96	3.62	1.19
	16	8.6	2.11	7.71	1.92

Freq.	Acceleration	Lighter		Heavier	
[Hz]	[r.m.s. m/s^2]	Borg	SD	Borg	SD
40	0.17	0.85	0.52	0.58	0.47
	0.8	2.3	0.86	1.61	0.59
	1.71	2.8	1.09	2.14	0.88
	7.91	7.38	3.22	5.09	1.31
50	0.08	0.16	0.16	0.18	0.2
	0.38	1.34	0.74	0.89	0.41
	3.98	3.79	1.32	3.57	1.36
	19	8.61	3.46	6.32	1.6
63	0.18	0.93	0.63	0.67	0.51
	0.85	1.73	0.95	1.49	0.79
	1.88	2.79	1.3	2.24	0.76
	9.09	4.84	1.84	4	1.79
80	0.07	0.2	0.22	0.16	0.17
	0.36	1.29	0.77	1.03	0.71
	4.26	3.84	1.6	2.85	0.85
	22	7	1.98	6.25	2.17
100	0.06	0.08	0.15	0.09	0.18
	0.78	1.69	0.74	1.36	0.56
	1.84	2.06	0.86	1.64	0.91
	10.2	5.07	2.56	3.64	1.29
125	0.06	0.12	0.19	0.13	0.17
	0.34	1.4	0.84	0.9	0.43
	4.46	2.79	1.35	2.43	1.16
	25	6	3.26	4.49	1.62
160	0.04	0.03	0.08	0.07	0.13
	0.64	1.27	0.77	1.17	0.69
	1.62	2.32	1.2	2.04	0.87
	10.31	3.93	1.72	3.84	1.78
200	0.06	0.09	0.18	0.11	0.18
	0.34	0.78	0.8	0.78	0.42
	4.71	2.59	1.15	2.44	1.25
	27	4.91	2.92	3.48	1.33
250	0.15	0.2	0.32	0.2	0.23
	1.41	1.3	0.92	1.5	0.89
	2.98	2.06	1.42	1.92	1.05
	13.27	3.48	1.62	3.01	1.48
315	0.4	0.36	0.49	0.44	0.41
	1.36	1.04	0.97	1.31	0.9
	8.53	3.01	2.14	2.44	1.11
400	0.8	0.52	0.53	0.78	0.67
	3.78	1.99	2.04	1.85	1.11
	6.35	2.21	1.4	2.17	1.24

[Table 8] Goodness of fit statistics obtained separately for the light participants data set (n = 20) and for the heavy participants data set (n = 20).

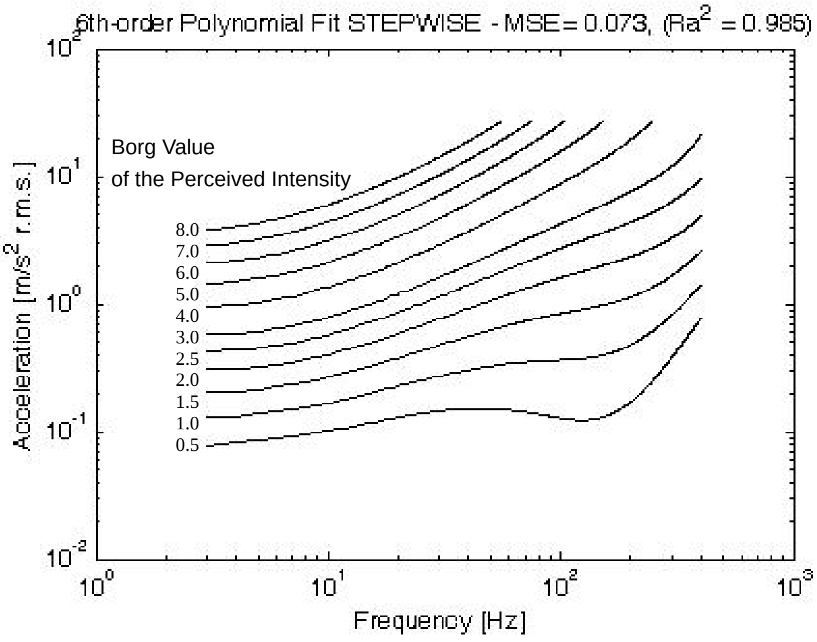
Regression method	Body mass	Polynomial order	Residual mean square (*MSE*)	Adjusted coefficient of determination (R_a^2)	Number of regression coefficients
Stepwise procedure	Light	6^{th}	0.147	0.975	12
	Heavy		0.06	0.986	12



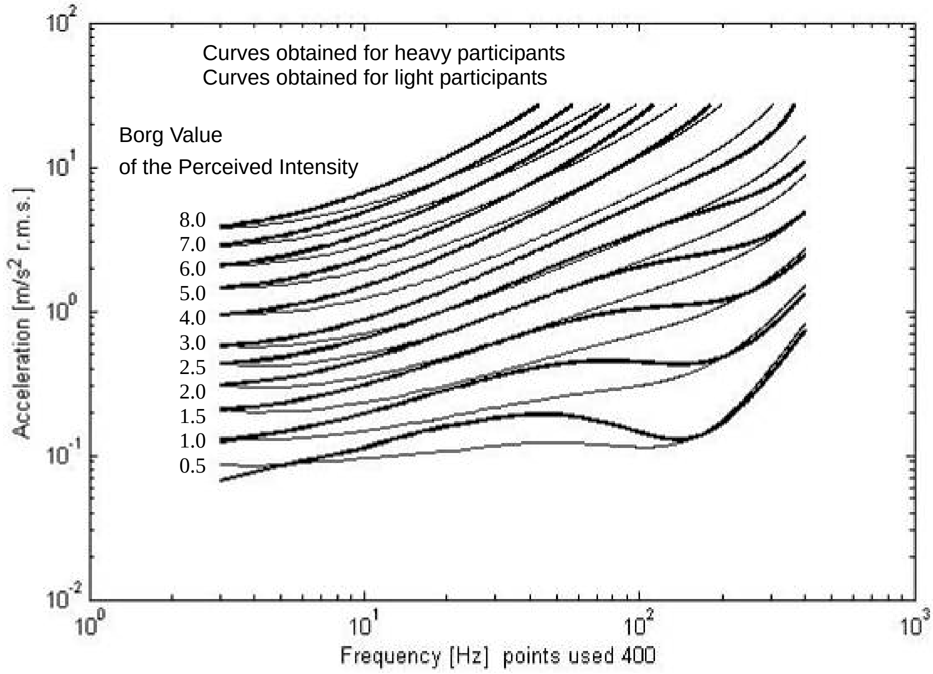
[Figure 1] Steering wheel vibration test rig and associated electronics used in the test experiement.

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		
≁		
●	Absolute maximum	Highest possible

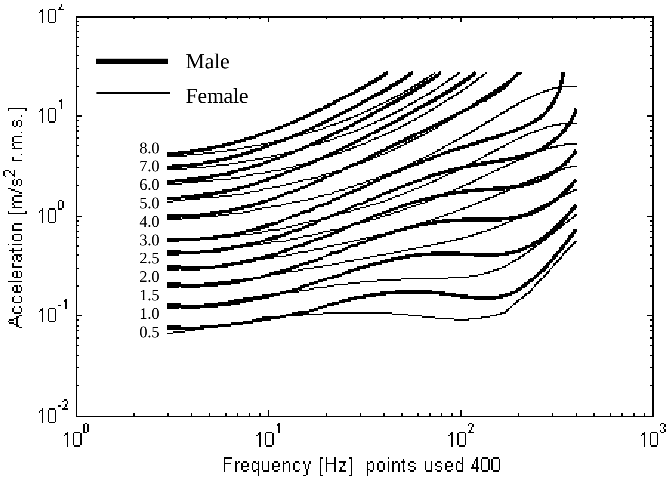
[Figure 2] Borg’s category ratio CR-10 scale (adapted from Borg 1998).



[Figure 3] Equal sensation curves for the complete group of 40 participants obtained for Borg subjective perceived intensity values from 0.5 to 8.0 using the regression formula obtained for sinusoidal vibration.



[Figure 4] Equal sensation curves obtained separately for the light test participants and the heavy test participants using the regression formulas obtained for sinusoidal vibration.



[Figure 5] Equal sensation curves obtained separately for the male test participants (n = 20) and for the female test participants (n = 20), obtained from previous study Jeon et al., 2009.