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Mechanical and Physical Risk Prevention

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REPORT **R-884**

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An exploratory study for characterizing seated body apparent mass coupled with elastic seats under vertical vibration

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SUMMARY

This study explored a thin-film body-seat interface pressure measurement system (Tekscan Inc.) for the characterization of the biodynamic responses of human subjects seated on elastic seats and exposed to vertical vibration. The study included a rigid seat and three elastic seats: a seat with a flat 8 cm thick polyurethane (PUF) block (seat A); a soft and contoured automotive seat (seat B); and an inflatable air-bubble cushion (seat C). The validity of the measurement system was initially examined with 11 subjects seated with (WB) and without (NB) a back support in the absence of vibration. The results showed that the seat pressure measurement system can accurately measure the static body weight supported by the seat. The peak error was in the order of 4% for the flat (seat A), and 6% for both the contoured (seat B) and the air (seat C) seats.

The validity of the measurement system was subsequently assessed under vertical vibration. For this purpose, the rigid seat was installed on a single-axis force plate that was mounted on the whole-body vibration simulator (WBVS), while the seat mat was placed on the seat pan for the measurement of the body-seat interface force. The dynamic force measured by the force plate served as a reference for comparing the seat mat data. The WBVS was programmed to generate three levels of random vibration with nearly constant acceleration power spectral density (PSD) in the 0.5 to 20 Hz frequency range (overall rms acceleration = 0.25, 0.50 and 0.75 m/s^2). The experiments were performed with different passive loads and human subjects. The force signals from the two measurement systems (seat mat and force plate) together with the acceleration signal were analyzed to derive the apparent mass (APMS) response. The results showed substantially lower APMS estimated by the seat mat at frequencies above 3 Hz compared to that from the force plate, irrespective of the seat load and excitation magnitude. These were attributed to the poor dynamic range and the lack of a scalable gain of the pressure measurement system. A correction function, ratio of APMS magnitude given by the force plate to that by the seat mat, was derived to account for the limitations of the pressure measurement system, for each load and vibration magnitude combination. The application of the correction functions resulted in comparable responses of both measurement systems.

Three series of experiments were subsequently undertaken to characterize the biodynamic responses of subjects seated on rigid and elastic seats, and to further examine the validity of the measurement system. The first two series, conducted simultaneously, involved the measurements of biodynamic responses of subjects seated on a rigid seat using the force plate and the seat mat, respectively. The results obtained from the first series served as a reference for the verification of the measurement system used during the second series of experiments. The third series involved the characterization of the APMS responses of subjects seated on three elastic seats, where the biodynamic force was measured using the seat mat. Owing to vibration attenuation properties of the visco-elastic seats, this final series of experiments involved the synthesis of identical levels of vibration at the seat surface. A methodology was developed for the synthesis of the desired vibration spectrum on the elastic seat using two micro-accelerometers installed in the vicinity of the ischial tuberosities of the subjects, which served as feedback for the WBVS vibration controller. Analyses of vibration levels measured at the seat and at the base revealed notable vibration attenuation by the elastic seats.

A total of 58 subjects (31 male and 27 female) participated in the experiments with a standing mass ranging from 45.5 to 106 kg. The experiments were performed with each subject sitting without (NB) and with (WB) a vertical back support on a rigid and on three elastic seats, and exposed to three different levels of broad-band vibration in the 0.5 to 20 Hz range. Selected anthropometric dimensions of the subjects such as stature, body fat, lean body mass, sitting height, C7 height, hip circumference and body-seat contact area were also recorded. The results obtained from the first series were analyzed to identify gender effect, and correlations with the anthropometric factors. The results showed strongly coupled effects of gender, body mass and anthropometric factors. The measured data were thus grouped within narrow ranges of body mass and anthropometric values to identify correlations between APMS responses and selected anthropometric factors. Comparisons of male and female subject responses clearly showed a strong gender effect coupled with anthropometric factors in a complex manner. Female subject responses revealed a distinct high magnitude second resonance peak at frequencies above 10 Hz, which was either not evident or less clear in the male subject responses. Male subjects invariably showed higher primary resonance frequency compared to female subjects of comparable body mass. The peak APMS magnitude increased with an increase in body mass and in most of the anthropometric parameters considered in this study.

The APMS responses derived from the seat mat (series 2) in conjunction with the correction functions agreed reasonably well with those obtained from the force plate. The peak difference between the responses obtained from the two methods was in the order of 6% under 0.75 m/s^2 excitation, and higher under 0.25 m/s^2 excitation, which was attributed to the poor dynamic range of the seat mat. It was thus concluded that the correction functions can adequately account for the frequency response of the measurement system, and hypothesized that these functions could be applied to the elastic seats. The APMS responses obtained with the elastic seats (series 3) were compared with those with the rigid seat for: (i) each individual subject; (ii) the mean responses of the subjects within each mass group; and (iii) the mean responses of all subjects. Examination of low frequency (near 1 Hz) APMS magnitude of each subject-seat combination revealed considerably lower body mass supported by the seat for some of the subjects. The deviation between the measured and expected values (75 to 80% of the standing body mass) exceeded 15% for some of the subjects, particularly under the lower excitation of 0.25 m/s^2. The datasets showing deviations in excess of 15% were excluded from the subsequent analyses. The remaining datasets for each seat were grouped under different mass groups of the two genders. The mean responses were analyzed to study gender, body mass, back support and vibration magnitude effects on the APMS of the subjects seated on the elastic seats.

The results showed that elastic seats tend to shift the primary resonance towards a lower frequency, while reducing the resonance peak. The results suggested strong influences of visco-elastic properties of seats in addition to gender and body mass-related factors. The mean peak APMS magnitudes of male and female subjects of similar body mass were comparable, while the primary resonance frequencies of female subjects were lower. The air-cushion seat (seat C) resulted in relatively higher peak APMS magnitudes for both genders, which was attributed to low damping of the seat. The flat PUF seat (seat A) with enhanced damping showed the lowest peak response magnitudes, irrespective of sitting and excitation conditions. It is thus concluded that the biodynamic responses of human subjects seated on elastic seats and exposed to vertical vibration differ significantly from those obtained with the rigid seat. Measured responses are considered to serve as important target values for developments in anthropodynamic manikins and seat design.

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1. WHOLE-BODY VIBRATION BIODYNAMICS – A BRIEF REVIEW

Vehicles (land, air and sea) expose people to mechanical vibration of periodic, random or transient nature. The exposure to such whole-body vibration (WBV) is known to be an important occupational risk factor worldwide. Many studies have suggested that prolonged exposure to intense WBV poses an increased risk of disorders of the lumbar spine and of the connected nervous system. The long-term effects of WBV have been presented in a number of review articles [1-6]. These studies invariably point to adverse effects of long-time vibration of the spine and spine degeneration, while low back pain (LBP) is being a secondary consequence. Several epidemiological studies have also suggested a strong association between occupational WBV exposure and LBP, where the focus group included vehicle drivers, a group which constitutes the largest population of workers exposed to WBV [7-9]. In 1996, the Comité Européen de Normalisation (CEN) estimated that 4 to 7% of all employees in the USA, Canada and some European countries are occupationally exposed to potentially harmful WBV [10]. Occupationally-induced LBP is associated with excessive financial costs, and loss of work days and quality of life. The total cost of LBP in Sweden was estimated in the order of 1860 million Euros in 2001, where the lost productivity accounted for 84% of the total cost [11]. Guo *et al.* [12] estimated a total of 101.8 million lost workdays attributed to LBP in 1988 in the USA.

While the association between WBV exposure and LBP is not debated, the definite extent of this association could not be determined possibly due to the contribution of a multitude of other co-varying factors such as prolonged sitting, awkward postures, bending and twisting as well as heavy lifting. Despite the presence of many confounders, epidemiological studies have clearly established that the health risks attributed to WBV exposure are primarily related to the intensity of WBV, generally defined in terms of frequency-weighted rms acceleration, and exposure duration [1,9]. The biodynamic responses of the human body to WBV form an essential basis for understanding mechanical-equivalent properties of the body and potential injury mechanisms. This knowledge can be used for the development of frequency-weighting methods for the assessment of exposure risks and for the elaboration of anthropodynamic manikins for the assessment of seats and the design of enhanced systems coupled with the human operator such as secondary suspensions (cabin and seat).

The reduction of vibration intensity has been the primary engineering and ergonomic design goal in order to prevent risks of WBV injuries among exposed workers. For vehicle drivers, suspension seats are vital for reducing the vibration exposure of the drivers. Vertical suspension seats are thus widely used in commercial, industrial, construction and public transport vehicles to reduce transmission of vibration along the vertical axis, which is known to be relatively higher compared to the horizontal vibration in most vehicles. The effectiveness of a suspension seat in reducing the vibration exposure strongly depends upon the suspension properties, the vibration environment of the target vehicle, and particularly the coupling with the biodynamic response of the human driver [13-15]. As an example, Fig. 1.1 illustrates comparisons of mean acceleration transmissibility of a seat loaded with human subjects and an equivalent inert mass. It is evident that the human driver contributes substantially to the overall vibration transmission performance of a suspension seat. The coupling effect, however, depends on the nature of the vibration and on the suspension properties in a highly complex manner. The current design methodologies for suspension seats lack appropriate tuning of suspension in light of the vibration environment (intensity and frequency components) of the target vehicle and considerations of the human driver. This is attributed to a lack of proven methods for integrating human body dynamics and vibration environment in the design process. Consequently, the suspension seats employed in a vehicle generally do not provide optimal isolation performance for the driver, and in some cases these may even amplify the transmitted vibration, particularly under high intensity vibration [16,17]. A suspension seat is a vital component not only for controlling the vibration dosage of the driver but also for proving controlled posture with appropriate ergonomic considerations. Considerable efforts have thus been made to enhance its performance. These may be grouped in two broad categories on the basis of the approach: (i) assessment methods for tuning of suspension seats; and (ii) design methods integrating the target vehicle vibration and the seated human body dynamics.

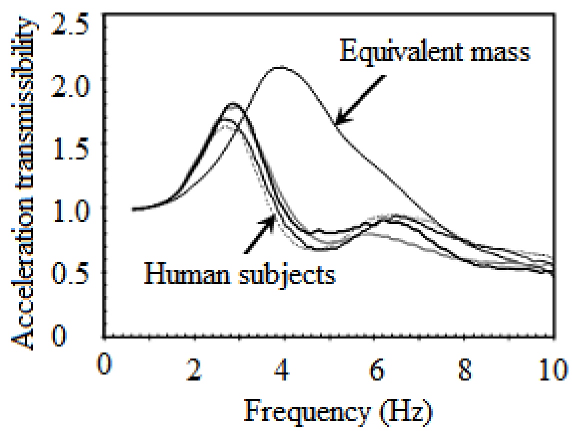


Figure 1.1: Comparisons of acceleration transmissibility of a vehicle seat loaded with human subjects and an equivalent inert mass [15].

The first group of studies has evolved into measurement methods for assessing performance of seats for a number of classes of target vehicles. These have evolved in standardized vibration isolation performance assessment methods for suspension seats [18,19], which require laboratory-based measurements of seats loaded with human subjects of particular body mass (e.g., 53.5 ± 1.5 kg and 100.5 ± 2.5 kg) exposed to pre-defined vibration spectra. Such methods require comprehensive resources in terms of vibration generators, vibration controller for synthesizing the desired vibration spectra of the target vehicle, and measurement and data analyses systems. The test methods involve repetitive tests and could yield considerable variability in the outcome, which is partly attributed to anthropometric differences among the human subjects and variations in the sitting postures. With these methods, information on the suitability of a suspension design is only provided in the post-design stage. Moreover, the standardized method, described in ISO-7096, has been criticized due to considerations of the limited number of human subjects of only two specific masses [20].

Alternatively, a number of passive and active anthropodynamic manikins have evolved with the intent to eliminate the use of human subjects for efficient assessments of vibration isolation effectiveness of suspension seats, and thereby to minimize the variability in the measurements [21-27]. These manikins are mostly designed on the basis of biodynamic responses of the seated body defined in ISO-5982 [28]. The primary goal of such manikins is to replicate the contributions of the human body dynamics to the overall isolation effectiveness of the coupled seat-occupant system. Such manikins could be applied not only to obtain isolation effectiveness of seats with minimal variability in the outcome, but also for tuning of suspension properties for different target vehicles.

The need to integrate the human body dynamics in the design process has been widely recognized for developing effective suspension seats. A number of human body vibration models have thus been developed on the basis of the measured biodynamic responses of the seated body exposed to vertical WBV. These have been integrated to the nonlinear or linear models of seats in order to account for human body contributions in the design stage. The resulting coupled occupant-seat models have been suggested as effective design tools for identifying improved designs of seats for particular target vehicles [29,30].

The applications of both the anthropodynamic manikins and the biodynamic models of the seated body, however, have met limited success thus far. While some of the laboratory studies on seats with biodynamic models and manikins have shown good agreements with the data acquired from the human-seat system under particular conditions and body mass [23-27, 31], others have identified substantial limitations of the current models and manikin designs. Only limited efforts have been made to assess the performance of models and manikins under ranges of representative conditions. Nelisse *et al.* [32] evaluated the suitability of two prototype manikins for assessing vibration isolation effectiveness of suspension seats. The study involved laboratory tests with five different suspension seats coupled with human subjects and manikins configured to three different body masses (55, 75 and 98 kg), and subjected to vibration spectra of a range of selected vehicles. The study assessed the manikins using three measures: (i) ability of the manikins to reproduce biodynamic behavior of the body under vertical vibration; (ii) ability to predict vibration isolation effectiveness of the human-seat systems under vibration environments of different vehicles in terms of Seat Effective Amplitude Transmissibility (SEAT); and (iii) ability to predict frequency response properties of the human-seat systems under vibration of selected classes of vehicles. The study concluded that the manikins provide poor estimates of the biodynamic responses of the body and an overestimation of isolation effectiveness of seats, when compared to those with human subjects. Considerable differences were observed between natural frequencies obtained with the manikin-seat and the coupled occupant-seat systems. The study also concluded that the manikins could serve as effective design/tuning and assessment tools, when adequately designed to reproduce the biodynamic behavior of the body. It was further shown that SEAT values of low natural frequency (<2Hz) seats coupled with manikins could be comparable with those of the seats loaded with an equivalent rigid mass, when the vehicle vibration predominated around low frequencies.

It has been widely suggested that biodynamic models of the human body need to be developed for representative postural and vibration conditions for effectively predicting behavior of the biological system and thus the potential injury mechanisms leading to a viable dose-response relationship [33-37]. Such models could further provide improved assessment methods and designs of effective interventions. The formulations of effective biomechanical models, however, necessitate thorough understanding and characterization of the biodynamic responses of the body to WBV, which is a formidable task considering the nonlinear dependency of the responses on various posture and vibration-related factors. A range of lumped-parameter, multi-body and finite element biodynamic models of the standing and seated human body have been formulated on the basis of measured biodynamic responses and the standardized ranges [38-44]. The properties and prediction abilities of some of the reported lumped-parameter models have been reviewed by Boileau *et al.* [29] and Liang and Chiang [45]. The biodynamic models have also been used for predicting vibration-induced relative deflections and compressive and shear stresses of various body substructures [41, 46-48], which could not be measured *in vitro*. The biodynamic models have been applied to models of seats and vehicles to account for the contribution of the human body in the design and analysis process [29,49-51,52-54]. These studies have shown considerable differences between the results predicted from vertical human-seat models and laboratory-measured data for the human-seat systems [15,51].

From the reported studies, it can be concluded that applications of seated body biodynamic models and anthropodynamic manikins have met limited success thus far, which can be mostly attributed to three important factors:

1. Lack of considerations of body coupling with elastic seats, since the human body biodynamic responses are invariably characterized with body seated on a rigid seat in order to attain uncoupled body responses to vibration. This condition is not at all representative of vehicle seats because a visco-elastic seat cushion substantially alters the body-seat contact, the sitting posture and the seated body weight distribution on the seat [55-57]. An elastic seat cushion also substantially alters the nature of vibration transmitted to the seated body. Moreover, seating on a soft flexible seat causes pelvic rotation and relative motions across the legs, which are absent with a rigid seat [58].
2. Lack of considerations of effect of body mass, which strongly influences the biodynamic response and thus the isolation effectiveness of a suspension seat. Although a few studies have characterized the biodynamic responses of the seated body of different masses [59], the distinct differences due to body mass are not reflected in the standardized target values [28].
3. Lack of considerations of back support and hands position. The standardized values, on which the models and manikins are based, have been derived for no back support and hands in lap. These conditions are not entirely representative of vehicle driving posture but affect the human response and thus the seat response greatly. A few studies have shown strong effects of back support on the measured biodynamic responses, while the effects are not reflected in the current models [60].

Apart from the above, the biodynamic responses are strongly influenced by the human anthropometry and the magnitude of vibration. A few studies have attempted correlations between biodynamic response magnitude in terms of apparent mass (APMS) and selected anthropometric parameters such as standing height, body mass, body mass index (BMI) and body fat percentage [59,61,62]. Even fewer studies have investigated the gender effect even though the population of female vehicle drivers in the passenger transportation and resource sectors has been steadily growing, while the findings are mostly contradictory. Female anatomy differs from the male anatomy, and the body fat content of females is considerably different from the males [63,64]. The APMS responses of the two genders may thus be expected to differ. Fairley and Griffin [40] and Rakheja *et al.* [65] reported insignificant gender effects on the basis of APMS responses to vertical vibration measured on 60 and 24 subjects, respectively, including males and females. Griffin and Whitham [66] showed a negative correlation of vibration transmitted to seated body head at 16 Hz with the body size (weight and hip) for male subjects, and with body mass and height for the female subjects. Another study by Griffin *et al.* [34] suggested higher magnitudes of vibration transmitted to the head of females than the males at frequencies above 5 Hz, and an opposite trend at frequencies up to 4 Hz. The statistical analysis of individualized one-dimensional single- and two-DOF model parameters, derived from vertical biodynamic data of male and female subjects, concluded insignificant gender effect [49]. The model parameters, however, consistently suggested considerably higher primary stiffness and lower damping for the male subjects than those of the females. Another study on the basis of normalized APMS responses reported important gender effect around 10 Hz [67]. Toward and Griffin [68] reported effect of gender only on the APMS resonance frequency when sitting against a reclined rigid back rest, while the gender effect for other back support conditions was not significant. Holmlund and Lundström [69], on the other hand, noted higher driving-point mechanical impedance (DPMI) magnitude in the vicinity of the primary peak magnitude for the male subjects compared to the female subjects, and an opposite trend near the second peak around 10 Hz. Lundström and Holmlund [70] and Holmlund [71] also suggested that female subjects absorbed more vibration power per kg of the seated body mass than the male subjects, which was speculated to be caused by greater fat to muscle mass proportion of the female anatomy. The contributions due to breast supports were also suspected and investigated, while the outcome did not show any effect of the support. On the basis of observed differences, development of different injury criteria for the two genders has been suggested [69-72]. The vibration transmissibility of cushioned seats with male and female occupants has been reported in another study, which suggested strong gender effect on the overall vibration isolation properties of seats [73]. This may be attributed to anthropometric and/or anatomical differences and thus the biodynamic properties of female subjects.

On the basis of measured APMS responses, Mansfield *et al.* [67] reported that the mean resonance frequency for the female subjects was slightly higher than that of the male subjects. However, Holmlund *et al.* [72] pointed out that the mean resonance frequency of the DPMI of the female subjects were lower than the male subjects. Mansfield *et al.* [67] reported lower normalized APMS magnitude for the male subjects as compared to the female subjects between 6 and 10 Hz. Furthermore, Holmlund *et al.* [72] and Holmlund and Lundstrom [69] reported that the DPMI of the female subjects showed a more distinct second peak at frequencies around 10 Hz, and in many cases the magnitude of this peak exceeded that of the primary peak. The contradictory findings of the reported studies with regards to the gender effect are most likely attributed to coupled effects of body mass and the anthropometry with the gender, since these have considered male and female subjects of considerably different body masses and anthropometry. It has been suggested that gender effects should be investigated by considering male and female subjects of comparable body mass [62].

The primary limitation of the reported biodynamic responses of the seated human arises from a lack of consideration of elastic body-seat interface representative of the vehicle seating. Characterization of reliable biodynamic responses of body seated on visco-elastic seats is vital for building models for integration in the suspension seat design and tuning process, and designs of manikins for assessing the isolation effectiveness of suspension seats. Furthermore, it is important to characterize such responses under representative vehicular vibration (frequency and magnitude) and postural conditions (lower back supported against a backrest and hands supports). It is also essential to investigate the vibration properties of female workers in a systematic manner to identify more definite differences, if any. The measurement of the biodynamic responses of human subjects seated on elastic seats, however, involves numerous difficult challenges, particularly the lack of a measurement system for acquiring body-seat interface force on a flexible cushion. Only a few studies have explored flexible and thin-film pressure mapping systems for measuring the body-seat interface force. These include the resistive and capacitive sensing grids, comprising relatively large number of force-sensing resistors and foam capacitors, respectively [57,74]. The majority of the reported studies, however, have been limited to measurement of the static body weight distributions on the seat cushion under different sitting postures [75,76]. These studies have shown that both the body-seat contact and pressure distribution strongly depend upon visco-elastic properties of the seat, seat geometry, and sitting posture, apart from the various anthropometric factors. Wu *et al.* [56] measured body-seat pressure distribution and variations in the contact force and contact area in the presence of vertical harmonic vibration up to 10 Hz. The biodynamic properties of the body seated on an elastic seat cushion and exposed to vertical vibration have been characterized in a single study [57] where a capacitive pressure sensing seat mat, developed by Novel Electronics, was used to measure the body-seat cushion interface force. The study showed considerably lower static APMS, in the order of 58% of the mean body mass. The study suggested that such a measurement system could be applied to characterize the biodynamic behavior of a body seated on soft seats, while the large error was attributable to the limited dynamic range of the measurement system and the mechanical properties of the protective elastomeric material applied to the capacitive sensors. The study, however, did not permit comparisons of APMS of the body seated on an elastic cushion with those reported for body seated on a rigid seat, since the vibration levels at the body-seat interface were not controlled.

2. OBJECTIVES OF THE STUDY

Considering that an elastic seat substantially alters the body-seat contact as well as the sitting posture and the seated body weight distribution on the seat, the biodynamic properties of the seated body on an elastic seat exposed to WBV are expected to differ from those acquired while sitting on a rigid seat. It is hypothesized that considerations of the body coupling with the visco-elastic seat cushion in addition to the body mass, to the representative back support condition and to the nature of vibration, in characterizing the biodynamic responses to vibration, could provide the essential target data for building effective body models for applications in designs of manikins and suspension seats for specific vehicles. The primary goal of this study was thus formulated to explore a methodology for characterizing the biodynamic responses of the human body seated on visco-elastic seat surfaces and exposed to vertical WBV so as to establish a basis for deriving target responses for developing occupant models and manikins in the near future. Furthermore, the effect of gender on the biodynamic responses is investigated considering the reported contradictory findings and the lack of data for the female driver population. The specific objectives of the study include:

1. Explore the validity of a thin-film pressure measurement system (Tekscan) for the measurement of the biodynamic force at the interface of the body and the visco-elastic seat under vertical vibration;
2. Develop a laboratory-based methodology to characterize the APMS of the body seated on soft elastic seats;
3. Evaluate the effects of selected anthropometric factors, particularly gender, on measured APMS responses; and the effects of body coupling with seats of different stiffness properties, including a rigid seat.

The study is conducted in two systematic phases. In the initial phase, the validity of the measurement system is examined through measurements of responses of 58 male and female subjects seated on a rigid seat and exposed to broad-band random vertical vibration in the 0.5 to 20 Hz range. The results obtained from this initial phase are used to develop correction functions to be applied to the interface force measured via the body-seat interface pressure measurement system and to demonstrate the validity of the measurement system. In the subsequent phase, the thin-film pressure sensing system together with the correction functions are used for characterizing the biodynamic responses of the body seated on 3 different elastic seats and exposed to WBV. The results from the first phase of the study are further analyzed to study the effects of gender and selected anthropometric dimensions on the measured apparent mass responses, where the current state of knowledge is relatively limited. The results obtained from the second phase of the study are analyzed to establish an understanding of the effects of elastic seats on seated human responses to WBV. The methodology developed would be subsequently used to develop target apparent mass responses of the body coupled with elastic seats for applications in seating design and developments in improved anthropodynamic manikins.

3. MEASUREMENTS OF BIODYNAMIC RESPONSES

3.1 Methods

The study involved three series of experiments for characterizing apparent mass (APMS) responses of human subjects exposed to vertical vibration. In the first series, the biodynamic responses of subjects were measured under vertical vibration while seated on a rigid seat. The driving-point force in this case was acquired using the force plate mounted underneath the rigid seat, as described in a number of reported studies [40,43]. The seat pressure measurement system was applied to the rigid seat in the second series to measure the same biodynamic responses of the same subjects under identical vibration excitation. The results obtained from the first series of experiments served as the reference for verification of the seat pressure measurement system used during the second series of experiments. The final series of experiment involved characterization of APMS of the subjects seated on three different elastic seats and exposed to identical vertical vibration at the seat surface.

3.2 Subjects

A total of 31 male and 27 female healthy adult subjects were recruited for the measurement of biodynamic responses under vertical vibration. The age of the subjects ranged from 19 to 58 years. A preliminary screening was done to ensure that the participants did not suffer from a back injury. Prior to the experiments, each subject was informed about the purpose of the study and safety controls of the whole-body vibration simulator (WBVS) through both verbal and written instructions. Each subject was asked for his/her consent of the protocol that had been approved by the Human Research Ethics Committee of Concordia University. The selected anthropometric body dimensions of each subject were also measured, which included body mass, stature, sitting height, hip circumference, etc., while body fat was computed using the US Navy formula [77]. These measures are summarized in Table 3.1. The body contact area on the seat was also measured for each subject sitting on the rigid seat under static conditions using the pressure sensing mat.

Table 3.1: Anthropometric body dimensions of the test subjects.

Particulars	Male (n=31)				Female (n=27)			
	Mean	SD	Max	Min	Mean	SD	Max	Min
Age, years	31.2	7.2	58.0	23.0	28.8	7.1	49.0	19.0
Stature, m	1.75	0.08	1.92	1.59	1.63	0.07	1.73	1.48
Body mass, kg	79.8	15.7	106.0	55.0	60.1	8.3	72.5	45.5
Body mass index, kg/m^2	26.12	4.24	34.99	19.96	22.52	2.73	26.31	15.78
Body fat, %	23.59	5.93	37.72	16.10	30.53	4.83	39.06	19.26
Body fat, kg	19.8	8.2	39.0	10.5	18.6	4.7	25.3	8.8
Lean body mass, kg	61.6	9.0	77.5	43.3	41.6	4.8	49.5	34.1
Sitting height, cm	88.8	6.2	96.7	81.3	81.0	7.7	88.3	63.2
Hip circumference, cm	103.6	7.4	116.0	88.0	99.9	5.5	109.0	89.5
Body contact area, cm^2	575	195	1050	211	515	175	890	250

SD – Standard deviation

Participants were divided in two different groups in order to study the effects of gender on the measured APMS. For the study of body mass dependency of the biodynamic responses, each gender group was further divided into three different body mass ranges. The male subjects were grouped in three body mass ranges around 60, 80 and 96 kg. The female subjects were grouped in a similar manner with body mass around 50, 60 and 72 kg. The experiments involving cushion seats, however, were conducted using a total of 56 subjects, as 2 of the subjects could not participate in the final series of experiments. The subjects were grouped so as to include a minimum of 9 subjects within each sub-group. The mean and range of body mass of subjects within each group are summarized in Table 3.2. Owing to coupled effects of body mass and gender, further attempts were made to identify gender groups with comparable body mass. Relatively small groups of male and female subjects could be identified with comparable body masses around 60 and 70 kg. These included 14 male and 14 female subjects, as summarized in Table 3.3, where these groups are denoted as 'G60' and 'G70', respectively.

Table 3.2: Mean body mass and ranges of subjects within different sub-groups.

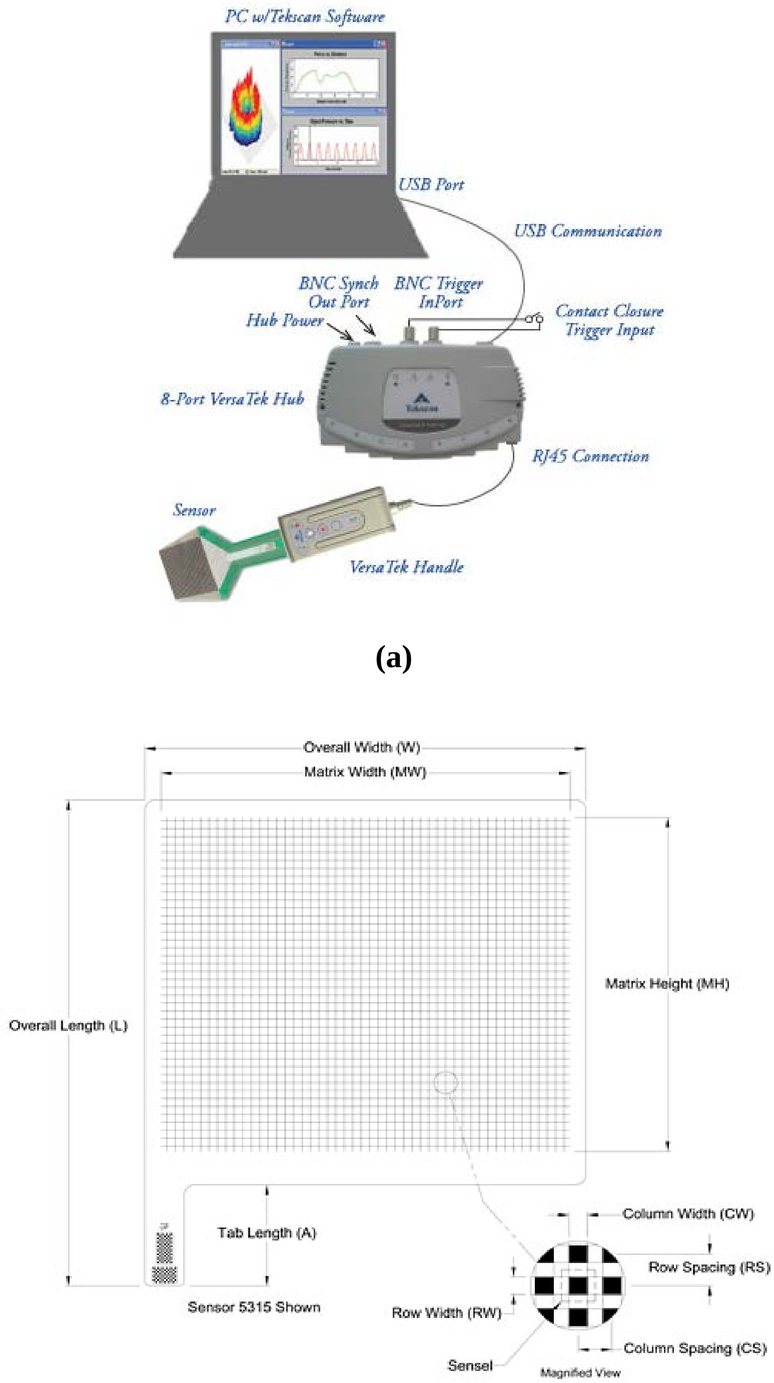
Gender	Mass Group	Number of subjects	Mass (kg)			
			Min	Mean	Max	SD
Female	50 kg	9	45.5	50.4	54.2	3.3
	60 kg	9	56.4	61.0	65.0	2.8
	72 kg	9	66.0	69.1	72.5	2.7
Male	60 kg	9	55.0	61.0	66.0	4.3
	80 kg	9	75.0	81.6	76.0	4.1
	96 kg	9	90.0	96.7	106.0	6.4

Table 3.3: Groups of male and female subjects with comparable body mass.

Gender	Group	Number of subjects	Mass (kg)	
			Mean	SD
Female	G60	7	61.0	2.6
	G70	7	69.6	2.7
Male	G60	7	60.4	4.2
	G70	7	70.3	3.7

3.3 Human-seat interface measurement system

A pressure sensing seat mat together with the signal processing hardware, developed by Tekscan Inc., was used for the measurement of the body-seat interface force. The measurement system comprises a thin-film pressure sensing mat, an 8-port hub coupled to the sensing mat through a data transmission handle for acquisition of the pressure signal, and a data-acquisition system. The sensing mat comprises a grid of 42 rows and 48 columns of sensels encased between two mylar sheets. The total thickness of the pressure sensing mat is 0.33 mm. Figure 3.1 illustrates a schematic of the measurement system. The sensing area of the mat is 487.7 mm long and 426.7 mm wide, while the pitch of the columns and rows is 10.2 mm. The grid is comprised of 2016 sensels with a density of 1 sensel/cm^2. The I-scan software, supplied by Tekscan Inc., permitted the analyses of pressure distributions and the contact force through integration of the pressure data over the contact area.



(a)

(b)

Figure 3.1: (a) Schematic of the seat pressure sensing system, developed by Tekscan; (b) seat pressure mat [78].

The sensing mats were selected for different ranges of pressure considering that the peak ischium pressure could vary from 25 to 202 kPa while sitting on a rigid seat [55] and from 25 to 45 kPa while sitting on an elastic seat [56]. Sensing mat with pressure range of 207 kPa was thus selected for application to rigid seats. A seat mat with a lower pressure range (36 kPa) was also acquired for the acquisition of the interface force on soft cushions. Preliminary measurements revealed an overloading of some sensels when applied to a very soft cushion. Consequently, the higher pressure range mat (207 kPa) was also used for soft cushions. The pressure sensing mat, together with the data acquisition system were calibrated using a pressure calibrator comprising a 500 mm × 500 mm diaphragm and a high precision pressure gage. The calibration process also involved smoothing of variations in digital outputs of different sensels. When subjected to uniform pressure loading, the I-scan software establishes a scale factor for each sensel by normalizing the digital output of that sensel by the average output of the entire sensing mat. This smoothing process was repeated for multiple loading conditions, as suggested by Tekscan [78]. The calibration was performed under constant pressures in the 8 to 200 kPa range in fixed increments (8, 15, 20, 25, 50, 75, 100, 150 and 200 kPa). The software permitted either linear or power law relation between the digital output and the applied pressure. In this study, the power law was used to define the calibration curve such that:

$$P = ax^{b} \tag{3.1}$$

where a and b are calibration constants, P is the applied pressure and x is the raw output of each sensel. A two-point method, recommended by Tekscan, was subsequently used to define the power relationship involving the measurement of raw digital outputs under only two pressures (8 and 150 kPa), while each pressure was maintained for nearly 150 s.

3.3.1 Measurement system verification under static loading

The validity of the measurement system was initially examined under different rigid loads, while the mat was placed on a flat rigid surface. The repeated measurements under different loads in the 10 to 100 kg range revealed very good agreements between the applied load and the load estimated by the measurement system software through an integration of the sensel outputs. The peak deviation was observed to be within 6%. The validity of the measurement system was subsequently examined with human subjects seated on different seat cushions. A total of 11 adult subjects (8 male and 3 female) were recruited for this validation phase. Table 3.4 summarizes the standing body mass of the subjects, which ranged from 45.5 to 103 kg (mean mass = 72.1 kg). A rigid seat structure was designed so as to accommodate three different seat cushions. These included: (A) a flat cushion of 8 cm thick polyurethane (PUF) block with a leather covering; (B) a soft and contoured automotive seat cushion; and (C) an inflatable air-bubble cushion (Fig. 3.2(a)). The stiffness and hysteresis properties of the three cushions were measured in the laboratory using the method recommended in SAE J 1013 [80]. The measured data revealed a static stiffness of 6.07, 4.13 and 4.24 kN/m for cushions A, B, and C, respectively. The results suggested that the contoured cushion (B) is significantly softer than the flat PUF cushion (A), and that the air-bubble cushion (C) stiffness is similar to that of the contoured cushion, while it could cause localized pressure peaks and valleys around each bubble, as seen in Fig. 3.2(b). The charging valve of the air cushion was carefully sealed so as to ensure the same charge pressure in all the subsequent tests.

Table 3.4: Standing body mass of the human participant considered for measurement of static seat loads.

Subject	1	2	3	4	5	6	7	8	9	10	11	Mean
Gender	M	M	M	M	M	M	M	M	F	F	F	
Mass (kg)	75	71	55	103	69	83	82	91	72.5	45.5	46.4	72.12

M – Male; F- Female

Each cushion was placed on a rigid seat structure, as seen in Fig. 3.3(a). The seat with the cushion was positioned on a weighing platform (Western Scale Co.; resolution 0.1 kg), as illustrated in Fig. 3.3(b). The reading of the platform loaded with the seat and cushion was set as zero. Each subject was advised to sit on the seat while his/her feet were supported on a footrest placed outside the weighing platform. The feet support height was adjusted so as to permit the subject to assume a relaxed and upright sitting posture. Each subject was advised to sit relaxed but upright with his lower legs vertical and his thighs horizontal (knee angle near 90^o). The measurements were performed for each subject sitting with no back support (NB) and with a vertical back support (WB) on the rigid as well as on the elastic seats, while each measurement was repeated three times. The study involved 24 measurements for each subject. The pressure mat signals for each subject-seat combination trial were recorded for a duration of 60 s. The total force derived from the seat pressure distribution together with the weighing platform reading was subsequently recorded. The repeated measurements of each combination revealed very good degree of repeatability. Furthermore, the mean force measured by the pressure mat agreed very well with the mean weighing platform readings, irrespective of the sitting posture (NB and WB) and the seat surface (rigid, and cushions A, B and C).

(a) (b)

Figure 3.2: (a) Schematic of air bubble cushion; and (b) peaks and valleys around each bubble.

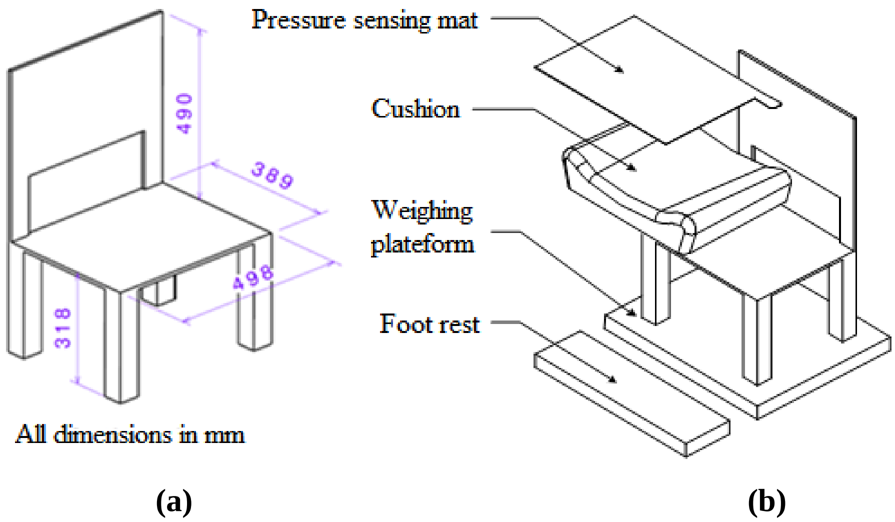


Figure 3.3: (a) Schematic of the rigid seat; and (b) rigid seat with a contoured cushion and the pressure mat.

Figure 3.4 illustrates very good correlations between the pressure mat and the weighting platform readings for the four seats and two back support conditions. The data revealed r^2 value in the order of 0.98, except for the air bubble cushion, which revealed a relatively lower r^2 value of 0.94 for the NB posture. The two measurements revealed very good agreements across all the subjects for the rigid and relatively stiff cushion *A* with peak deviation below 4%. The seat mat measurements with contoured and air bubble cushions showed peak deviations in the order of 6%.

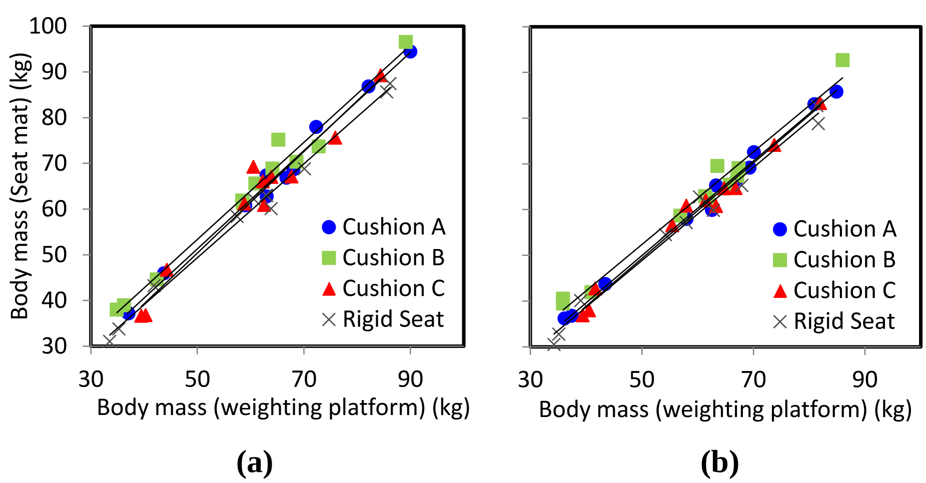


Figure 3.4: Correlations between the mean sitting body mass measured by the seat mat and the weighing platform: (a) back not supported (NB); and (b) back supported against a vertical back support (WB) (Cushion A: Flat PUF; Cushion B: Contoured PUF; and Cushion C: Air-bubble).

3.3.2 Dynamic measurement setup and methods – rigid seat

The biodynamic responses of subjects seated on a rigid seat were measured using two methods, which constitute the first two series of experiments conducted simultaneously. The first series involved the measurements of the driving-point force using the force plate mounted underneath the rigid seat, as described in a number of reported studies [40, 43]. For this purpose, the seat was installed on a whole body vibration simulator (WBVS). The WBVS consists of a platform supported by two servo-controlled hydraulic actuators that can produce vertical motion up to ±10 cm. A steering column was also installed on the platform to realize a driving-like sitting posture, as shown in Fig. 3.5. In order to perform the experiments in a safe manner, the actuators were equipped with various safety control loops, while the peak acceleration was limited to 2 m/s^2. Furthermore, emergency stop switches were provided to both the operator and the subject. Activation of any of these switches causes the system to shut down in a ramp-down manner.

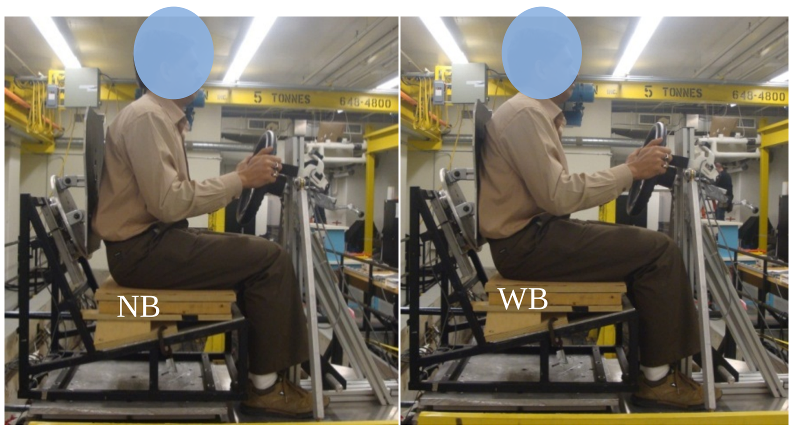
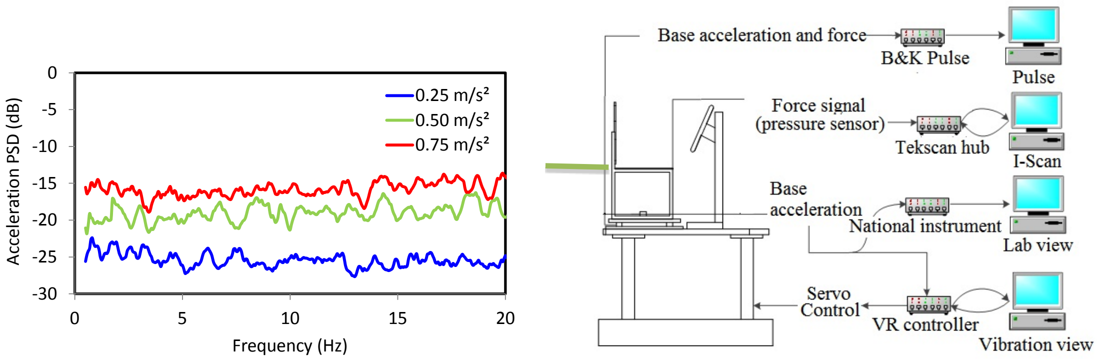


Figure 3.5: Pictorial illustrations of the two sitting postures (NB and WB).

A rigid seat with a vertical back support and a 449 mm × 456 mm pan was installed on a single-axis 560 mm × 560 mm force plate that was mounted on the WBVS platform. The force plate integrated four Kistler load cells connected to a charge amplifier through a summing junction. A single-axis accelerometer (Bruel & Kjær-4370) was installed on the force plate to measure vertical acceleration at the seat base. The seat acceleration signal also served as the feedback for the vibration controller (Vibration Research Co., 8500). The controller was programmed to generate white noise random vibration with nearly constant acceleration power spectral density (PSD) in the 0.5 to 20 Hz frequency range. Three different magnitudes of vibration were synthesized so as to obtain overall rms accelerations of 0.25, 0.50 and 0.75 m/s^2. Figure 3.6(a) illustrates PSD of the measured acceleration signals corresponding to selected excitations. It should be noted that the chosen vibration levels were relatively low compared to those used in many reported studies, which have employed rms accelerations up to 2 m/s^2 [60]. This study, however, involved the synthesis of chosen vibration magnitudes at the body-cushion interface, apart from the rigid seat. Owing to vibration isolation potential of the seat cushions, it was anticipated that synthesizing a higher vibration level at the cushion surface, in the order of 1 m/s^2 rms, would cause the platform vibration to exceed 2 m/s^2. Furthermore, the chosen rms acceleration magnitudes would be more representative of the ride vibration properties of a wide range of vehicles [80]. The total force developed by the seat structure and the subject, together with the seat acceleration, were acquired in a multi-channel vibration analyzer (Pulse Labshop). The data were subsequently analyzed to derive the APMS responses of the subjects.



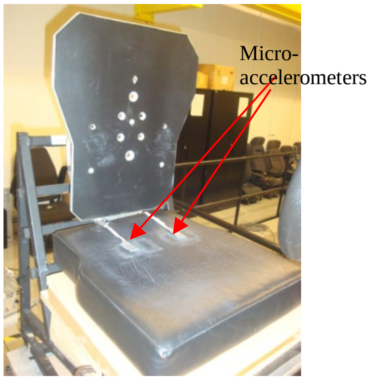
(a) **(b)**

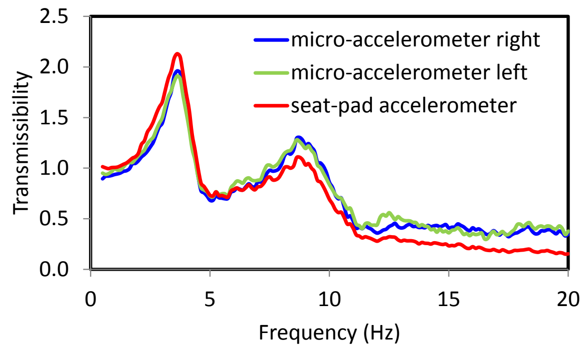
Figure 3.6: (a) Acceleration power spectral density of the synthesized random vibration signals; (b) schematic of the WBVS with vibration controller and data acquisition system for the rigid seat.

The biodynamic force due to the seated body under vibration was also measured using the seat pressure sensing mat, which was placed on the seat pan (second series). The body-seat interface force signal from the I-scan software together with the seat acceleration signal was acquired into a National Instruments data acquisition system for subsequent analyses of the data. Figure 3.6(b) schematically illustrates the measurement and data acquisition systems used in the experiments. The measurements were performed for each subject sitting with and without a back support (Fig. 3.5). In the case of the back supported posture, the subjects were advised to support their lower back against a vertical backrest, as shown in Fig. 3.5. The feet support height was adjusted so as to permit the subject to assume a relaxed and upright sitting posture with his lower legs vertical and his thighs horizontal (knee angle of 90^o). The subject posture, particularly the position of his back, was visually monitored by the experimenter during each trial. For both sitting posture, i.e. NB and WB, the subjects were asked to place their hands on the steering wheel, as seen in Fig. 3.5. The force-plate and the acceleration signals were acquired in a multi-channel vibration analysis system for deriving the apparent mass (APMS) responses of the subjects. The computed APMS was inertia corrected to account for the seat and seat structure mass [62]. The resulting corrected APMS served as the reference for verification of biodynamic responses derived from the force measured by the seat pressure mat.

3.3.3 Dynamic measurements setup and methods - cushion seats

The rigid seat used in the previous setup was modified to accommodate selected cushions. In particular, the height of the seat pan was reduced so as to achieve the same sitting heights when a cushion was placed on the rigid seat. The seat was designed such that the selected cushions could be placed on the rigid seat pan, as illustrated in Fig. 3.7(a). In order to realize the same levels of vertical vibration at the body-seat interface, it was necessary to install the feedback accelerometer on the cushion surface. The standardized seat-pad accelerometer, however, could not be applied since it would greatly alter the body-seat contact pressure. Consequently, two micro-accelerometers (ADXL 330, 14×14 mm; 1.4 mm thick; each weighing 2 grams) were fixed on the cushion surface, as shown in Fig. 3.7(a), so as to minimize the effects of the accelerometer on the body-seat interface pressure. These were installed around the ischial tuberosities of the subjects to ensure adequate contact of the accelerometers with the seat.



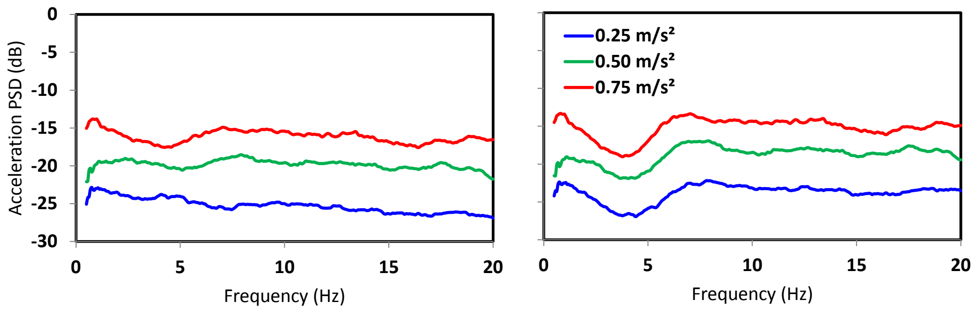


(a) **(b)**

Figure 3.7: (a) Mounting of the accelerometers on an elastic seat; (b) comparisons of acceleration transmissibility measured by micro-accelerometers and standardized seat-pad-accelerometer (81 kg subject; 0.5 m/s^2).

In order to verify the validity of the micro-accelerometers, a seat pad accelerometer, as recommended in the ISO 2631-1 [81], was also placed on the cushion, while an 81 kg subject was asked to sit on the cushion. The WBVS was operated to measure the transmission of the platform vibration to the body-seat interface using the standardized accelerometer and the micro-accelerometers. The signals from both micro-accelerometers together with the seat pad and the base accelerometers were acquired in the multi-channel vibration analyzer. The acceleration transmissibility characteristics of the seat base to human-cushion interface, derived from each of the accelerometer signals using the H_1 frequency response estimator, are compared in Fig. 3.7(b) under the 0.5 m/s^2 excitation. The measured responses show that the two micro-accelerometers yield similar measurements, which are also comparable with the standardized seat pad accelerometer. The micro-accelerometers were subsequently used to synthesize the desired vibration spectra and to measure the human-seat interface acceleration, while the large size seat pad accelerometer was removed. The mean of the two micro-accelerometer signals was used as the feedback to the vibration controller to synthesize the desired vibration spectra at the seat cushion.

Considering that a seat cushion exhibits nonlinear stiffness and damping properties that are dependent upon the seated body mass, and the magnitude and frequency of vibration, the vibration signals were synthesized for 3 different subjects with body mass near 55, 81 and 90 kg. The nature of the vibration generated at the human-cushion interface was also dependent upon the visco-elastic properties of the cushion. The synthesis was thus carried out for all the selected cushions. This involved the generation of a total of 27 drive files for realizing acceleration spectra with 0.25, 0.50 and 0.75 m/s^2 rms acceleration for each of the 3 subjects and 3 cushions. For this purpose, each subject was advised to sit on a selected seat cushion assuming postures as in the case of the rigid seat (NB and WB), while holding the steering wheel. The WBVS and vibration controller were subsequently operated to achieve the desired vibration spectra. As an example, Figure 3.8 illustrates spectra of vibration generated at the platform and at the seat A surface with an 81 kg subject. The acceleration spectra clearly show that the vibration level at the seat base (WBVS platform) is substantially greater than that at the cushion at frequencies above 5 Hz. This is attributed to attenuation of high frequency vibration by the cushion. The results further show nearly flat PSD of acceleration at the seat cushion. The vibration synthesis using feedback from the cushion-mounted accelerometers thus permits comparable vibration exposure of subjects seated on cushion as well as on rigid seats.



(a) (b)

Figure 3.8: (a) Power spectral density of acceleration synthesized at seat cushion A and (b) power spectral density of acceleration measured at seat base (81 kg subject with seat A).

The force sensing seat mat was subsequently placed on the seat cushion for measurement of human-seat interface force. The force signal from the seat mat together with the micro-accelerometer signals were acquired for each trial involving a subject-cushion-vibration level combination, in the multi-channel National Instruments data acquisition system. Each trial was repeated three times. The measured signals were subsequently analyzed to derive APMS of the seated human subject.

3.3.4 Data analysis

A multi-channel signal analysis system (Bruël & Kjær Pulse v. 15) was used to acquire the acceleration and force signals at the seat base. The acquired data were analyzed to derive the APMS responses of the subjects seated on a rigid seat considering a bandwidth of 50 Hz and a sampling period of 60 s. The human-seat interface pressure data were analyzed to derive the driving-point force at the human-seat interface for both the rigid and cushion seats using a sampling frequency of 128 Hz for a duration of 60 s. The recorded force signals together with the seat acceleration were exported to a multi-channel National Instrument data acquisition system, and analyzed using the LabVIEW™ software.

3.3.5 Measurements of biodynamic responses with rigid seats – two approaches

The biodynamic responses of the subjects seated on the rigid seat were characterized using two different methods. In the first approach, the APMS was derived from the total force and acceleration measured at the seat base, as it has been widely reported [40, 43]. The complex APMS of the seated subjects was computed using the H_1 frequency response estimator such that [82]:

$$\bar{M}_b(j\omega) = S_{\ddot{z}_b F_b}(j\omega)/S_{\ddot{z}_b}(j\omega) \tag{3.2}$$

where $\bar{M}_b(j\omega)$ is the complex APMS of the subject and the seat structure, $S_{\ddot{z}_b F_b}(j\omega)$ is the cross-spectral density of the measured acceleration $\ddot{z}_b$ and force F_b, $S_{\ddot{z}_b}(j\omega)$ is the auto spectral density of the seat base acceleration and ω is the circular frequency of vibration.

The APMS in Eq. (3.2) relates the total force due to the subject and the seat structure with the seat acceleration. The APMS of the subject alone is derived upon subtracting the APMS of the seat structure alone. The APMS of the seat alone was thus measured for each vibration condition, and applied as a correction to Eq. (3.2), in the following manner [63]:

$$M_b(j\omega) = \bar{M}_b(j\omega) - M_0(j\omega) \tag{3.3}$$

where $M_b(j\omega)$ is the complex APMS of the seated subject and $M_0(j\omega)$ is the APMS of the seat structure alone, which was observed as a nearly constant value equal to the seat structure mass up to 10 Hz, as seen in Fig. 3.9. The magnitude of APMS increased slightly at frequencies above 10 Hz, which is attributed to a resonance of the WBVS platform near 40 Hz.

In the second approach, the APMS was determined from the driving-point force derived from the seat mat using the LabVIEW™ software. The measured pressure distribution was initially analyzed in the I-scan software to derive the total body force through the integration of the pressure distributed over the contact area. Owing to a possible time lag between the force and acceleration signals, the APMS were computed using both the H_1 and H_3 frequency response functions, such that:

$$M_1(j\omega) = S_{\ddot{z}_b F_p}(j\omega)/S_{\ddot{z}_b}(j\omega) \tag{3.4}$$

$$M_3(j\omega) = S_{F_p}(j\omega)/S_{\ddot{z}_b}(j\omega) \tag{3.5}$$

where $M_1(j\omega)$ and $M_3(j\omega)$ are the APMS computed using the H_1 and H_3 frequency response functions, respectively. $S_{F_p}(j\omega)$ is the auto-spectral density of the force F_p measured at the seat pan and $S_{\ddot{z}_b F_p}(j\omega)$ is the cross spectral density of F_p and $\ddot{z}_b$.

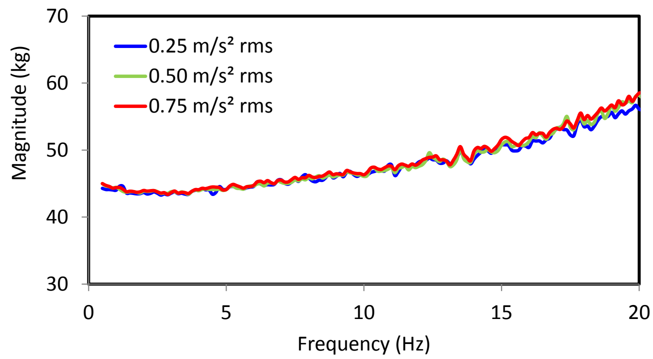


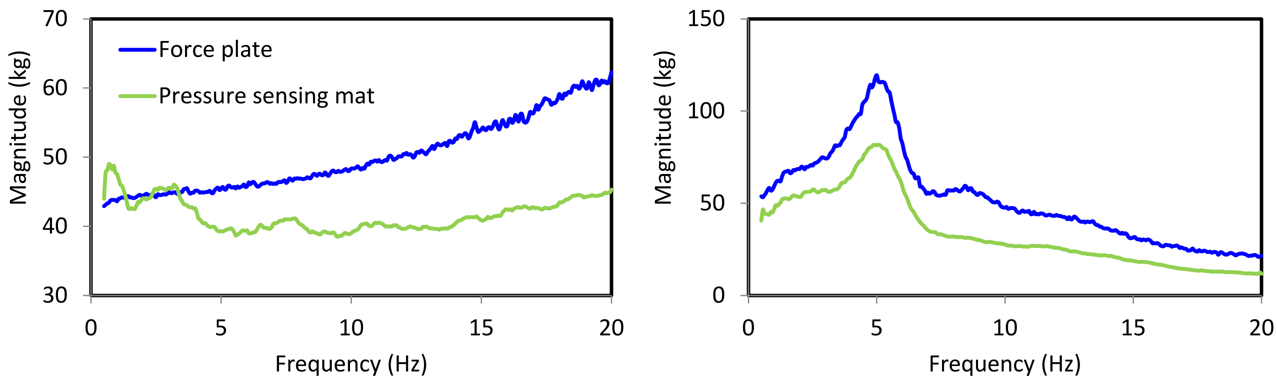
Figure 3.9: Measured apparent mass magnitude of the rigid seat and its supporting structure.

Both functions revealed quite comparable APMS magnitudes. Since the H_3 function does not yield phase information, the H_1 function was retained for computing the APMS. It should also be noted that the seat mat yields the biodynamic force developed by the seated body alone. An inertia correction due to the seat structure is thus not required. In both approaches, the cross- and auto-spectra were computed over a bandwidth of 50 Hz using 12 averages, a Hanning window and 75% data overlap. The coherency of the force and acceleration signals was constantly monitored, and a sample was rejected when the coherence was below 0.9. The complex APMS data were exported to an Excel spreadsheet for further analysis on the contributory factors.

3.3.6 Measurement system verification under dynamic conditions

The APMS responses obtained from the two approaches provided the essential basis for verifying the validity of the seat pressure measurement system. The verification of the measurement system could only be limited to the rigid seat, since reliable data for the cushioned seats were not yet available. The validity of the measurement system was examined by comparing the APMS responses obtained using the two approaches based on the forces acquired from the conventionally-used force plate and the seat mat. The seat was initially loaded with different rigid loads, ranging from 10 to 64 kg and force signals from the force plate and the seat mat were acquired under 0.25, 0.50 and 0.75 m/s^2 rms acceleration excitation. The magnitude of the APMS was computed for each load and vibration excitation condition. The APMS computed from the force plate signal was also inertia corrected for the contribution of the seat structure mass, as described in Eq. (3.3). Comparisons revealed large differences between the two measurements in the entire frequency range, irrespective of the seat load and the excitation level. The differences, however, were somewhat comparable for all the seat loads and excitation levels considered. As an example, Fig. 3.10(a) illustrates comparison of the APMS magnitudes derived from the two measurement systems, when the seat was loaded with a 44 kg mass and exposed to 0.50 m/s^2 rms acceleration excitation.

The results obtained from the force plate show an APMS magnitude of nearly 44 kg at very low frequency, which is identical to the seat load mass. The APMS magnitude, however, tends to increase with increasing frequency and is substantially higher at frequencies above 10 Hz, which is attributed to hopping of the unrestrained rigid load on the seat. The APMS magnitude, derived from the seat mat is comparable with that derived from the force plate only at low frequencies, while it is considerably lower than the magnitude derived from the force plate at frequencies above 3 Hz. The results suggest that the seat mat measurement system would yield considerable errors in the biodynamic responses measured with human subjects. Similar degree of error was also observed for the measurements obtained with human subjects. As an example, Fig. 3.10(b) compares the APMS magnitude responses obtained for an 83 kg subject using both measurement systems, while subjected to 0.50 m/s^2 excitation. The results are presented for a subject sitting without a back support (NB). The results show considerable differences between the APMS magnitude responses acquired using the force plate and the pressure sensing seat mat over the entire frequency range. Similar trends were observed with all subject and vibration conditions, where the APMS magnitude measured from the pressure sensing mat was considerably lower than that measured from the force plate.



(a) (b)

Figure 3.10: Comparisons of the APMS magnitude responses derived from the force plate and the pressure sensing mat: (a) 44 kg rigid load; and (b) 83 kg subject.

The observed differences in the measurements from the pressure sensing mat were attributed to two primary factors: (i) a varying frequency response of the seat-pressure measurement hardware; and (ii) the relatively poor dynamic range of the pressure sensels. The experiments were subsequently repeated using different sampling frequencies of 64 and 256 Hz. The APMS responses, derived from the pressure sensing mat, however, were observed to be identical, irrespective of the sampling rate. It was thus concluded that the hardware could acquire dynamic forces accurately, without compensation, only for frequencies up to 3 Hz.

The ratio of the APMS magnitude derived from the force plate to that from the seat mat was subsequently computed for its application as a correction function. Figure 3.11 illustrates the magnitude ratios obtained for the 44 kg load and the 83 kg subject. The results show that the magnitude ratio increases nearly linearly with the frequency for both loads. The data acquired with human subjects also revealed considerable deviations at low frequencies, as seen in Fig. 3.11(b), which resulted in a magnitude ratio in the order of 1.3 near 0.5 Hz as compared to almost 1 for the rigid load. This discrepancy was attributed to the poor resolution of the sensels, which was 0.83 kPa for the relatively high pressure range mat (207 kPa) used in the study. The sensel resolution was considered acceptable for the concentrated rigid load but not for the human subject. The seated body yields pressure concentrations near the ischial tuberosities and near the thighs, when supported by the seat. The pressure values around the extremities of the contact region, however, may be below the sensel resolution, particularly under low vibration levels. This suggests the need for a correction function that can account not only for the frequency response, but also for the poor resolution and dynamic range. The magnitude ratios, shown in Figure 3.11, were thus considered as correction functions for compensating the frequency response of the seat pressure measurement system. As the pressure values depended upon the seated body mass, the vibration level and the buttock contact area, correction functions (*CF*) were derived for each subject and for each vibration level condition. The APMS responses were more accurately obtained by:

$$M_s(j\omega) = CF(\omega)\frac{S_{\ddot{z}_b F_p}(j\omega)}{S_{\ddot{z}_b}(j\omega)} \tag{3.6}$$

where $CF = a_1 f + a_2$ is the correction function with a_1 and a_2 being the linear regression coefficients, and M_s is the corrected APMS of the subject obtained from the pressure sensing mat.

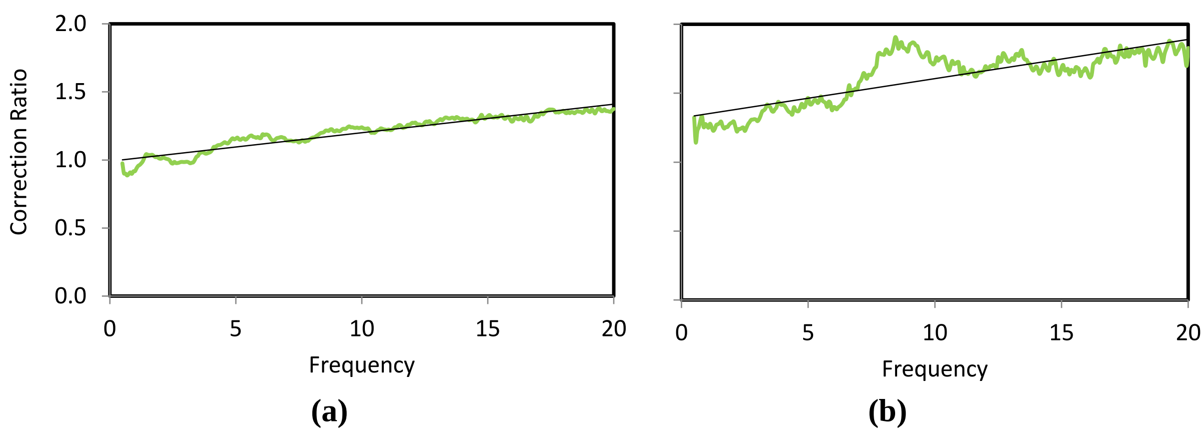


Figure 3.11: Ratio of magnitudes of APMS measured from the force plate to that from the pressure sensing mat: (a) 44 kg rigid load; and (b) 83 kg subject.

The CF derived for all the subjects and excitation conditions revealed very similar linear trends. While the frequency dependence (coefficient a_1) was quite comparable for all subjects and excitation conditions, the low frequency offset (coefficient a_2), mostly attributed to the dynamic range, varied with the subject mass and with the excitation level. However, the effect of the vibration magnitude on a_2, however, was relatively small under the 0.50 and 0.75 m/s^2 rms excitations, but it was notably large for the 0.25 m/s^2 rms excitation, which was attributed to relatively lower pressure variations under lower vibration. Figure 3.12 illustrates the mean and standard deviations of coefficients a_1 and a_2, derived from the data acquired with all subjects, and for all excitation and back support combinations. The results suggest relatively small differences between the coefficient values under the 0.50 and 0.75 m/s^2 excitations, while the coefficients derived under the 0.25 m/s^2 excitation are larger. The observed variation in the coefficients with respect to the use of a back support is also small. Consequently, two correction functions were derived, corresponding to the lower (0.25 m/s^2) and to the higher (0.50 and

0.75 m/s^2) excitation levels for each individual subject and applicable for both back support conditions. It was further hypothesized that the same correction factors would be equally applicable for measurements on an elastic seat.

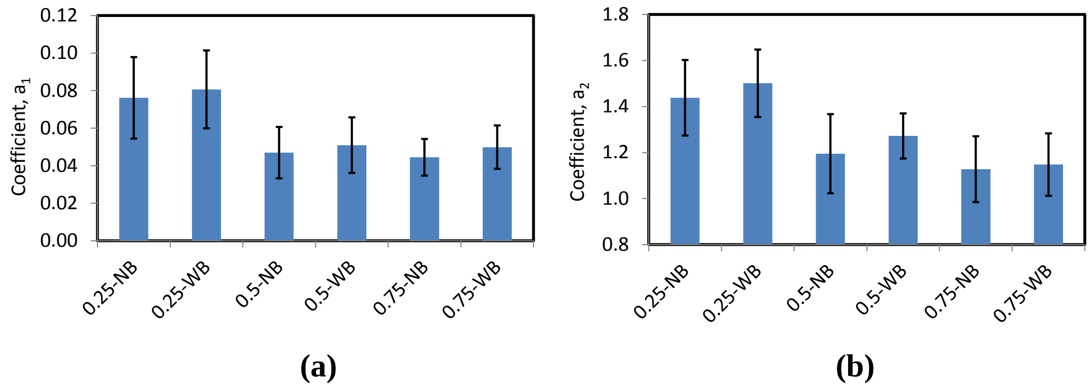


Figure 3.12: Mean and standard deviations of regression coefficients corresponding to each sitting posture and excitation condition: (a) a_1; (b) a_2.

4. HUMAN ANTHROPOMETRY EFFECTS ON THE APPARENT MASS RESPONSES

4.1 APMS response characteristics of subjects seated on a rigid seat

The data acquired with a rigid seat were initially analyzed to identify gender effect on the APMS responses derived from the force plate signal. Owing to some coupling between the gender and the anthropometry, the data were systematically analyzed to study the effects of selected anthropometric factors such as body mass, body fat, lean body mass, buttock circumference, C7 height and contact area. The analyses involved the apparent mass (APMS) responses of 31 male and 27 female subjects seated on a rigid seat with and without a vertical back support, and exposed to three different levels of random vibration (0.25, 0.50 and 0.75 m/s ^{2} rms).

The measured APMS responses of the subjects were initially analyzed to assess the degree of inter-subject variability in a qualitative sense. As an example, Fig. 4.1 compares the APMS magnitude and phase responses of all the subjects under the 0.50 m/s^2 rms acceleration excitation. The results are presented for both seating conditions, i.e. without back support (NB) and with vertical back support (WB). The results show large differences in both the magnitude and the phase responses, while the predominant magnitude peaks occur within narrow frequency bands. The responses obtained for the no back support posture exhibit peak APMS magnitude in the 4.10 to 6.60 Hz range, while the peak APMS for the back supported posture occur in the 4.06 to 6.94 Hz range. Distinct secondary peaks are also evident in the responses of many subjects in the 8 to 13 Hz range.

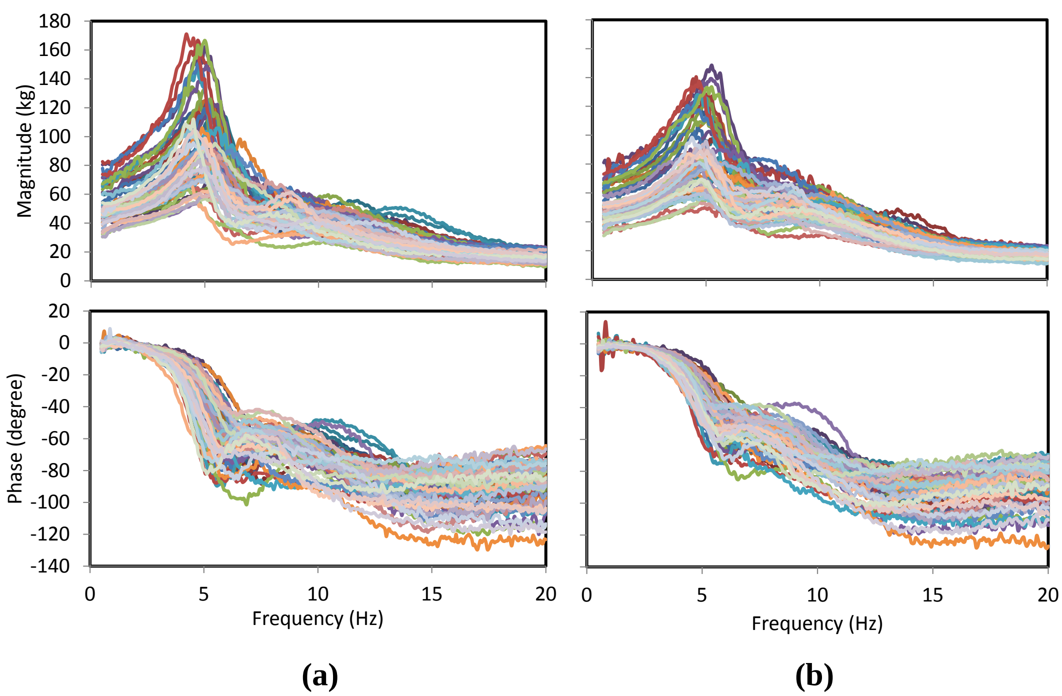
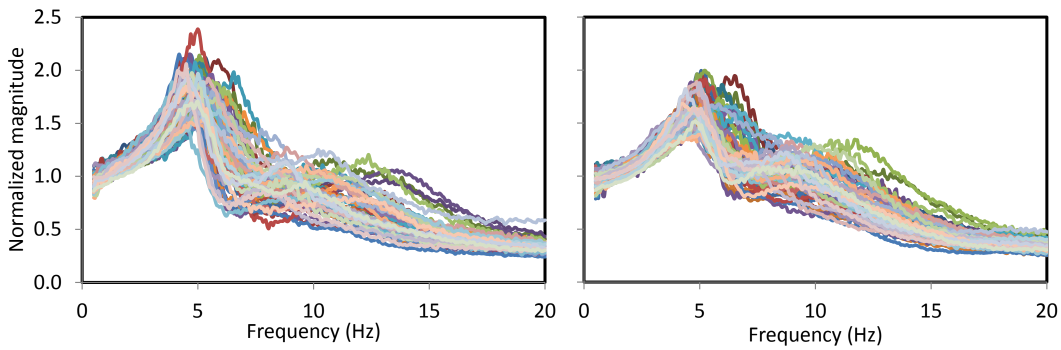


Figure 4.1: APMS magnitude and phase responses of 58 subjects: (a) NB - no back support; and (b) WB - vertical back support (excitation: 0.50 m/s^2).

The measured data show considerable scatter, irrespective of the sitting posture, which is more prominent at lower frequencies, 0.5 to 6.5 Hz, and is mostly caused by the body mass variations. For the no back support posture, the coefficient of variation (CoV) ranged from 25 to 34% within this frequency range. Within that same range of frequencies, the results for the vertical back support condition revealed slightly lower CoV, in the 23 to 30% range. An opposite trend, however, was observed in the corresponding scatter in the phase responses. The scatter in the measured data at lower frequencies may be reduced through normalization of the APMS magnitude with respect to the static sitting mass. Figure 4.2 illustrates normalized APMS magnitude responses of 58 subjects for the two sitting conditions and 0.50 m/s^2 excitation. Although the normalized responses exhibit considerably lower scatter at lower frequencies, the scatter at higher frequencies tends to increase. The CoV peak values of the normalized data were around 29% for the NB posture and 22% for the WB posture. The results suggest that the scatter in the data cannot be eliminated through normalization with respect to the body mass alone.



(a) **(b)**

Figure 4.2: Normalized APMS magnitude responses of 58 subjects sitting: (a) NB - no back support; and (b) WB - vertical back support (excitation: 0.50 m/s^2).

4.2 Gender effect

The effect of gender on the measured APMS responses are investigated by grouping the data for the 31 male and 27 female subjects. Figures 4.3 to 4.5 illustrate comparisons of the mean APMS magnitude responses of the male and female subjects for the three vibration levels and the two sitting conditions. The results show that the APMS response magnitudes of the male subjects are higher than those of the female subjects in the entire frequency range. Near the secondary mode of vibration, the mean magnitudes of female subjects are more prominent as compared to the male subjects for all the vibration levels and sitting conditions considered. It should be noted that this second peak is relatively less clear due to data averaging. The mean phase responses of the two genders, however, are comparable.

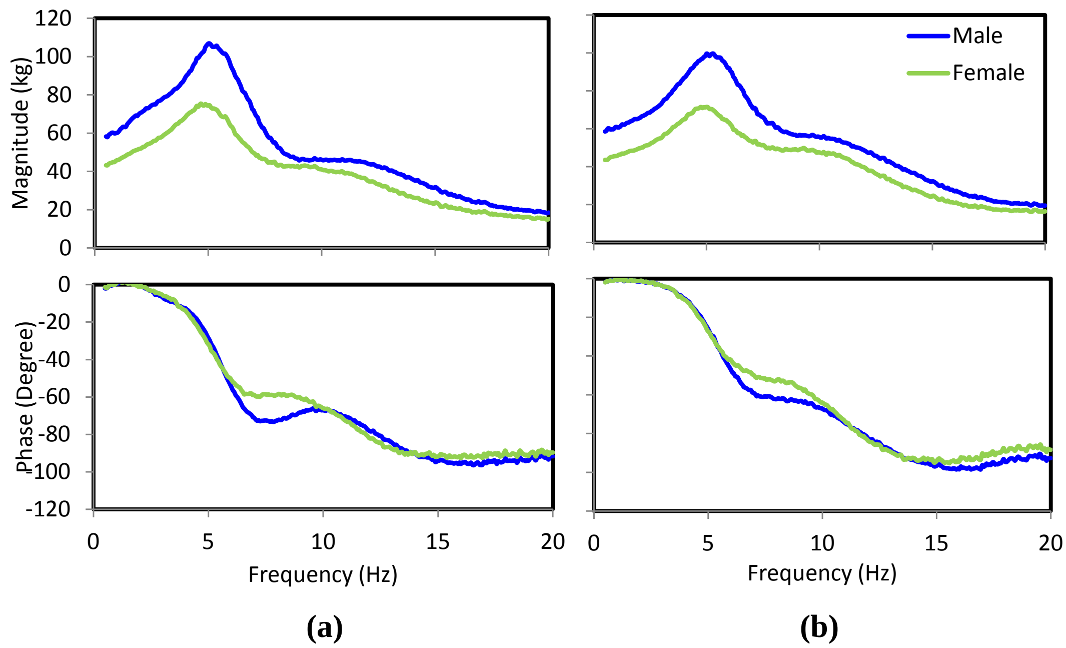


Figure 4.3: Comparisons of mean APMS magnitude and phase responses of 31 male and 27 female subjects seated with: (a) no back support; and (b) vertical back support (0.25 m/s^2 excitation).

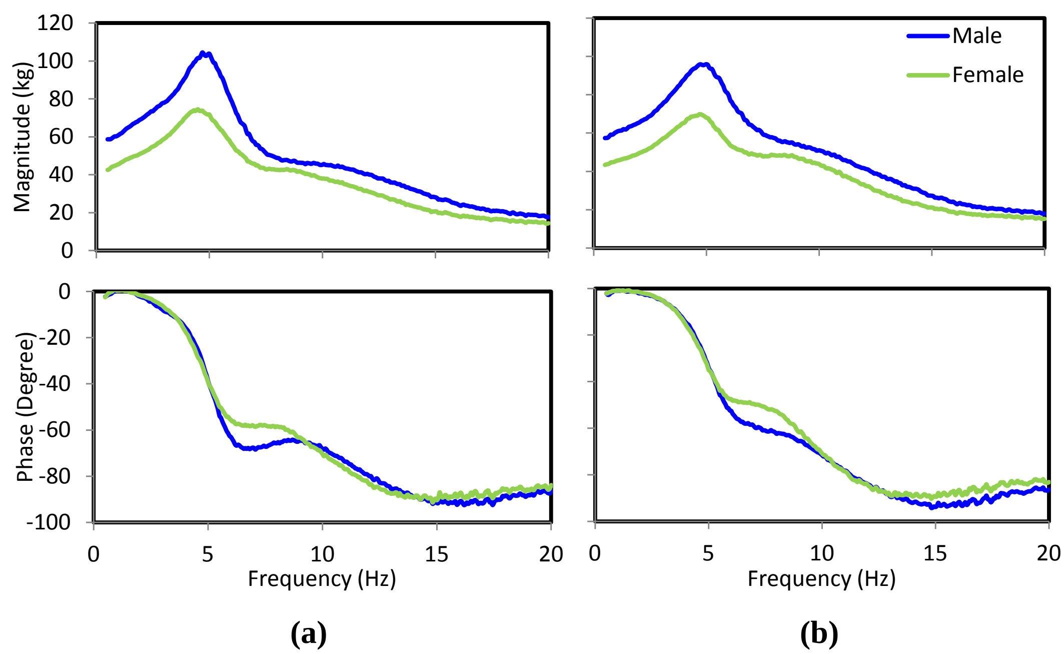
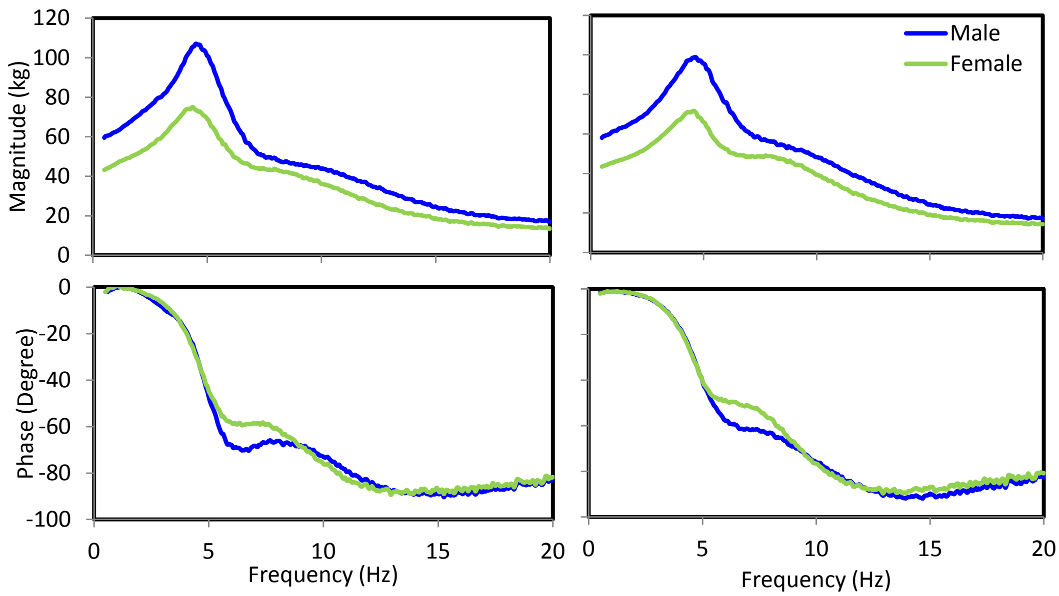


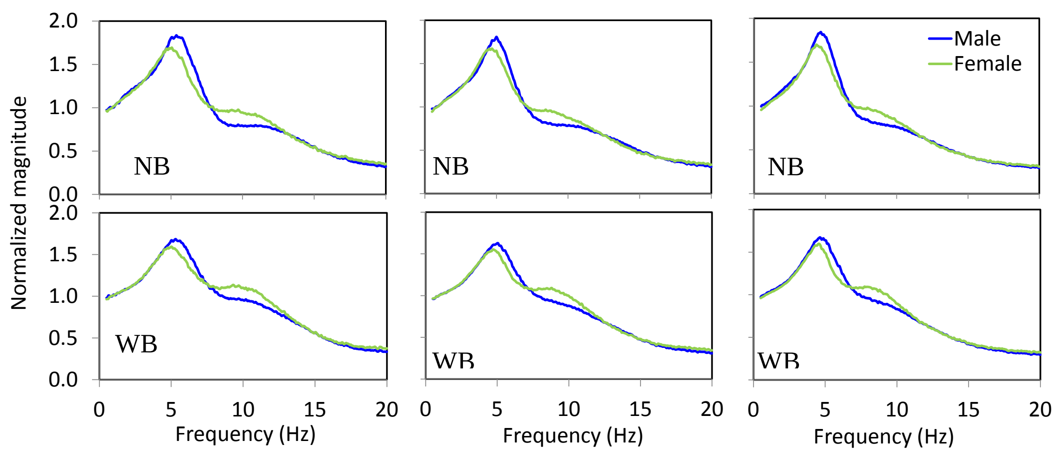
Figure 4.4: Comparisons of mean APMS magnitude and phase responses of 31 male and 27 female subjects seated with: (a) no back support; and (b) vertical back support (0.50 m/s^2 excitation).



(a) **(b)**

Figure 4.5: Comparisons of mean APMS magnitude and phase responses of 31 male and 27 female subjects seated with: (a) no back support; and (b) vertical back support (0.75 m/s^2 excitation).

The differences in the magnitude responses of the two genders could be partly attributed to the difference in their respective mean body mass. The mean body mass of the male and female participants were 79.8 and 60.1 kg, respectively. The means of the normalized magnitude responses of the two groups were subsequently obtained and are presented in Fig. 4.6.



(a) **(b)** **(c)**

Figure 4.6 Comparisons of mean normalized APMS magnitude responses of 31 male and 27 female subjects for different sitting postures, and vibration magnitudes: (a) 0.25 m/s^2; (b) 0.50 m/s^2; and (c) 0.75 m/s^2.

The results show that the male subjects yield higher normalized APMS magnitude around the primary resonance, while female subjects yield higher normalized magnitude around the secondary peak. The results in Figs. 4.3 to 4.6 also show that the mean primary peak frequency of the male subject responses (5.06 Hz for NB and 5.35 Hz for WB support) is relatively greater than that of the female subject responses (4.69 Hz for NB and 5.00 Hz for WB support). It is thus deduced that both the body mass and the gender yield coupled effects on the measured APMS responses. Furthermore, normalization of the measured responses alone cannot eliminate this coupling effect. It has been suggested that the APMS responses of seated subjects should be expressed for particular body mass or for narrow body mass ranges [43, 59, 62, 65, 83], which could facilitate the study of important contributory factors such as the gender.

In this study, attempts were made to group acquired data under comparable body mass ranges for both genders. This task, however, was quite challenging considering the relatively higher body mass of the male group compared to the body mass of the female group. Only data collected from subjects with body mass in the vicinity of 60 and 70 kg could be considered for the study of gender effects. These included 7 female and 7 male subjects for each of the two mass ranges, denoted as G60 (55 to 65 kg) and G70 (65 to 75 kg) as shown in Table 3.3. The data for these subjects were subsequently analyzed to derive the respective mean magnitude responses to identify a gender effect, if any, decoupled from the body mass effect. Figure 4.7 compares the mean magnitude responses of the male and female subjects of comparable body mass for the two back support conditions and the three vibration levels. Results attained through analyses of variance (ANOVAs) considering three main factors (G – gender, BS – back support and E – excitation magnitude) suggest that the resonance frequency of the female subjects was significantly ($p<0.001$) lower than that of the male subjects in both mass groups (Table 4.1). The results also show significant effects of the back support and excitation conditions, and negligible interactions among the main factors. Paired *t*-tests for the two mass groups, performed at various discrete frequencies, also show significant variations in the APMS magnitude between the male and female subjects, particularly in the 4 to 8 Hz range (Table 4.2).

Table 4.1: *p*-Values obtained from a three-factor (G, BS and E) analysis of variance (ANOVA) of the primary resonance frequency and peak APMS magnitude for the two groups of body mass (60 and 70 kg) (α = 0.05).

Body mass	Measure	G	BS	E	G * BS	G * E	BS * E	G * BS * E
G60 (60 kg)	Frequency	**<0.001**	0.166	**0.007**	0.529	0.361	0.679	0.938
	Magnitude	0.125	**<0.001**	0.126	0.391	0.323	0.579	0.892
G70 (70 kg)	Frequency	**<0.001**	0.270	**<0.001**	0.658	0.360	0.573	0.902
	Magnitude	0.719	**<0.001**	0.557	0.385	0.764	0.739	0.759

G - gender (male and female), BS - back support (NB and WB), E - excitation magnitude (0.25, 0.50 and 0.75 m/s^2)

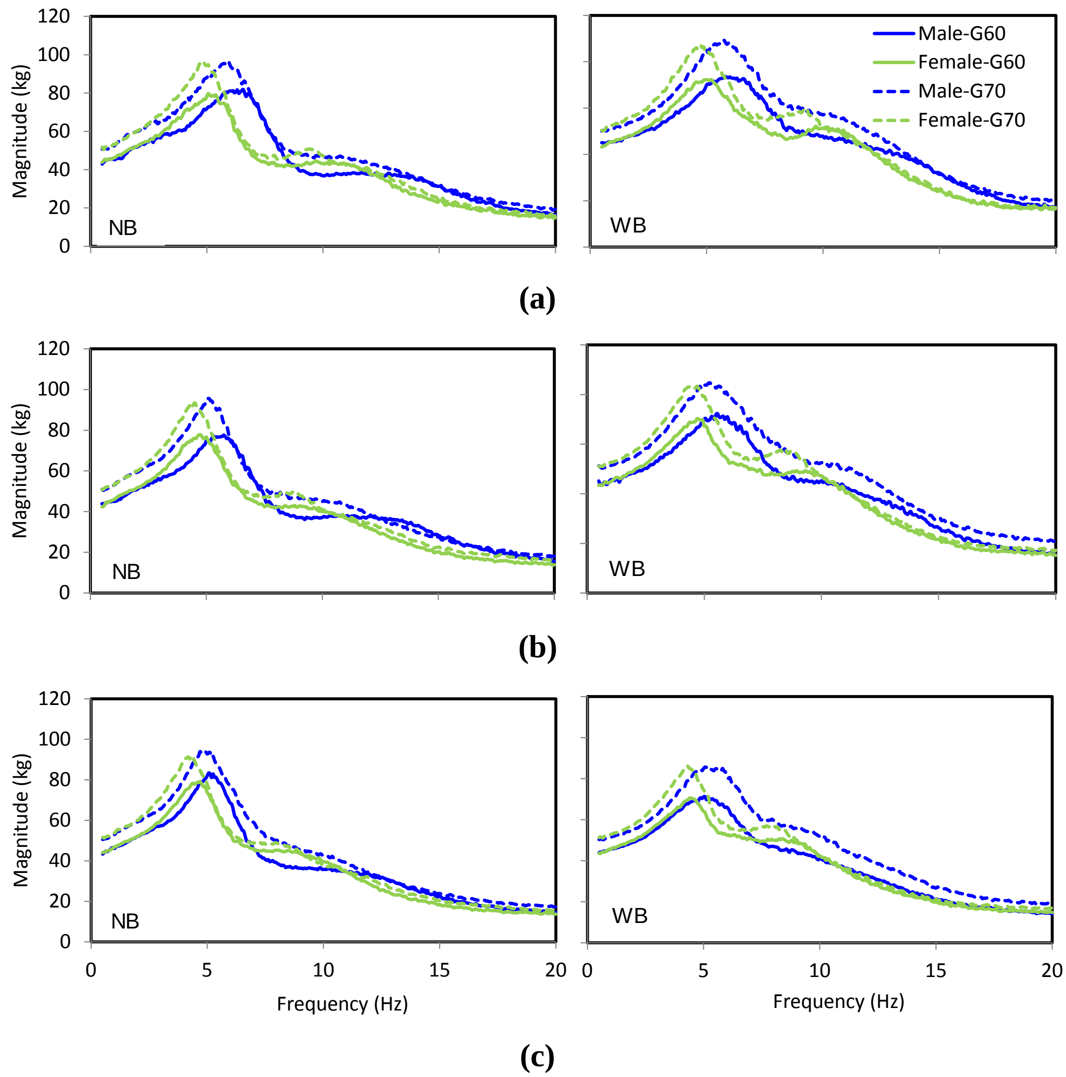


Figure 4.7: Mean magnitude responses of male and female subjects within the two mass groups (60 and 70 kg), corresponding to the different sitting and excitation conditions: (a) 0.25 m/s^2; (b) 0.50 m/s^2; and (c) 0.75 m/s^2.

Table 4.2: *p*-Values obtained from paired *t*-tests of the APMS magnitude for the two mass groups (G60 and G70) of male vs. female subjects, corresponding to the two sitting conditions and the three levels of excitation.

Frequency (Hz)	NB - No back support						WB - Vertical back support					
	0.25 m/s^2		0.50 m/s^2		0.75 m/s^2		0.25 m/s^2		0.50 m/s^2		0.75 m/s^2	
	G60	G70	G60	G70	G60	G70	G60	G70	G60	G70	G60	G70
3	–	–	+	–	–	–	–	+	–	–	–	–
4	–	–	+++	–	+	–	–	+	–	–	–	–
4.5	+	+	+++	–	–	–	–	–	–	–	–	–
5	++	–	–	+	+	+	–	–	–	–	–	++
5.5	+	–	+	++	+	++	–	+	+	++	++	++
6	–	++	+	+	+	+	–	+	++	++	++	++
6.5	++	+++	+	–	–	+	+	++	++	++	+	++
7	+++	++	–	–	–	–	++	+	++	++	–	+
8	+++	+	–	–	–	–	+	–	–	–	–	–
9	+	–	+	–	+	–	–	–	–	–	–	–
10	–	–	–	–	–	+	+	–	–	–	–	++
15	–	++	–	+	–	+	+	+	+	–	–	++

$p>0.05$ –; $p<0.05$ +; $p<0.01$ ++; $p<0.001$ +++

4.2.1 Influence of excitation magnitude

Figure 4.8 illustrates the effect of the excitation magnitude on the mean APMS magnitude responses. The results are presented for the 31 male and 27 female subjects, and the two back support conditions. The softening tendency of the human body is evident from the results which show a decrease in the primary resonance frequency with an increase in the excitation magnitude, irrespective of the gender group and the back support condition. The peak APMS magnitude obtained under the different excitations, however, are quite comparable. Such trends have also been reported in earlier studies [40, 59, 62, 68, 72]. This softening tendency among the male and female subjects is further studied by considering changes in the primary resonance frequency and the corresponding APMS magnitude with an increase in the excitation magnitude from 0.25 to 0.75 m/s^2. The responses of the male subjects exhibit greater softening tendency compared to those of the female subjects. The primary resonance frequency for the male subjects decreased by 0.86 and 0.72 Hz for the NB and WB postures, respectively, with an increase in the excitation magnitude from 0.25 to 0.75 m/s^2. The corresponding changes for the female subjects were 0.43 and 0.53 Hz, respectively (Table 4.3). The measured data were further studied considering the two gender groups of comparable body mass (Groups G60 and G70). This facilitated the decoupling of the body mass effect. The comparisons, summarized in Table 4.4, suggest that changes in the primary resonance frequency of the female subject responses are in the order of 0.49 and 0.44 Hz for the NB and WB postures, respectively, for the G60 mass group, and 0.46 and 0.42 Hz for the NB and WB postures, respectively, for the G70 mass group. A greater softening tendency was evident for the male subjects, where the changes in the primary frequency are 1.02 and 0.83 Hz for respectively the NB and WB postures, for mass group G60, and 0.70 and 0.59 Hz for the NB and WB postures, respectively, for mass group G70. These results also suggest relatively greater softening tendency when seated without a back support.

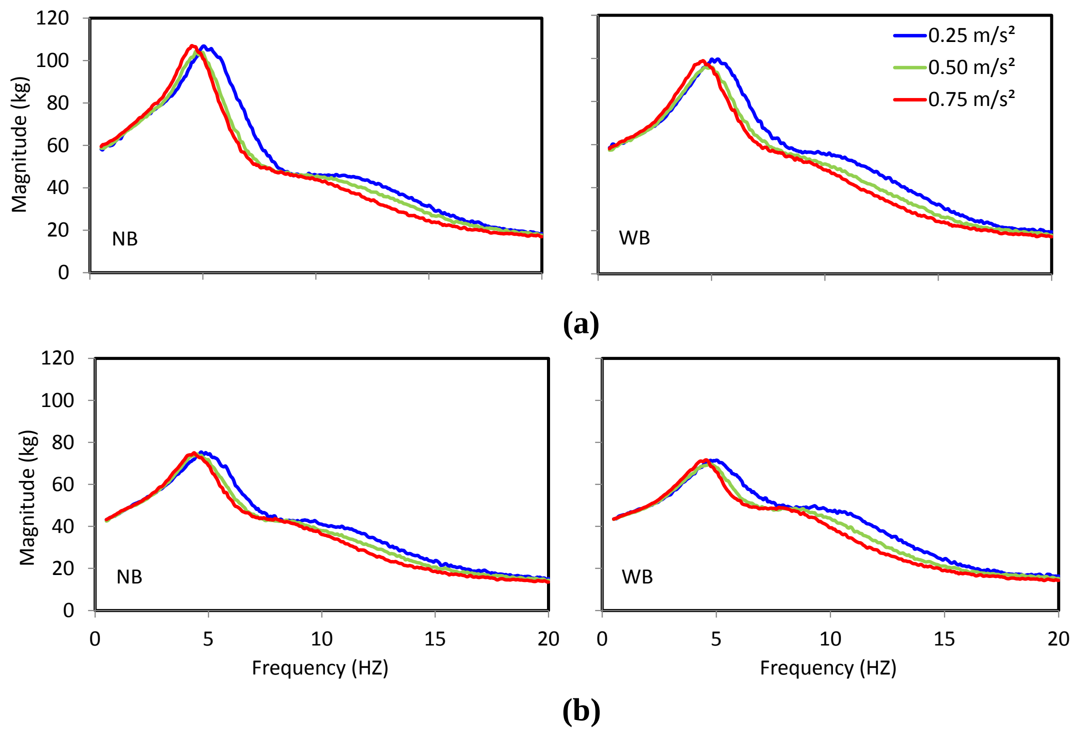


Figure 4.8: Influence of excitation magnitude on mean APMS magnitude responses: (a) male; and (b) female subjects.

Table 4.3: Mean (standard deviation) of the primary resonance frequency and corresponding APMS magnitude under different levels of excitation for the 31 male and 27 female subjects.

Gender	Male		Female	
Posture	NB	WB	NB	WB
Excitation (m/s^2)	Primary resonance frequency (Hz)			
0.25	5.86 (0.55)	5.65 (0.69)	5.18 (0.59)	5.19 (0.63)
0.50	5.29 (0.61)	5.26 (0.75)	4.90 (0.49)	4.84 (0.53)
0.75	5.00 (0.52)	4.93 (0.57)	4.75 (0.48)	4.66 (0.41)
	Peak APMS magnitude (kg)			
0.25	121.9 (29.0)	106.5 (24.6)	82.5 (15.1)	75.7 (14.0)
0.50	116.7 (30.2)	104.3 (25.2)	81.7 (15.4)	72.9 (13.9)
0.75	119.3 (29.9)	105.5 (24.0)	82.1 (15.4)	74.5 (13.6)

Table 4.4: Mean (standard deviation) of the primary resonance frequencies and corresponding APMS magnitude of the male and female subjects within the two mass groups (G60 and G70), under the different levels of excitation.

	Group – G60				Group – G70			
Gender	Male		Female		Male		Female	
Posture	NB	WB	NB	WB	NB	WB	NB	WB
Excitation (m/s^2)	Primary resonance frequency (Hz)							
0.25	6.31 (0.41)	6.08 (0.81)	5.12 (0.52)	4.92 (0.36)	5.90 (0.31)	5.85 (0.59)	4.92 (0.42)	4.84 (0.42)
0.50	5.64 (0.50)	5.94 (0.78)	4.84 (0.27)	4.76 (0.20)	5.35 (0.41)	5.32 (0.32)	4.71 (0.33)	4.59 (0.34)
0.75	5.29 (0.24)	5.25 (0.65)	4.63 (0.34)	4.48 (0.19)	5.20 (0.50)	5.26 (0.57)	4.46 (0.30)	4.42 (0.28)
	Peak APMS magnitude (kg)							
0.25	88.6 (7.7)	78.6 (5.4)	82.1 (7.4)	74.6 (8.1)	102.1 (7.8)	94.1 (4.2)	99.8 (10.1)	91.8 (5.6)
0.50	82.7 (9.9)	77.6 (7.0)	79.4 (7.1)	71.6 (7.2)	99.5 (7.3)	86.9 (5.3)	99.7 (8.0)	87.6 (5.6)
0.75	86.4 (9.8)	77.9 (6.7)	81.7 (8.1)	72.5 (8.5)	103.1 (8.2)	92.7 (6.4)	99.3 (6.0)	89.5 (5.3)

4.2.2 Body mass effect

The effect of the variations in body mass on the APMS magnitude responses are evaluated by grouping the data acquired for the male and female subjects within three mass groups: around 60, 80 and 96 kg for the male subjects; and around 50, 60 and 72 kg for the female subjects. The mean responses of the male and female subjects within each mass group are compared for the two back support conditions and for an excitation level of 0.50 m/s^2, in Fig. 4.9. The peak APMS magnitude increases with body mass for both genders, as expected. The responses of the light-weighted subjects, however, show considerably higher primary resonance frequency than the heavier subjects. The results further show extreme differences in the APMS magnitudes at low frequencies up to nearly the primary resonance frequency. Subsequently, the means of the normalized responses are obtained and compared in Fig. 4.10. While the normalization reduces the extreme differences at low frequencies, it emphasizes the mass effect at higher frequencies, particularly in the 4 to 15 Hz range. The normalized magnitude responses also show higher magnitude for subjects within the higher body mass group up to about 8 Hz, but lower magnitudes at higher frequencies. The normalization of the data thus yields opposite trends in the APMS magnitude at higher frequencies.

4.2.3 Other anthropometric parameters

The influences of selected anthropometric parameters on the measured APMS responses are further investigated to gain better understanding of the gender effects. These include stature, body mass index (BMI), body fat, lean body mass, hip circumference, sitting height and C7 height. For this purpose, the male and female subjects were grouped within narrow ranges of each parameter so as to reduce the coupled effects of the various parameters. The body-seat contact area and mean peak pressure, which invariably occurred around the ischial tuberosities, were also obtained for each subject from the body-seat interface pressure data. These relate to both the body mass and the build, primarily to the hip circumference.

The measured data are also grouped for different ranges of contact area and mean peak pressure. Table 4.5 summaries the ranges used for grouping the subjects for each parameter considered. The mean APMS responses of the groups corresponding to each parameter were subsequently derived for both male and female subjects. The mean responses are compared in Figs. 4.11 to 4.13, which illustrate the effect of factors related to stature (standing height, sitting height and C7-height), body mass (BMI, body fat, percent body fat and lean body mass) and build (hip circumference, body-seat contact area and mean peak pressure), respectively. The results are presented only for the NB posture and 0.50 m/s^2 excitation level, although similar trends were observed under other the excitation levels and for the WB sitting posture.

The results show notable variations in APMS magnitude with variations in the selected anthropometric factors for both male and female subjects. Higher peak magnitude is observed with higher values of most of the anthropometric parameters, namely BMI, body fat, lean body mass, hip circumference and contact area. Furthermore, a decrease in the primary resonance frequency was observed for the male subjects with higher anthropometric dimensions, while no clear trends were showed for the female subjects.

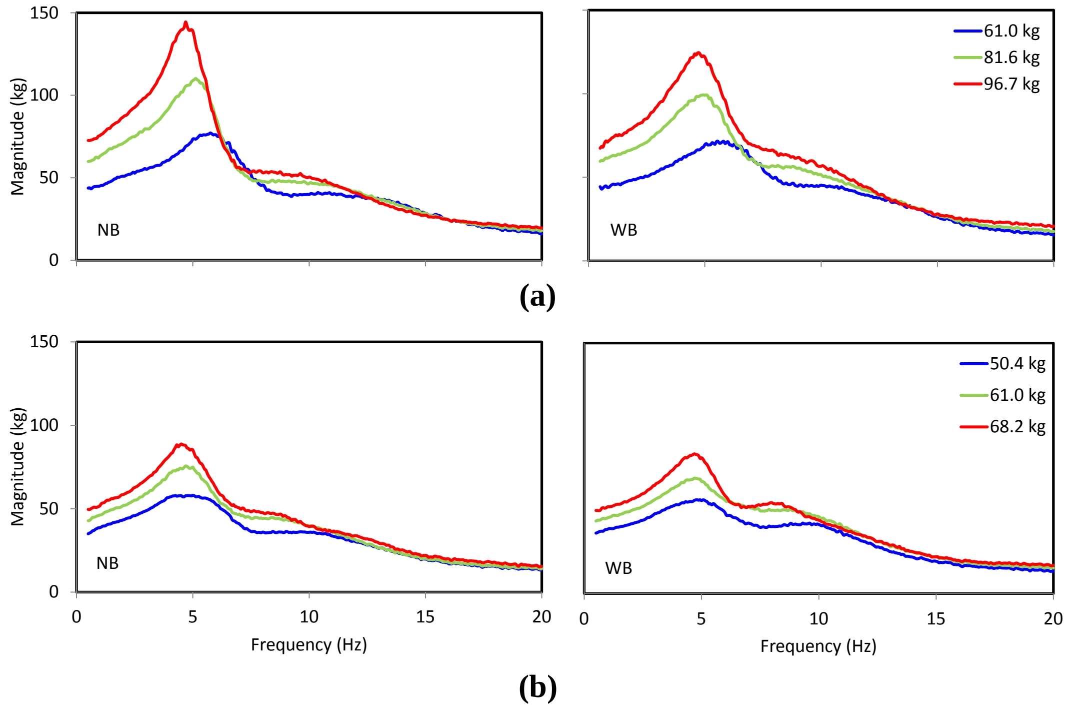


Figure 4.9: Comparisons of the mean APMS magnitude of male and female subjects within three mass groups for different sitting conditions (NB and WB) and a 0.50 m/s^2 excitation level: (a) male; and (b) female subjects.

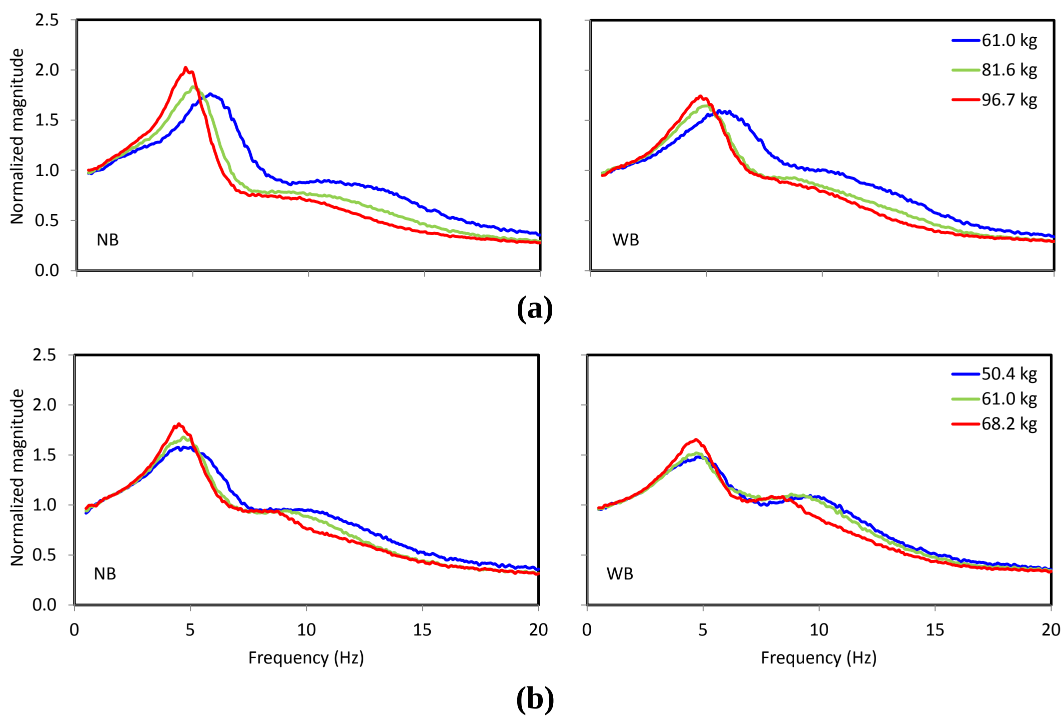


Figure 4.10: Comparisons of the mean normalized APMS magnitude of male and female subjects within three mass groups for different sitting conditions (NB and WB) and a 0.50 m/s^2 excitation level: (a) male; and (b) female subjects.

Table 4.5: Ranges of selected anthropometric factors used to define subgroups of male and female subjects.

Gender		Male		Female	
Anthropometric parameter		Range	n	Range	n
Stature-related	Stature (m)	1.60-1.72	10	1.48-1.60	9
		1.73-1.77	10	1.61-1.67	9
		1.78-1.92	8	1.69-1.73	9
	Sitting height (cm)	83.0-87.5	8	77.5-82.8	8
		88.0-92.9	10	83.0-85.5	8
		93.7-96.7	8	87.0-90.2	8
	C7 height (cm)	59.4-64.5	9	56.5-59.6	8
		65.8-68.7	10	60-62.5	8
		69.6-74.4	8	63-67.6	8
Mass-related	BMI (kg/m^2)	20.0-23.1	12	15.8-20.9	9
		23.3-27.5	11	21.5-23.9	8
		28.4-35.0	8	24.4-26.3	10
	Body fat (kg)	8.6-12.9	11	12.3-15.6	8
		13.5-19.1	10	16.4-20.5	9
		20.5-29.3	7	21.5-25.3	9
	Body fat (%)	16.1-18.7	9	19.3-26.8	9
		20.4-23.8	10	27.9-33.8	9
		26.9-31.2	6	33.9-39.1	9
	Lean body mass (kg)	43.3-56.8	9	34.1-37.7	8
		58.1-64.5	10	38.9-44.6	11
		65.3-77.5	11	45.4-49.5	8
Build-related	Hip circumference (cm)	91.8-97.5	9	89.5-95.0	8
		98.3-106.4	11	97.0-103.0	9
		107.0-116.0	9	104.0-109.0	10
	Contact area (cm^2)	265-443	10	250-425	9
		500-595	8	445-575	9
		615-695	8	600-760	6
	Mean peak pressure (N/cm^2)	8.1-10.4	11	5.8-8.4	9
		11.5-14.5	10	8.7-10.2	9
		15.2-20.7	8	10.6-14.0	8

n = number of subjects

Owing to the coupled effects of the different anthropometric parameters, the data were grouped for male and female subjects with comparable anthropometric dimensions to further analyze the gender effect on the mean measured responses. Table 4.6 summarizes the data grouping and ranges of the considered parameters. While no trends could be observed with the stature-related factors, the mass- and build-related factors show notable gender effect on the mean APMS responses. As an example, Figs. 4.14 to 4.16 show the gender effect on the mean APMS responses of the subjects sitting without a back support and exposed to 0.50 m/s^2 excitation for the selected comparable values of stature-, mass- and build-related factors, respectively. Though the anthropometric body dimensions of the male and female subjects were comparable, the results show that the peak APMS magnitude responses of the male subjects are significantly higher than those of the female subjects (p<0.005), except in the case of the lean body mass. For comparable lean body mass, the peak APMS magnitude responses of the female subjects are somewhat higher. However, for the same body fat and mean peak pressures, the primary resonance frequency of the male and female subject responses are comparable.

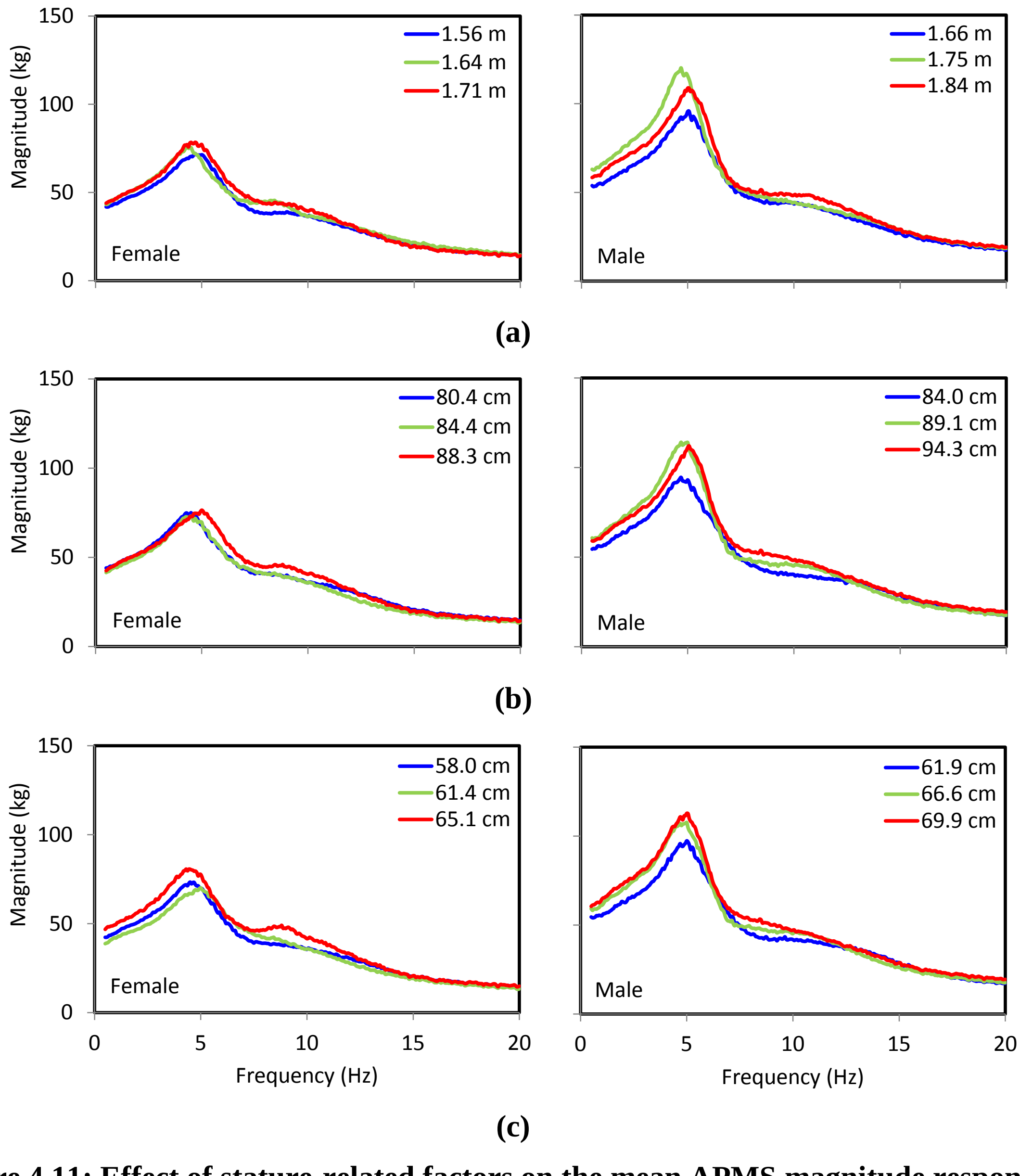


Figure 4.11: Effect of stature-related factors on the mean APMS magnitude responses of male and female subjects: (a) stature; (b) sitting height; and (c) C7 height (NB posture, 0.50 m/s^2 excitation).

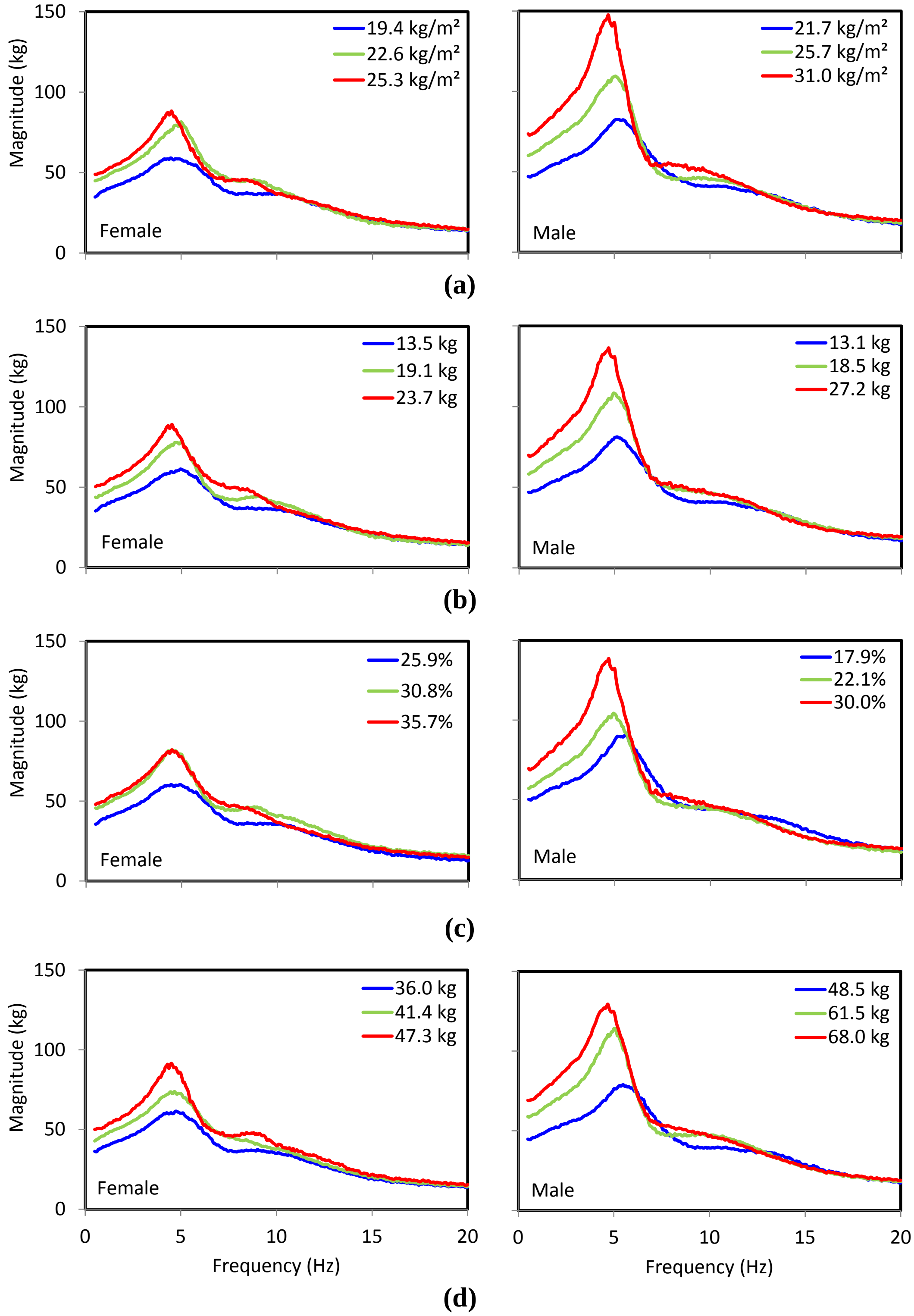


Figure 4.12: Effect of mass-related factors on the mean APMS magnitude responses of male and female subjects: (a) BMI; (b) body fat; (c) body fat percentage; and (d) lean body mass (NB posture, 0.50 m/s^2 excitation).

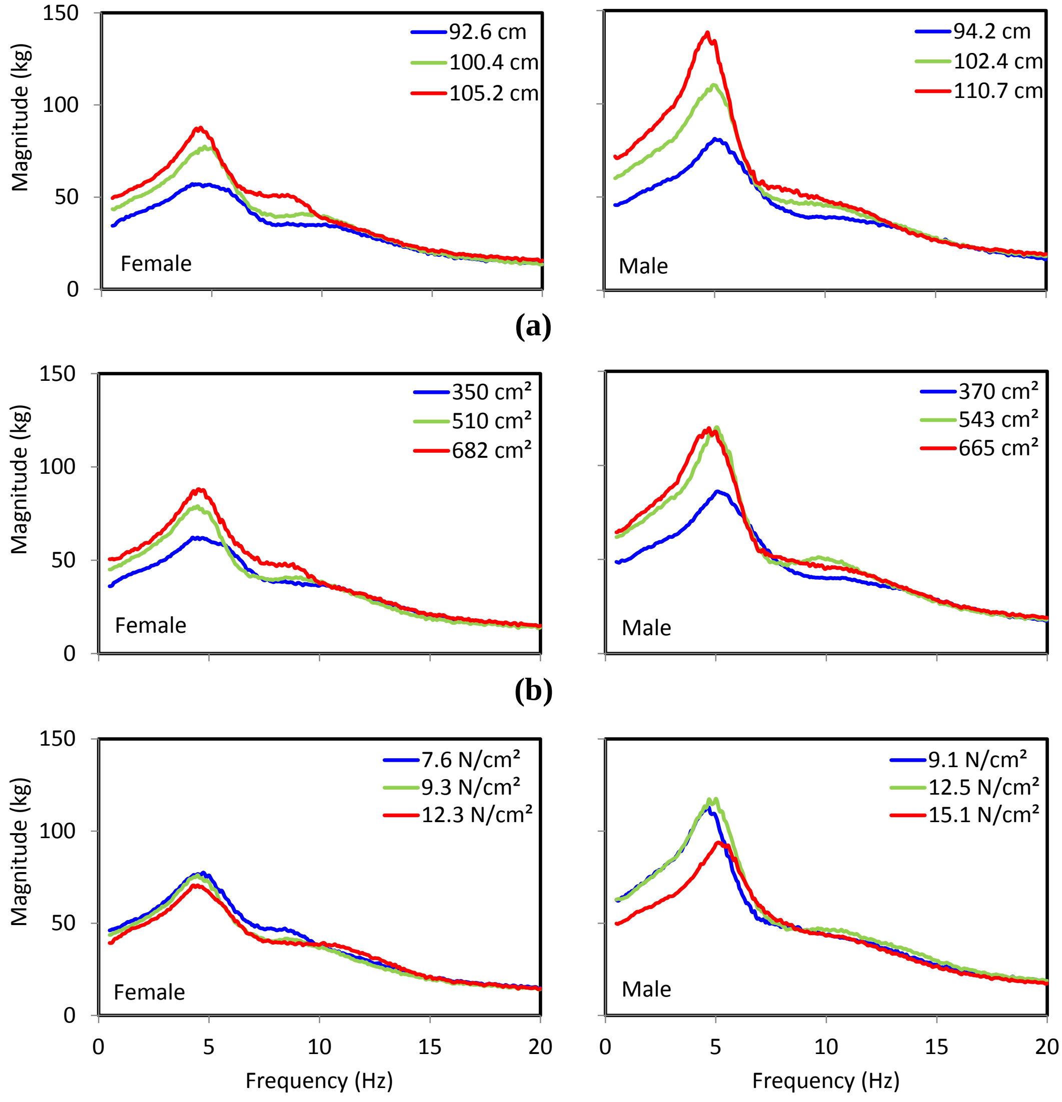


Figure 4.13: Effect of build-related factors on the mean APMS magnitude responses of male and female subjects: (a) hip circumference; (b) contact area; and (c) mean peak pressure (NB posture, 0.50 m/s^2 excitation).

Table 4.6: Ranges of selected anthropometric factors used to compare the APMS responses of male and female subjects.

Gender		Male		Female	
Anthropometric parameters		Range	n	Range	n
Stature-related	Stature (m)	1.60-1.72	10	1.61-1.67	9
	Sitting height (cm)	83.0-87.5	8	83.0-85.5	8
	C7 height (cm)	65.8-68.7	10	63-67.6	8
Mass-related	BMI (kg/m^2)	23.3-27.5	11	24.4-26.3	10
	Body fat (kg)	19.0-29.0	9	21.5-25.3	9
	Body fat (%)	26.9-31.2	6	27.9-33.8	9
	Lean body mass (kg)	43.3-54.5	8	45.4-49.5	8
Build-related	Hip circumference (cm)	98.3-106.4	11	97.0-103.0	9
	Contact area (cm^2)	615-695	8	600-760	6
	Mean peak pressure (N/cm^2)	8.1-10.4	11	8.7-10.2	9

n: number of subjects

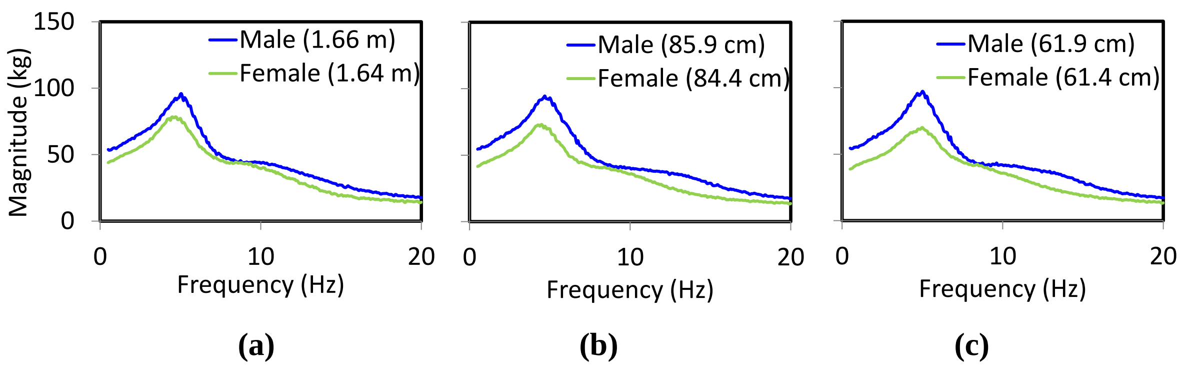


Figure 4.14: Effect of gender on the mean APMS magnitude responses considering comparable stature-related factors: (a) standing height; (b) sitting height; and (c) C7 height (NB posture, 0.50 m/s^2 excitation).

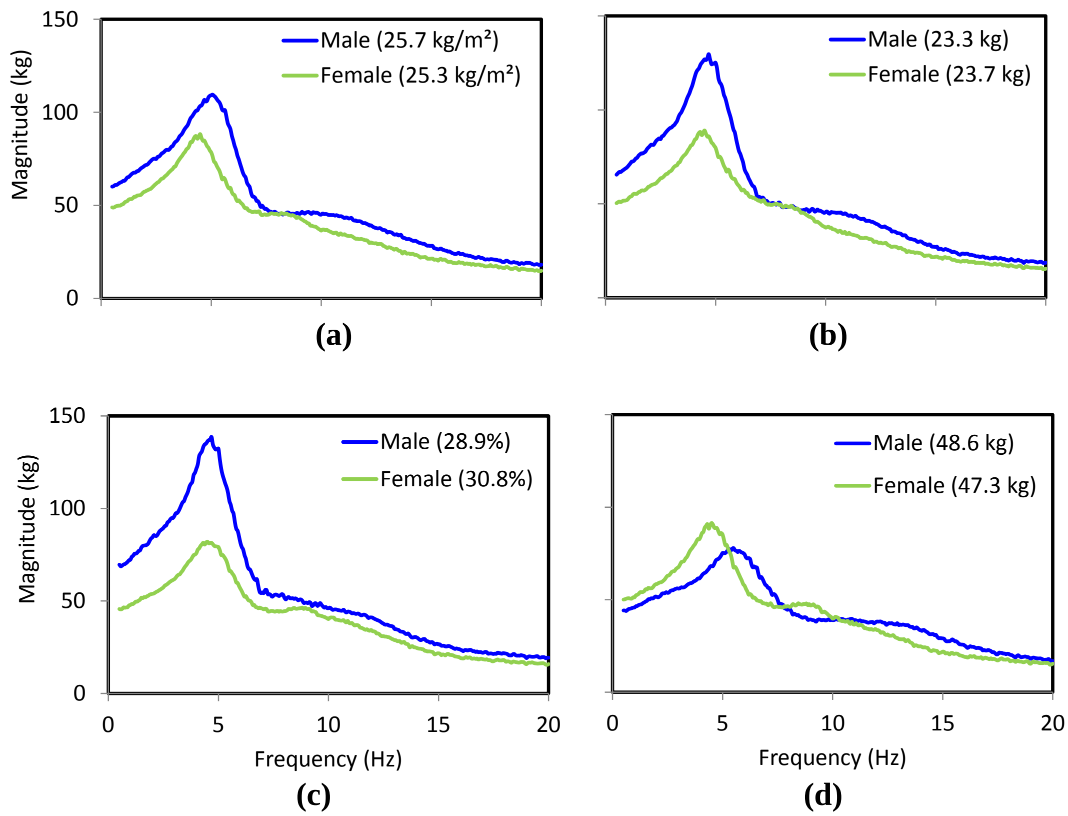


Figure 4.15: Effect of gender on mean APMS magnitude considering comparable mass-related factors: (a) BMI; (b) fat body mass; (c) fat body percentage; and (d) lean body mass (NB posture, 0.50 m/s^2 excitation).

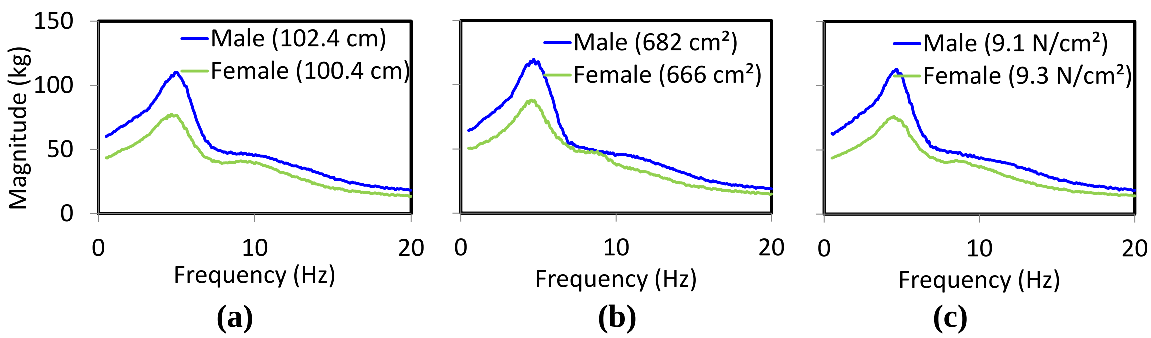
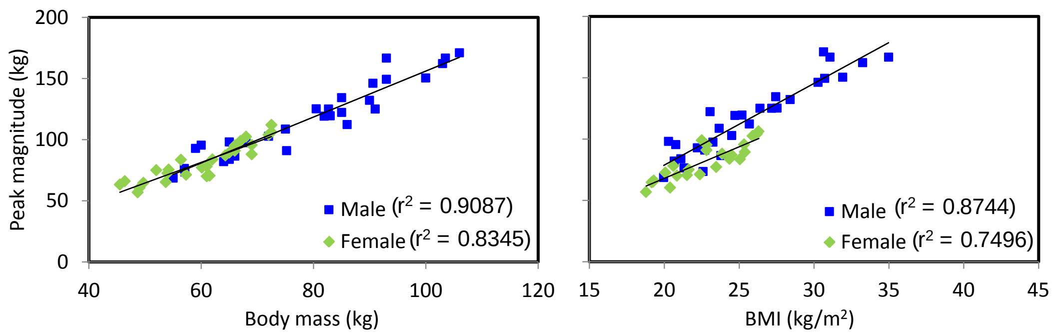


Figure 4.16: Effect of gender on mean APMS magnitude considering comparable build-related factors: (a) hip circumference; (b) contact area; and (c) mean peak pressure (NB posture, 0.50 m/s^2 excitation).

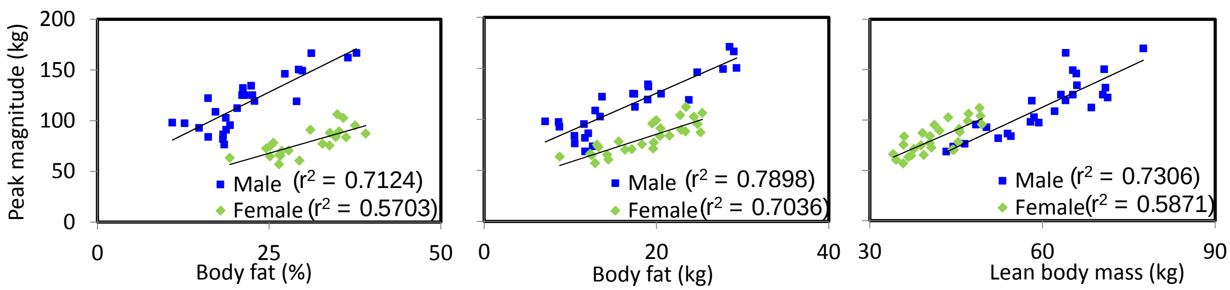
4.2.4 Peak response variations

The results shown in Figs. 4.11 to 4.16 suggest highly complex and coupled effects of anthropometric factors, apart from the body mass and the gender. The data are thus further analyzed to study the correlation between the mean peak APMS and the corresponding frequency with the selected anthropometric factors. Figures 4.17 and 4.18 illustrate variations in the peak APMS magnitudes of the male and female subjects over the ranges of the mass-related factors. The results are presented only for the NB posture and the 0.50 m/s^2 excitation level. Similar correlations, however, were observed for the WB posture and other excitation magnitudes.



(a) (b)

Figure 4.17: Correlation between the peak APMS magnitude of male and female subjects with: (a) body mass; and (b) BMI (NB posture, 0.50 m/s^2 excitation).



(a) (b) (c)

Figure 4.18: Correlation between the peak APMS magnitude of male and female subjects with: (a) body fat percentage; (b) body fat; and (c) lean body mass (NB posture, 0.50 m/s^2 excitation).

In a similar manner, Fig. 4.19 illustrates the variations in the peak APMS magnitudes with variations in the selected build-related factors. In general, the results show considerable dispersion in the peak response with all of the anthropometric parameters considered. Moreover, the male subject responses are better correlated with the body fat, when compared to the female subject responses, while the correlation with the body mass shows an opposite trend.

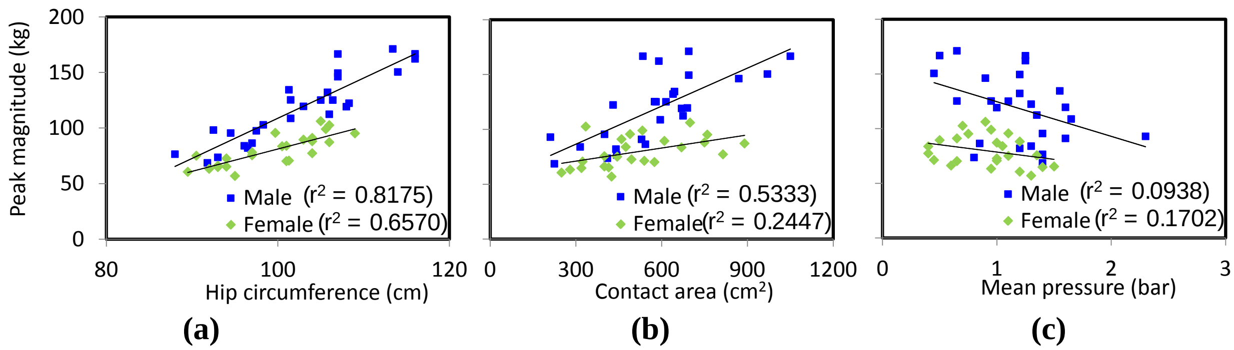


Figure 4.19: Correlation between the peak APMS magnitude of male and female subjects with: (a) hip circumference; (b) contact area; and (c) mean pressure (NB posture, 0.50 m/s^2 excitation).

Figures 4.20 to 4.22 illustrate variations in the primary resonance frequency observed from the male and female subject data with different body mass, and mass- and build-related factors. The results, in general, show that the primary resonance frequency of the male and female subjects is negatively correlated with most of the anthropometric parameters. The responses of the male subjects generally exhibit better correlations than those for the female subjects. Moreover, the responses obtained without a back support were better correlated compared to those acquired with a back support (results not shown). For both genders as well as for all sitting conditions, the correlation coefficients decreased as the magnitude of the excitation increased.

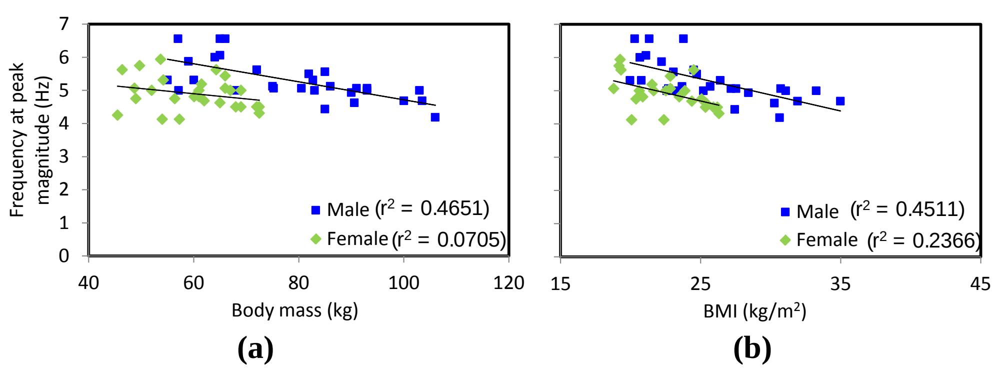


Figure 4.20: Correlation between the frequency corresponding to the peak APMS magnitude of male and female subjects with: (a) body mass; and (b) BMI (NB posture, 0.50 m/s^2 excitation).

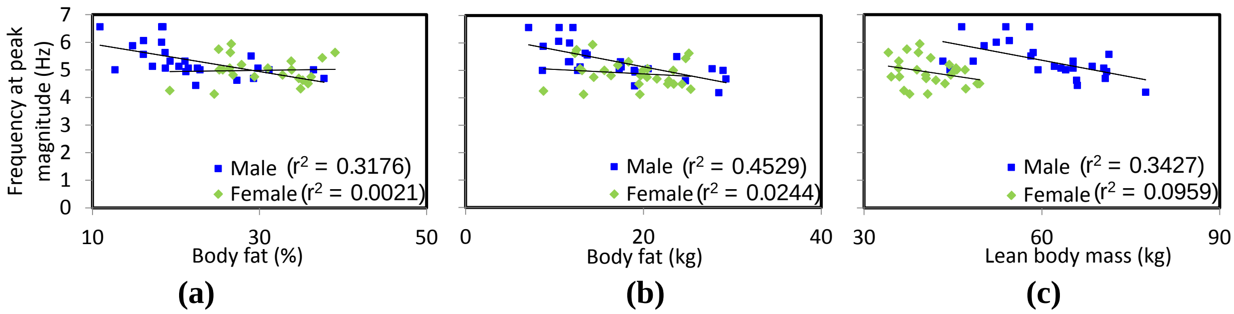


Figure 4.21: Correlation between the frequency corresponding to the peak APMS magnitude of male and female subjects with: (a) body fat percentage; (b) body fat; and (c) lean body mass (NB posture, 0.50 m/s^2 excitation).

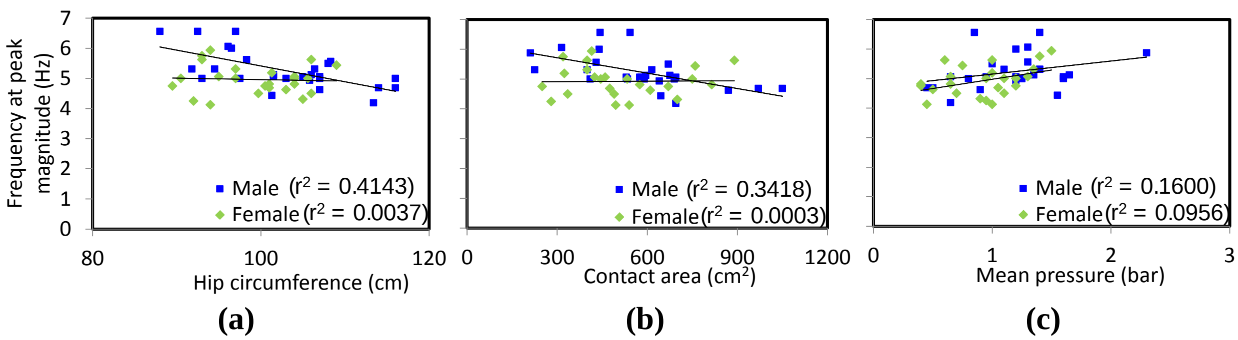


Figure 4.22: Correlation between the frequency corresponding to the peak APMS magnitude of male and female subjects with: (a) hip circumference; (b) contact area; and (c) mean pressure (NB posture, 0.50 m/s^2 excitation).

4.3 Discussion

The general trends in the measured responses were similar to those reported in earlier studies, which have been synthesized in the course of this study [60]. The primary and secondary resonance frequencies with no back support and vertical back support were within 4 to 7 and 8 to 15 Hz ranges, respectively. Large variations in body mass of the subjects (45.5 kg to 106 kg) caused considerable scatter in the measured APMS responses at lower frequencies up to nearly 6.5 Hz. These were consistent with trends reported in earlier studies [59, 61, 62, 68]. While the data scatter at lower frequencies could be reduced through normalization with respect to the body mass supported by the seat, the normalization resulted in greater scatter of the data at higher frequencies. Furthermore, the normalization altered the response trends. For example, the largest normalized magnitude occurred for the lower body mass subjects (male - 61.0 kg and female - 50.4 kg) at frequencies above 6 Hz, whereas the absolute APMS peak responses would be expected to be higher for higher body mass, as shown in Fig. 4.10. The results invariably suggest strongly coupled effects of the gender and various anthropometric parameters, which are discussed in the following sub-sections.

4.3.1 Effect of gender on the APMS response

Holmlund *et al.* [72] reported lower mean resonance frequency of the driving-point mechanical impedance (DPMI) of the female subjects compared to the male subjects. Mansfield *et al.* [67], on the other hand, reported slightly higher mean resonance frequency of the female subject APMS responses compared to those of the male subjects. Toward and Griffin [68] observed significant effect of gender on the resonance frequency from the responses acquired with a reclined rigid backrest, while the effect was not evident when sitting without a backrest, or against a vertical rigid backrest or a reclined elastic back rest. Furthermore, Mansfield *et al.* [67] reported lower normalized APMS magnitude of male subjects in the 6 to 10 Hz range compared to the female subjects. Holmlund *et al.* [72], and Holmlund and Lundstrom [69] reported a more distinct second peak in the DPMI responses of the female subjects around 10 Hz and for many subjects this peak exceeded the primary peak in magnitude. All of the reported studies have evaluated gender effects from the responses of male and female subjects of substantially different body masses. Wang *et al.* [62] suggested coupled effects of gender and body mass on the APMS responses, which was evident from the data obtained in this study (Fig. 4.7). In the present study, the relatively higher peak normalized APMS response of the male subjects is attributed to their higher body mass compared to the female subjects. Furthermore, higher body mass resulted in the lower value of normalized APMS response of the male subjects near the secondary resonance frequency when compared to the female subjects.

From the responses obtained with the 5 subjects of similar body mass (male: 71.4±7.4 kg; female: 71.4±3 kg), Wang *et al.* [62] observed the presence of a more clear second resonance peak above 15 Hz for the female subjects. Furthermore, the APMS magnitude responses at higher frequencies were greater for the female subjects compared to the male subjects. The results obtained in the present study also revealed higher magnitudes of APMS response for the female subjects compared to the male subjects of comparable mass, while male subject responses revealed higher APMS magnitude at lower frequencies. According to a few researchers, the secondary resonance peak may be attributed to pelvic and viscera mass of the human body. Kitazaki and Griffin [84] identified the pelvic pitch mode at 8.1 and 8.7 Hz, and a higher visceral mode at 9.3 Hz. These are also supported by the results reported by Coermann [85], which showed peak relative motions of the pelvis near 5 and 9 Hz. Matsumoto and Griffin [86] also observed peak seat-to-pelvis transmissibility in the 7 to 10 Hz range. The modes observed near 8.7, 9.1 and 9.3 Hz have been suggested to correspond to the secondary resonances observed in the APMS responses. Irrespective of the body mass, the male and female body structures show differences in the shape of their pelvises. The male pelvis is taller, narrower, and more compact than the female pelvis, which is larger and broader [64]. Females have most of the body fat (adipose tissue) deposited in the pelvis and thighs, causing higher pelvic mass as compared to males. Therefore, a higher APMS magnitude at the secondary mode of vibration may be caused by the higher pelvic mass. Moreover, the higher fat mass within the pelvic and thigh region may have resulted in a relatively lower secondary resonance frequency of the female subjects.

The responses of the two genders of comparable body mass, obtained in this study, show higher primary resonance frequency of the male subjects, suggesting relatively higher stiffness for the male subjects. This difference in body stiffness is likely due to anatomical differences between the two genders. Females possess higher fat mass and lower muscle mass compared to the male subjects. The stiffness-to-mass ratio of females is thus relatively lower due to higher ratio of body fat mass to lean body mass, which would result in lower resonance frequency [70]. Furthermore, muscles are visco-elastic materials showing thixotropic behavior, i.e., viscosity decreases when stress is applied, making them shear rate-dependent, whereas the body fat (adipose tissue) is anti-thixotropic material, i.e., an increase in shear rate would yield higher viscosity [87]. The results also revealed more uniform but lower mean body-seat interface pressure and higher contact area of female subjects compared to the male subjects with comparable body mass. Relatively greater uniformity of the distributed pressure of female subjects could also contribute to lower primary resonance frequency.

Many studies have reported a softening tendency of the human body with increasing excitation magnitude [40,59,62,68,72]. For both body mass groups (60 and 70 kg), the male subject responses in the present study showed relatively greater softening effect compared to the female subjects. This may have been caused by lower body fat mass and higher muscle mass, i.e., the lean body mass of the male subjects in comparison to the female subjects. The lean body mass of the male and female subjects within group G60 were 49.6 and 41.9 kg, respectively, while those of the subjects within group G70 were respectively 58.8 and 47.6 kg. While muscles thixotropic behavior is known to contribute to lower primary resonance frequency under higher excitation magnitudes, the body fat also contributes to the resonance frequency. Toward and Griffin [68] also reported significantly less softening tendency in female APMS responses with increase in vibration magnitude.

Patra *et al.* [59] reported that at frequencies greater than the primary resonance frequency, the APMS response is influenced by variations in the excitation magnitude. The APMS responses in the 6 to 8 Hz range showed far greater effect for the NB posture. For the NB posture, the APMS responses obtained in this study are comparable with those reported in [59] beyond the primary resonance frequency. Unlike female subjects, male subject responses in the present study showed greater variations in the APMS magnitude in the 6 to 8 Hz frequency range. Studies concerning the back supports effects on the APMS responses under vertical vibration have shown that the backrest support restrains the peak vertical APMS magnitude considerably, with only slight effect on the primary resonance frequency [59,61,62]. The present study observed similar trends in the APMS responses with the NB and WB posture for the 31 male and 27 female subjects under 0.25, 0.50 and 0.75 m/s^2 excitations (Fig. 4.7).

The ISO 5982 standard [28] also recognizes important body mass effects and defines ranges of idealized APMS values for subjects of three different body masses (55, 75 and 90 kg), which were derived from a model based on the APMS response of only male subjects. However, for the same body mass, the two genders exhibit different APMS response characteristics, where the differences are also largely dependent on many physical characteristics other than the body mass, sitting condition and the magnitude of excitation. Therefore, for female subjects, the idealized values defined in ISO 5982 [28] may not be applicable. The study of the APMS responses of both genders having higher body mass may give a little more insight, as this study focused on both genders with relatively lower body mass of 60 and 70 kg. Furthermore, for the revision of the ISO 5982 standard, it would be desirable to study the other biodynamic characteristics of male and female subjects of comparable body masses, as suggested by Rakheja *et al.* [60].

4.3.2 Effects of anthropometric parameters on APMS

According to reported studies [43,59,62,65], heavier subjects exhibit higher APMS magnitude and lower primary resonance frequency, as compared to lighter subjects. Identical trends are also evident in the results of the present study (Fig. 4.9). The studies, with only a few exceptions, have reported either mean or median biodynamic responses of subjects, which do not clearly demonstrate the body mass effect on peak response and the corresponding frequencies, nor do they relate to properties of subjects of particular body masses. Moreover, the mean and median responses tend to suppress the secondary biodynamic response peaks. The results obtained in this study suggest important effects of the gender that are strongly coupled with the body mass, which cannot be addressed by the widely reported mean responses. For the purpose of standardization, it is thus essential to consider subject population of particular body masses to establish the reference values.

Similarly to the body mass effect, the peak APMS magnitude increases with an increase in the dimensions of most anthropometric parameters considered in this study (Figs. 4.11 to 4.13). Higher correlations (r^2>0.7) of the body mass with other anthropometric parameters such as BMI, body fat, lean body mass and hip circumference may have resulted in such responses. Additionally, variations in stature-related anthropometric parameters (stature, sitting height and C7 height), which are very poorly correlated (r^2<0.3) with the body mass, did not show definite trends with peak APMS magnitude (results not shown). The variation in mean contact pressure was also poorly correlated with the body mass (r^2<0.3), while its effect on APMS responses was not evident. Toward and Griffin [68] reported that peak APMS magnitude increases with increase in stature and BMI, which are highly correlated. Holmlund *et al.* [72] reported that even though stature was related to body mass, it did not in any way affect the peak magnitude and the corresponding frequency of the DPMI responses.

In previous studies, significant positive correlation has been observed between body mass and the vertical APMS or DPMI magnitude at frequencies up to and slightly above the primary resonance frequency, while there is a negative correlation of the primary resonance frequency with the body mass [61,62,65,88]. For most of the anthropometric parameters considered in the present study, the measured responses showed identical trends in the peak APMS magnitude and in the primary resonance frequency (Figs. 4.17 to 4.22). There may be a variety of reasons for the poor correlation between the primary resonance frequency and the anthropometric parameters. The human body is a very intricate system and the recruited subjects varied largely in body dimensions, body type (endomorphic, ectomorphic and mesomorphic), type of muscles (proportion of fast twitched and slow twitched fibers), and pressure distribution over the seat pan due to different buttocks profiles. Furthermore, some subjects failed to maintain a consistent sitting posture throughout the experiment. This change in posture tends to modify muscle tensions in the abdominal region, thus changing the body stiffness and the natural body frequency.

5. APPARENT MASS RESPONSES OF SUBJECTS SEATED ON ELASTIC SEATS

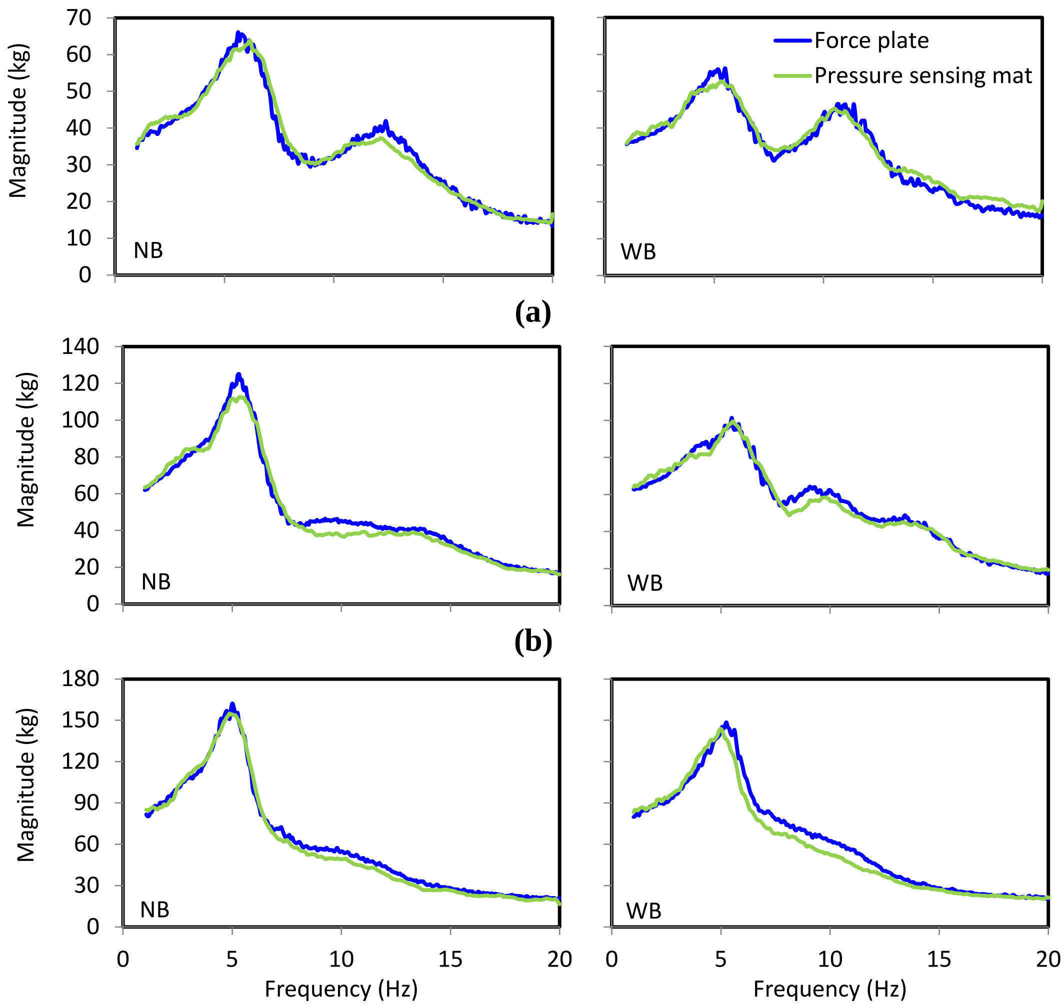
The apparent mass (APMS) responses of human subjects seated on selected elastic seats (seat A- a flat PUF; seat B - a contoured PUF; and seat C - an air cushion) are evaluated upon application of the correction function presented in section 3. The responses are obtained under three levels of broad-band random vibration (0.25, 0.50 and 0.75 m/s^2 rms acceleration) generated at the seat-human interface, and two sitting conditions (NB and WB). The validity of the correction function is demonstrated using the data acquired on the rigid seat, where the responses obtained from the force plate served as the reference values. The corrected responses obtained for the rigid and elastic seats are subsequently compared under identical levels of vibration and sitting conditions to illustrate the effects of the elastic seats on the responses.

5.1 Verification of the correction functions – Rigid seat

The force data acquired from the seat pressure measurement system placed on the rigid seat was analyzed together with the measured acceleration data to derive the APMS responses. Correction functions described in section 3.3.6 were subsequently applied to account for the poor dynamic range and to compensate the frequency response of the measurement system. The resulting APMS responses, when compared with those reported in section 4, permitted the verification of the proposed correction functions and the measurement system. The comparisons were performed for the data obtained under selected vibration for: (i) each individual subject; (ii) the mean responses of subjects within each mass group; and (iii) the mean responses of all subjects. The corrected APMS responses for individual subjects compared very well with the corresponding responses derived from the force plate signal for all the vibration levels.

As an example, Fig. 5.1 illustrates comparisons of the APMS magnitude derived from the two measurement systems for 3 different subjects with different body mass (46.6, 82.7 and 103 kg), while exposed to 0.50 m/s^2 excitation. The results are presented for both sitting conditions (NB and WB), which show reasonably good agreements in the responses acquired from the two measurement systems. The comparisons also show some differences, particularly at frequencies above 7 Hz. The difference in the primary resonance is also evident for the lightweight subject (46.4 kg). The peak APMS magnitude of this subject obtained from the force plate is 66.1 kg at 6.25 Hz, while the corrected response obtained from the seat mat shows peak magnitude of 63.7 kg at 6.19 Hz. For the WB condition, the error is also greater for the light subject, with the peak magnitude derived from force plate being 56.2 kg at 5.50 Hz, compared to 52.7 kg at 5.31 Hz for the seat mat. The errors in peak magnitude and corresponding frequency are in the order of 3.6% and 10%, respectively for the NB condition, and 6.3% and 3.4% for the WB condition. The observed error is partly caused by the lower pressure of the lightweight subject and the poor dynamic range of the pressure sensing mat. The error magnitudes were relatively lower for the medium- and higher weight subjects.

Figure 5.2 illustrates comparisons of the mean APMS responses of all the subjects under the three excitation magnitudes and the two sitting conditions. The responses obtained from the two methods compared reasonably well in the entire frequency range for both sitting conditions and the different vibration levels. Relatively larger differences, however, are evident between the responses under lower excitation (0.25 m/s^2), which is again attributed to the limited dynamic range of the seat pressure measurement system. The comparisons showed differences of 3.0% and 3.2% in peak APMS magnitude for the NB and WB condition, respectively. Differences in the order of 6.0% and 2.9% were obtained for the NB and WB sitting conditions, respectively, under the 0.75 m/s^2 excitation.



(c)

Figure 5.1: Comparisons of APMS magnitude responses of three subjects sitting without (NB) and with (WB) a back support and subjected to a 0.50 m/s^2 excitation, obtained from the force plate and the seat pressure measurement system. Subject mass: (a) 46.4 kg; (b) 83.7 kg; and (c) 103 kg.

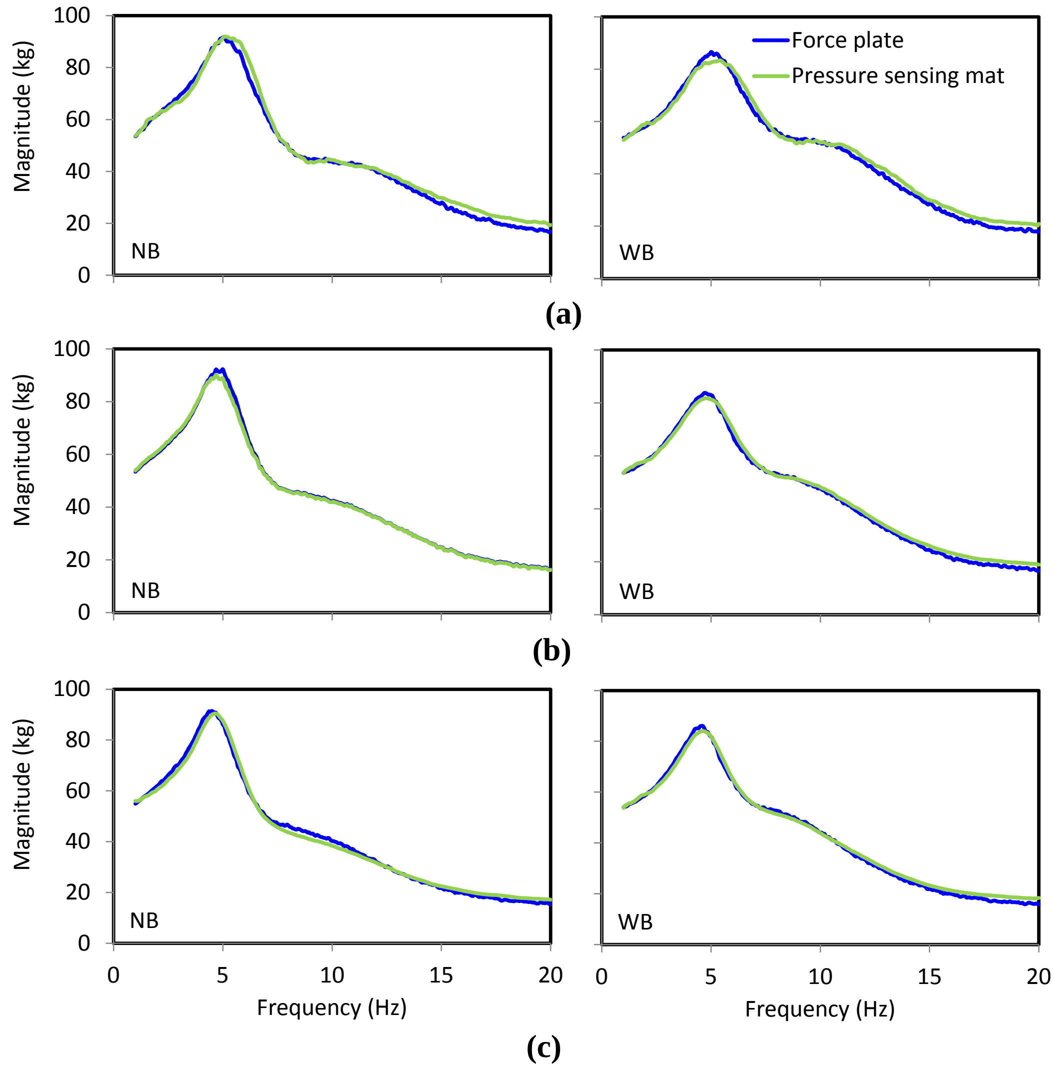
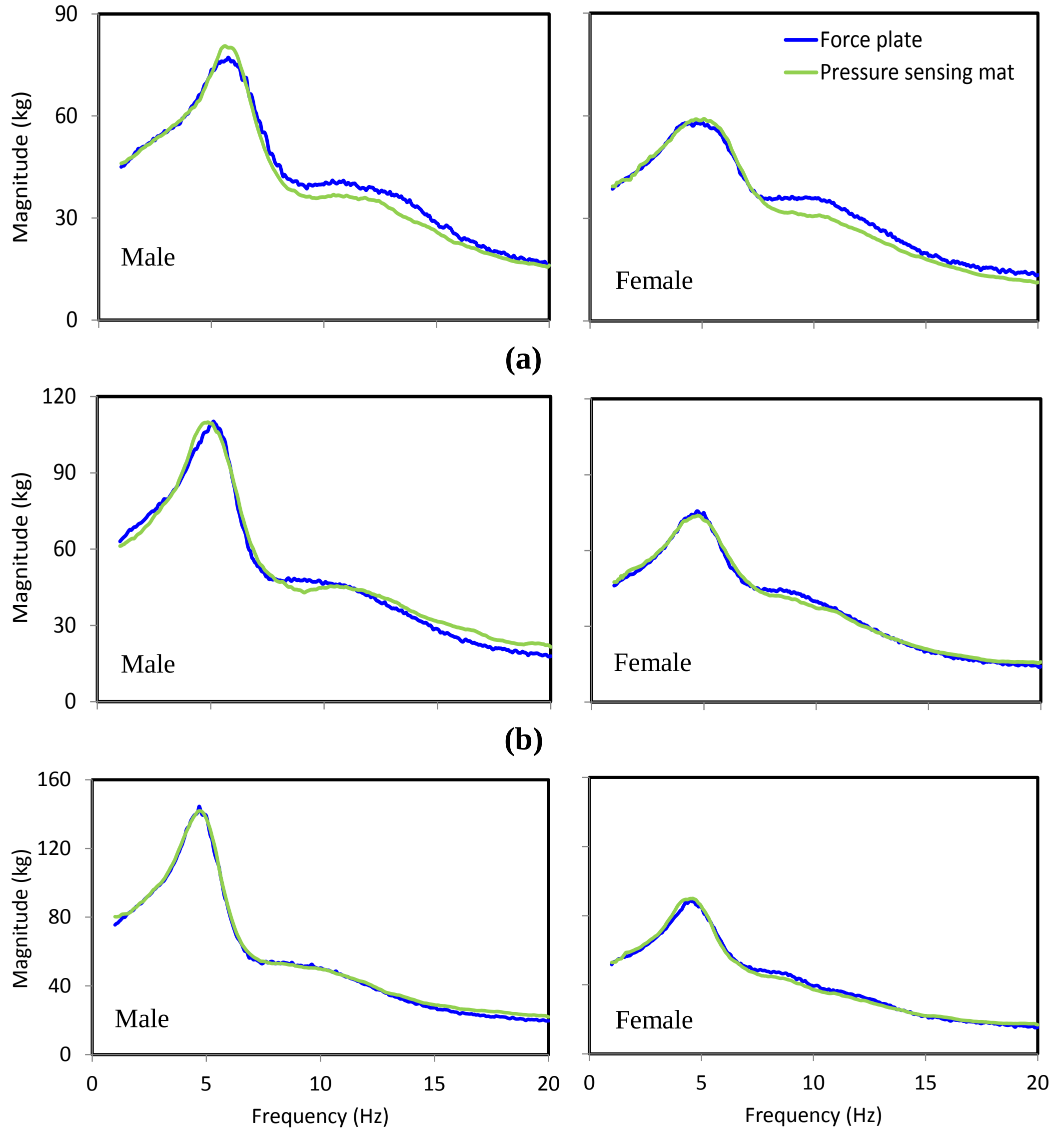


Figure 5.2: Comparisons of mean APMS magnitude responses of 31 male and 27 female subjects seated with (WB) and without (NB) a back support and exposed to : (a) 0.25 m/s^2; (b) 0.50 m/s^2; and (c) 0.75 m/s^2 excitation.

Figure 5.3 compares the APMS responses of the male and female subjects within specific body mass groups for the NB sitting condition and three excitation magnitudes. The mean responses of the male and female subjects were obtained for three different groups of mass range (60, 80 and 96 kg for male subjects; 50, 60 ad 72 kg for female subjects; see Table 3.2), while each group consisted of 9 subjects. The results again show greater differences in the APMS acquired from the two methods under the lower excitation level of 0.25 m/s^2. The results, obtained from two methods, exhibit very good agreements under higher excitation magnitudes, particularly up to 10 Hz. Comparisons of the responses obtained from the pressure sensing system and the conventionally used force plate (Figs. 5.1 to 5.3) suggest that the APMS responses of subjects seated on a rigid seat could be accurately characterized by the pressure sensing system, when the proposed correction functions are applied to account for the frequency response of the measurement system.



(c)

Figure 5.3: Comparisons of mean APMS magnitude responses of male and female subjects, within different mass groups, seated without (NB) a back support and exposed to a 0.5 m/s^2 excitation: (a) male – 60 kg; female -50 kg; (b) male – 80 kg; female -60 kg; and (c) male – 96 kg; female -72 kg.

5.2 Application of correction functions to elastic seats data

The correction functions, derived for each seat and excitation combination, are applied to the responses of the subjects seated on elastic seats. The applicability of the measurement system is examined by observing the trends in the individual responses acquired for three elastic seats in relation to those derived for the rigid seat. The measured responses, invariably, showed large differences between the responses of the subjects seated on rigid and elastic seats, as it was expected. As an example, Figure 5.4 illustrates comparisons of the measured APMS of an 81 kg subject seated on the rigid and the selected elastic seats, assuming NB and WB postures and exposed to a 0.50 m/s^2 excitation. The figure presents the corrected as well as the uncorrected APMS responses of the subject seated on the elastic seat, while the response with the rigid seat is obtained directly from the force plate data.

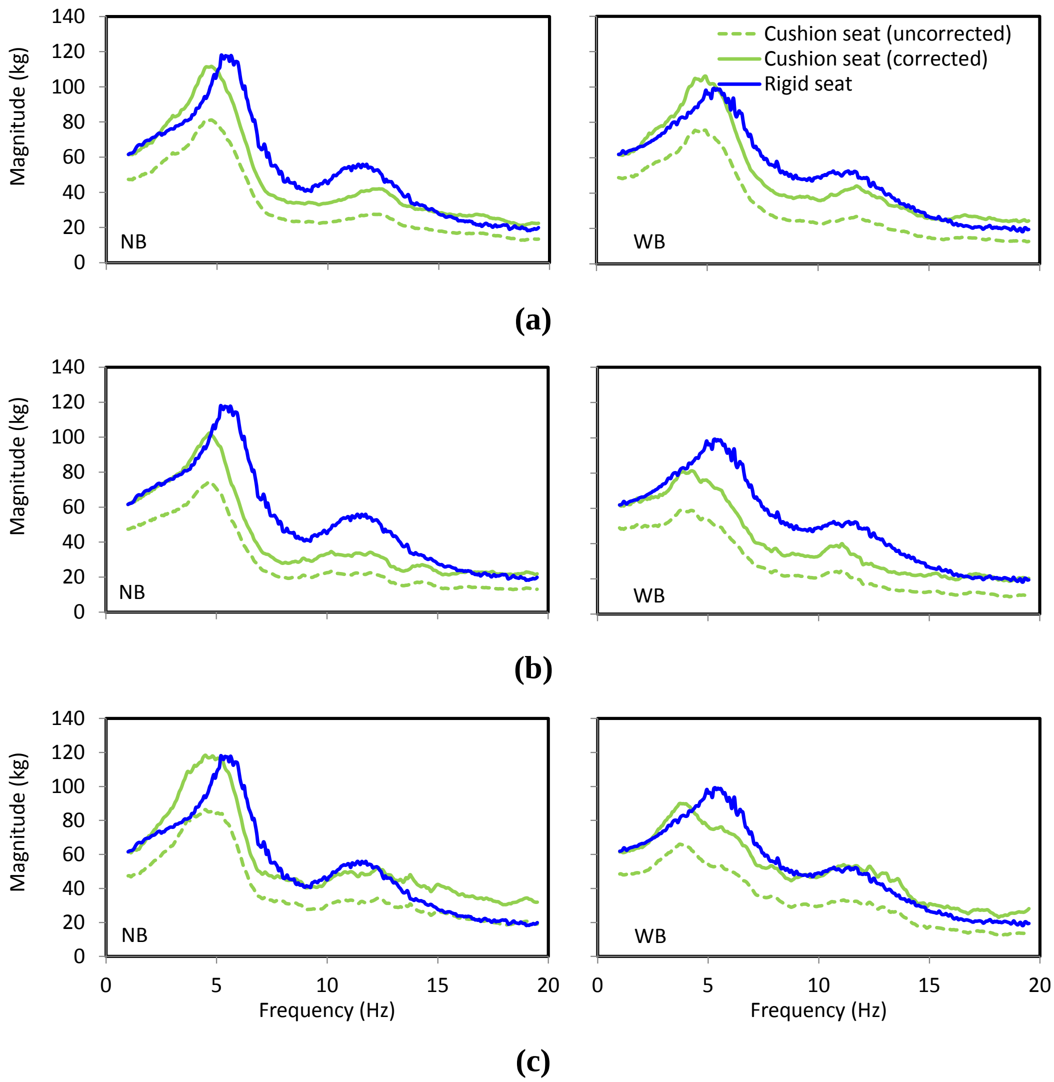


Figure 5.4: Comparisons of corrected and uncorrected APMS responses of an 81 kg subject seated on cushion seats and a rigid seat with NB and WB postures under a 0.50 m/s^2 excitation (a) A - flat PUF; (b) B- countered PUF; and (c) C- air cushion.

The results clearly show large differences between the uncorrected responses measured with the elastic seats and those obtained with the rigid seat in the entire frequency range. Similar large differences are also evident near the low frequency of 1 Hz, which is expected to be close to the static seated mass of the subject. Upon application of the correction functions, the low frequency APMS magnitudes of the subject seated on the elastic seats approach that obtained for the rigid seat. The comparisons, however, show considerable differences between the corrected responses of the elastic and rigid seats, particularly around the primary resonance. These differences are attributed to the elastic properties of the cushion seats, and changes in the human-seat contact area and body weight distribution. The results, in general, show lower peak APMS magnitude for the elastic seats compared to the rigid seat, except for the flat PUF cushion (seat A) when seated with a back support. It should also be noted that the responses do not show the presence of a peak corresponding to the resonance frequency of the elastic seat (around 4.3 Hz), which is due to the equalization of the vibration level at the occupant-seat interface by the vibration controller. Similar trends were also observed in the data acquired for all the subjects. From the comparisons, it was concluded that the pressure measurement system, together with the correction functions, can be applied to estimate the APMS responses of human subjects seated on elastic seats and exposed to vertical vibration. The corrected APMS responses, however, showed low frequency magnitudes that are 9% and 8% lower than those obtained for the rigid seat, for the NB and WB sitting condition, respectively. This suggests that a measurement system with enhanced dynamic range would be highly desirable.

The biodynamic force developed at the occupant-seat interface is expected to depend strongly on several factors. These include the visco-elastic properties of the cushion, the contouring of the cushion surface, the sitting condition that can alter the pressure distribution on the seat cushion, the thigh contact with the seat, and anthropometry-related factors. Depending upon the build, an individual subject may cause localized low pressure contact zones on the seat mat, particularly around the periphery of the overall contact area. Owing to the relatively poor dynamic range of the measurement system, the contributions of such low pressure zones may not be adequately accounted for. The corrected data obtained for the 56 subjects who participated in the elastic seat experiments (2 of the subjects could not participate in this series of experiments) were thoroughly examined in view of the low frequency APMS magnitude, which was expected to be in the order of 75 to 80% of the standing body mass. Some of the data revealed deviations in excess of 15%, particularly under the lower excitation of 0.25 m/s^2. These large deviations were believed to be caused by the poor dynamic range of the pressure sensing system together with the sitting condition that resulted in low pressure contact zones. The data showing deviations in excess of 15% were thus excluded from subsequent analyses. The selected datasets, grouped under different mass groups of the two genders for the three elastic seats, are summarized in Table 5.1. Relatively fewer dataset, however, could be selected for the WB posture, particularly under the 0.25 m/s^2 excitation. The grouping of selected datasets were undertaken so as to study the effect of the seat, gender, body mass, excitation magnitude and back support.

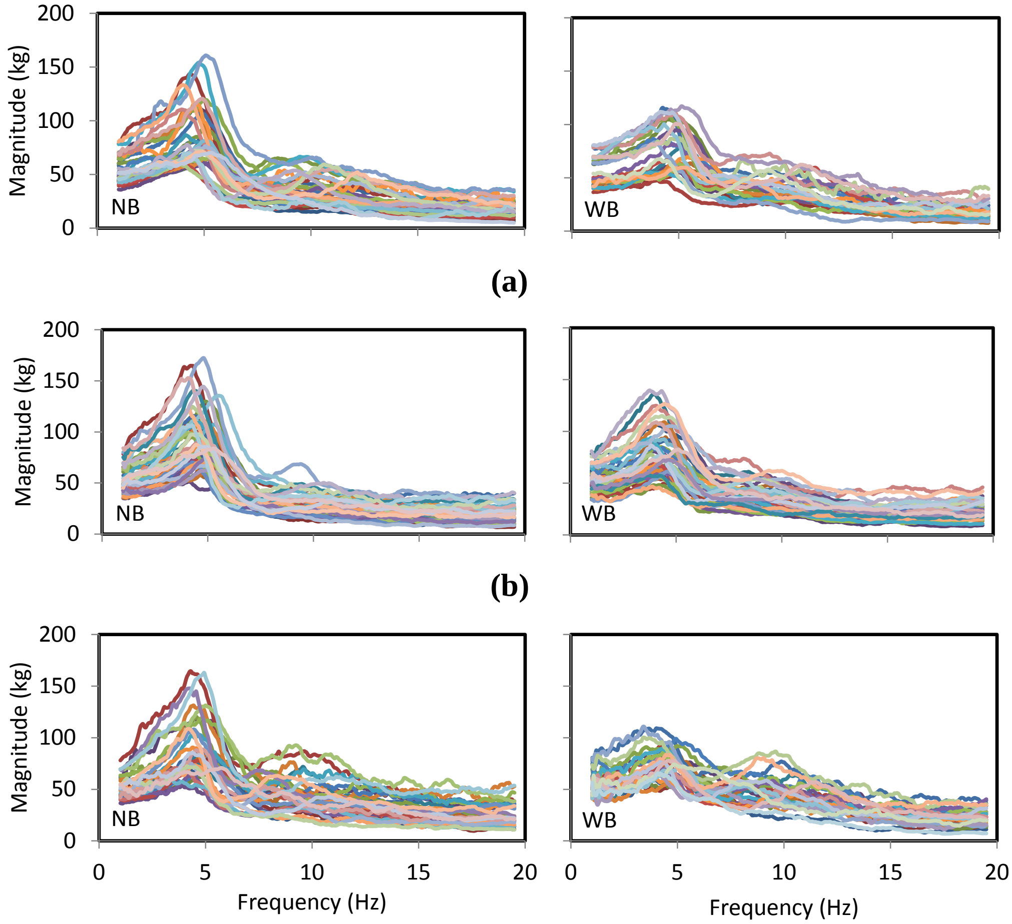
Table 5.1: Selected datasets for the analysis of the APMS responses of subjects seated on elastic seats.

Cushion	Sitting Condition	Excitation (m/s^2)	Datasets *n*	Body mass (kg) Mean	Body mass (kg) SD	Male (kg) ≈ 60	Male (kg) ≈ 70	Male (kg) ≈ 80	Male (kg) ≈ 96	Female (kg) ≈ 50	Female (kg) ≈ 60	Female (kg) ≈ 72
Seat A-Flat PUF	NB	0.25	30	72.0	18.2	5	2	5	7	5	5	1
		0.50	37	73.2	16.2	4	2	7	8	3	8	5
		0.75	41	71.7	15.4	5	2	7	7	4	9	7
	WB	0.25	23	73.5	17.9	5	1	6	6	4	0	1
		0.50	27	72.9	17.8	4	1	5	6	3	4	4
		0.75	31	71.9	16.8	4	2	5	6	4	5	5
Seat B-Contoured PUF	NB	0.25	39	71.9	16.6	6	3	6	8	5	6	5
		0.50	46	70.7	16.2	7	4	7	8	7	7	6
		0.75	38	70.3	14.4	4	3	5	6	6	6	8
	WB	0.25	30	73.0	15.8	5	6	4	6	3	2	4
		0.50	43	72.4	16.1	6	6	7	8	5	6	5
		0.75	40	71.4	16.9	4	4	6	8	7	7	4
Seat C-Air Cushion	NB	0.25	34	71.7	16.4	5	3	5	6	5	3	7
		0.50	34	71.3	15.0	5	5	5	4	4	5	6
		0.75	35	70.5	13.2	5	4	5	4	4	6	7
	WB	0.25	31	71.1	17.1	8	3	3	6	5	2	4
		0.50	34	71.4	15.9	4	5	5	6	5	5	4
		0.75	35	71.2	14.5	7	4	7	5	4	5	3

5.3 Characteristic of the APMS responses of subjects seated on elastic seats

5.3.1 *Inter-subject variability*

The measured APMS responses of the subjects seated on the elastic seats are initially analyzed to assess inter-subject variability of the data in a qualitative sense. As an example, Fig. 5.5 illustrates the variations in the APMS response magnitudes of the selected subjects for the three elastic seats and the two back support conditions, while exposed to the 0.50 m/s^2 excitation. The results show large differences in the response magnitudes, while the predominant magnitude peaks occur within narrow frequency bands. The responses obtained for the seats A, B and C with the NB posture revealed peak magnitudes in the 3.5 to 5.4, 3.8 to 5.5 and 3.4 to 5.8 Hz ranges, respectively; while the peaks for the WB sitting condition occurred in the 3.6 to 5.4, 3.8 to 5.5 and 3.4 to 5.8 Hz ranges, respectively. The observed ranges of primary resonance frequencies are lower than those observed for the rigid seat (NB: from 4.1 to 6.1 Hz; and WB: from 4.06 to 6.94 Hz). Distinct secondary peaks are also evident in the responses of many subjects in the 7 to 13 Hz range.



(c)

Figure 5.5: APMS magnitude responses of subjects seated on (a) seat A - flat PUF; (b) seat B - contoured PUF; and (c) seat C - air cushion, for the NB and WB postures (excitation: 0.50 m/s^2).

The measured data show considerable scatter at lower frequencies, which is mostly caused by the body mass variations, as it was observed for the rigid seat. For the NB posture, the coefficient of variation (CoV) ranged from 22 to 34%, 23 to 33% and 21 to 37% for seats A, B and C, respectively, in the 1 to 6 Hz frequency range. Within the same frequency range, the data for the WB posture revealed slightly lower CoV in the 23 to 30%, 22 to 31% and 22 to 35% ranges for seats A, B and C, respectively. Irrespective of the sitting posture, unlike the rigid seat data, the CoV did not decrease with an increase in frequency for the NB posture. The CoV ranged from 27 to 48%, 27 to 40% and 30 to 42% for seats A, B and C, respectively, at frequencies above 7 Hz. The data obtained above 7 Hz for the WB posture also revealed relatively lower CoV ranging from 23 to 42%, 27 to 40% and 27 to 42%, respectively. These again are partly attributed to the frequency response of the measurement system.

The scatter in the lower frequency range may be reduced through normalization of the APMS magnitude with respect to the static sitting mass, as described in section 4.1. Figure 5.6 illustrates the normalized APMS responses of the selected subjects for the three seats and the two sitting conditions, while exposed to the 0.50 m/s^2 excitation. The normalized responses exhibit slightly lower scatter in the entire frequency range. The peak values of the CoV of the normalized data were obtained near 38%, 37% and 36% for seats A, B and C, respectively, for the NB posture, and 35%, 36% and 37%, respectively, for the WB posture. Similar to the results obtained for the rigid seat, the results for the elastic seats suggest that the scatter in the data cannot be eliminated through normalization with respect to the body mass alone.

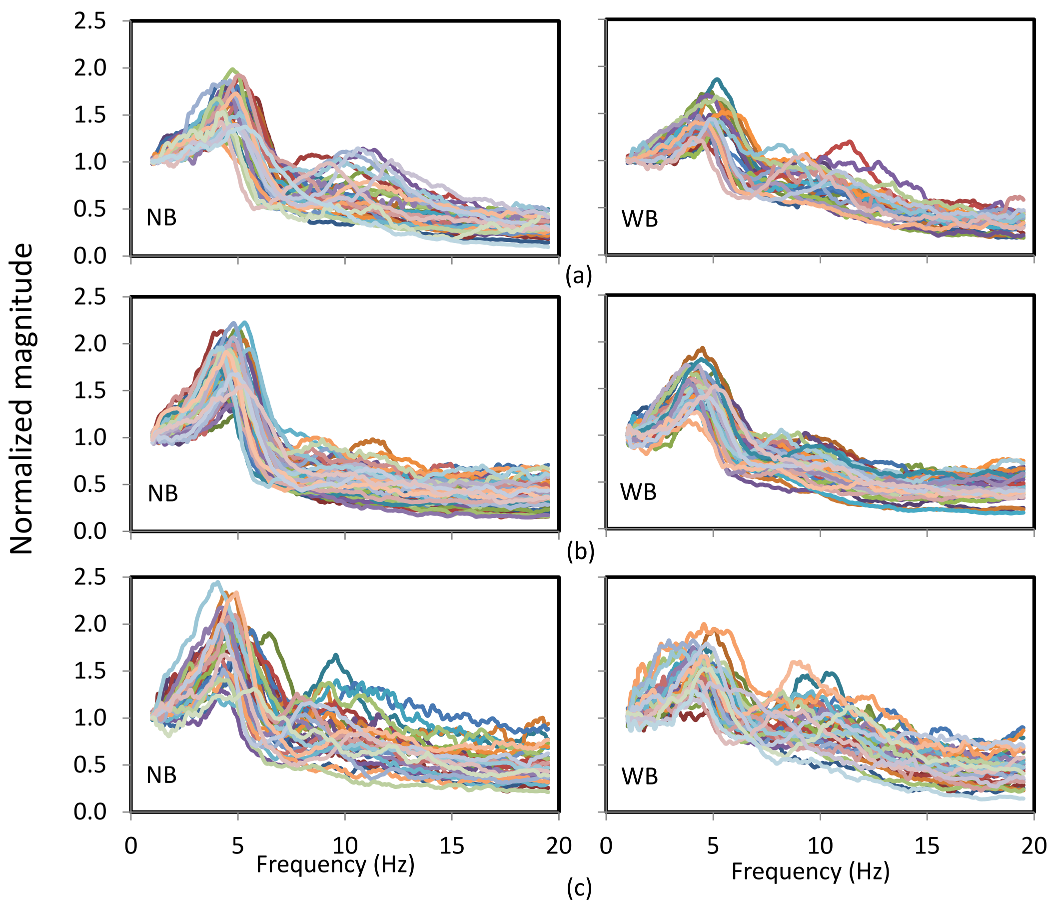


Figure 5.6: Normalized APMS magnitude responses of subjects seated on (a) seat A - flat PUF; (b) seat B - contoured PUF; and (c) seat C - air cushion, for the NB and WB postures (excitation: 0.50 m/s^2).

5.3.2 Comparisons of mean responses obtained with elastic and rigid seats

The mean APMS responses of the subjects seated on the elastic seats are compared with those obtained for the rigid seat in Fig. 5.7 for the two sitting and three excitation conditions. The figures show means of selected datasets of subjects of comparable body mass (NB: 70.3 to 73.2 kg; WB: 71.2 to 73.5 kg) seated on the selected elastic seats and the rigid seat. The results exhibit nearly identical magnitudes at low frequencies for the elastic and rigid seats. The important effects of elastic seat, however, are clearly evident at higher frequencies.

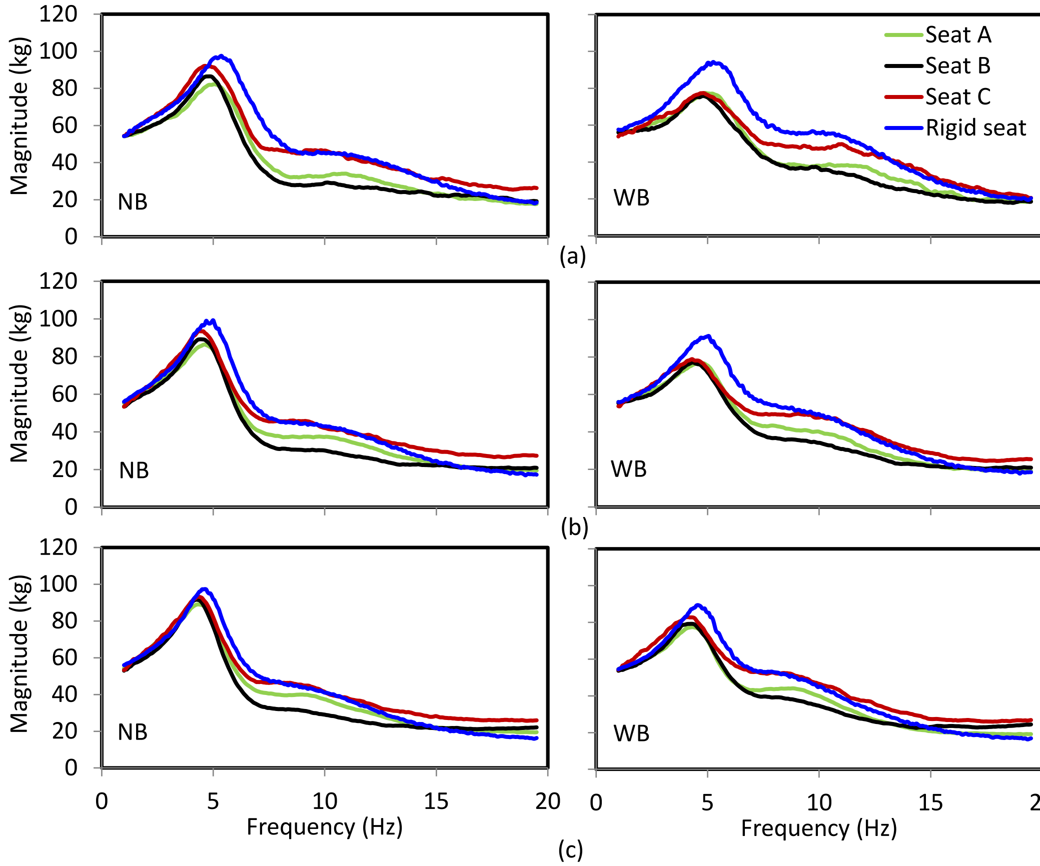


Figure 5.7 Comparisons of mean APMS responses of subjects seated on rigid and cushion seats with (WB) and without (NB) a back support and exposed to: (a) 0.25 m/s^2; (b) 0.50 m/s^2; and (c) 0.75 m/s^2 excitation.

The effects of the seats were evaluated with one-way analyses of variance (ANOVAs) of the magnitudes at different frequencies for each of the three excitation levels and of the two sitting conditions. The results presented in table 5.2 suggest that the APMS magnitudes of the subjects seated on the elastic seats are significantly different from those obtained with the rigid seat, particularly at frequencies above 6 Hz, irrespective of the sitting and excitation conditions considered in the study. The differences in the APMS magnitudes between the elastic and rigid seats appear to be greater in the vicinity of the primary and secondary resonance frequencies. The APMS responses obtained with the air cushion (seat C) are greater than those obtained with the PUF seats (seats A and B) suggesting further dependence on the seat damping and surface geometry. For seat C, the APMS responses at frequencies above the secondary resonance are also greater compared to the rigid seat, while those for PUF seats are comparable with the rigid seat in the 15 to 20 Hz range.

Table 5.2: *p*-Values obtained from one-way analyses of variance (ANOVAs) of APMS magnitudes for the elastic and rigid seats with two back support and three excitation conditions (α = 0.05).

	NB - No back support			WB - Vertical back support		
Frequency, Hz	0.25 m/s^2	0.50 m/s^2	0.75 m/s^2	0.25 m/s^2	0.50 m/s^2	0.75 m/s^2
1	0.989	1.000	0.882	0.997	0.995	0.993
2	0.679	0.415	0.473	0.804	0.413	0.252
3	0.315	0.282	0.447	0.397	0.244	0.328
4	0.247	0.339	0.483	0.390	0.655	0.587
5	0.314	0.127	0.169	0.320	**<0.005**	0.074
6	**<0.01**	**<0.01**	**<0.005**	0.086	**<0.01**	**<0.005**
7	**<0.001**	**<0.001**	**<0.001**	**<0.005**	**<0.001**	**<0.001**
8	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
9	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
10	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
11	**<0.005**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
12	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
13	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.005**
15	**<0.005**	**<0.005**	**<0.001**	**<0.001**	**<0.001**	**<0.02**
19	**<0.001**	**<0.001**	**<0.001**	**<0.01**	**<0.001**	**<0.001**

The peak mean APMS magnitudes and the corresponding frequencies obtained with the elastic seats are compared with those obtained with the rigid seat in Table 5.3, for the two back support and the three excitation conditions. The comparisons show lower peak APMS magnitude and corresponding frequency for the elastic seats compared to the rigid seat. For the NB sitting condition and the 0.50 m/s^2 excitation, the peak mean magnitudes for seats A, B and C are 91.5, 95.3 and 98.8 kg, occurring at 4.70, 4.64 and 4.61 Hz, respectively, compared to 107.1 kg for the rigid seat occurring at 5.01 Hz. Similarly for the WB condition and the 0.50 m/s^2 excitation, seats A, B and C resulted in peak magnitudes of 81.6, 80.5 and 83.7 kg near 4.71, 4.56 and 4.45 Hz, respectively, compared to 96.3 kg at 5.16 Hz for the rigid seat. These suggest considerably higher peak APMS magnitude for the subjects seated on a rigid seat compared to the elastic seats. Furthermore, the peak APMS magnitude of the subjects seated on the rigid seat occur at a higher frequency compared to the elastic seats. Identical trends in the APMS magnitude and in the primary resonance frequency were observed for the two sitting postures and for all three excitation levels.

Three-factor analyses of variance (ANOVAs) were subsequently performed to analyze the effect of the seat type on the peak APMS magnitude and the primary resonance frequency. These included 4 levels for the seat type (one rigid and three elastic seats), two levels for the back support (NB and WB) and three levels for the excitation factor. The results, including the interactions among the main factors and presented in Table 5.4, suggest strongly significant effect of the seat ($p<0.001$) on the peak magnitude and the primary resonance frequency. The effect of back support is also significant on both the peak magnitude and the corresponding frequency, while the excitation magnitude affects only the primary resonance frequency.

Table 5.3: Means (standard deviations) of primary resonance frequencies and peak APMS magnitudes of subjects seated on elastic and rigid seats with two sitting and three excitation conditions.

Seat	A - Flat PUF		B - Contoured PUF		C - Air cushion		Rigid	
Support	NB	WB	NB	WB	NB	WB	NB	WB
Excitation (m/s^2)	Primary resonance frequency (Hz): mean (standard deviation)							
0.25	5.1(0.60)	5.2(0.57)	5.0(0.53)	4.8(0.48)	5.0(0.70)	5.0(0.85)	5.6(0.61)	5.7(0.65)
0.50	4.7(0.47)	4.7(0.58)	4.6(0.46)	4.6(0.52)	4.6(0.60)	4.5(0.60)	5.0(0.54)	5.2(0.75)
0.75	4.5(0.45)	4.4(0.50)	4.4(0.42)	4.2(0.39)	4.5(0.50)	4.2(0.51)	4.8(0.53)	4.8(0.50)
	Peak APMS magnitude (kg)							
0.25	88.9(28.9)	82.9(20.2)	93.0(29.7)	80.3(21.6)	99.6(30.8)	83.2(26.9)	107.3(36.4)	100.8(29.1)
0.50	91.5(29.3)	81.6(21.7)	95.3(29.4)	80.5(21.5)	98.8(34.1)	83.7(23.5)	107.1(32.4)	96.3(29.4)
0.75	94.1(30.2)	83.1(23.2)	96.2(26.8)	82.3(24.9)	97.8(30.7)	88.0(24.7)	106.4(31.2)	94.4(27.3)

Table 5.4: *p*-Values obtained from three-factor analyses of variance (ANOVAs) showing the effect of seat, back support and excitation level on the primary resonance frequency and the peak APMS magnitude (α = 0.05).

Measure	S	BS	E	S*BS	S*E	BS*E	C*BS*E
Frequency	**<0.001**	**0.041**	**<0.001**	0.259	0.963	0.951	0.993
Magnitude	**0.001**	**<0.001**	0.182	0.806	0.973	0.985	0.797

S - Seat (rigid, flat PUF, contoured PUF and air cushions), BS - back support (no back support and vertical back support), E - excitation magnitude (0.25, 0.50 and 0.75 m/s^2)

Results presented in Table 5.3 also show that irrespective of the sitting condition and excitation magnitude, the peak APMS magnitudes of the subjects seated on the air cushion (seat C) is higher than the PUF cushions (seats A and B). The peak APMS magnitude for the contoured cushion (seat B), however, is greater than that for the flat cushion (seat A) with the NB posture but lower with the WB sitting posture. The primary resonance frequencies observed from the data acquired with the elastic seats show somewhat different trends. The primary resonance frequencies observed from the responses measured with seat A are higher than those obtained with seats B and C, irrespective of the sitting and excitation conditions considered. This is mostly attributed to a higher stiffness of seat A. The observed frequencies, however, may relate to resonance frequencies of the coupled seat-occupant system, unlike those obtained with a rigid seat.

The results further show that the APMS magnitude responses obtained near the secondary resonance with the rigid seat are higher than those obtained with the elastic seats. This peak of seat C, however, is comparable to that obtained with the rigid seat. This may be attributed to very light damping of the air cushion seat. For the NB posture and the 0.50 m/s^2 excitation, the APMS magnitudes obtained with seats A, B and C are approximately 43.1, 34.2 and 51.7 kg, respectively, occurring near 8.93, 8.92 and 8.41 Hz. The results obtained for the rigid seat for the same conditions show considerably higher peak magnitude of 49.1 kg, which occurs at a relatively higher frequency of 9.74 Hz. For the WB support and 0.50 m/s^2 excitation, the peak magnitudes are 45.9, 38.7 and 55.6 kg for seats A, B and C occurring at 8.77, 8.56 and 8.57 Hz, respectively, compared to 56.8 kg for the rigid seat at 8.89 Hz. Identical trends were also evident in the responses obtained under the other two excitation magnitudes.

The means of the normalized magnitude responses obtained with the elastic and rigid seats are also derived and presented in Fig. 5.8. The results show that the responses obtained with the rigid seat yield higher normalized peak magnitude and corresponding frequency compared to those obtained with the elastic seats. The elastic seats thus tend to shift the primary resonance towards a lower frequency, while reducing the resonance peak that may be attributed to their visco-elastic properties. The selected elastic seats also show considerable differences in the peak magnitude and the corresponding frequency, which is also evident in Table 5.3, and is likely to be attributable to differences in visco-elastic properties of the seats, body-seat contact area and distribution of body weight over the seat.

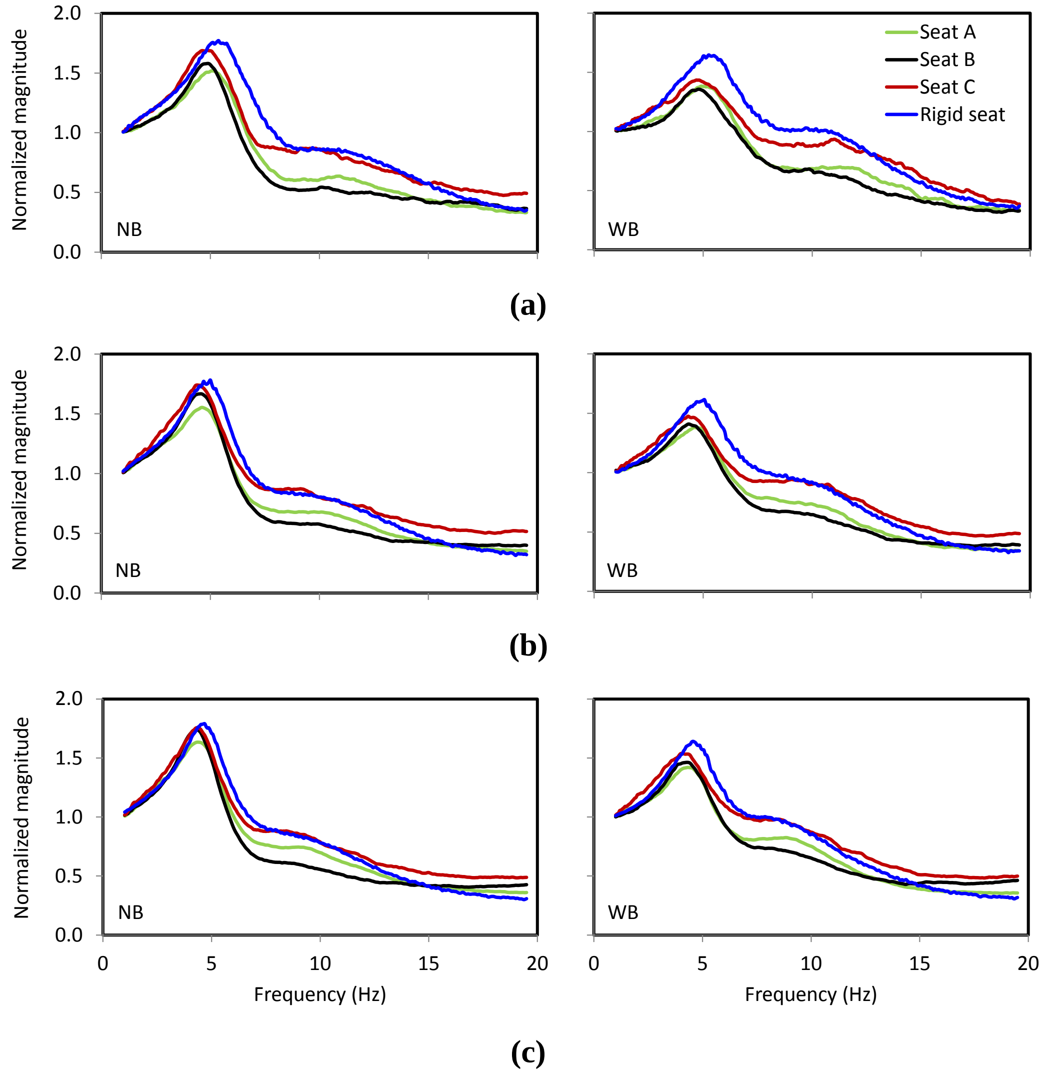


Figure 5.8: Comparisons of mean normalized APMS responses of subjects seated on rigid seat and elastic seats with (WB) and without (NB) a back support and subjected to vertical vibration of magnitude: (a) 0.25 m/s^2; (b) 0.50 m/s^2; and (c) 0.75 m/s^2.

5.3.3 Effect of back support

Selected datasets are further analyzed to study the effect of back support on the APMS responses of the subjects seated on the elastic seats under different excitations. The results in Fig. 5.9 illustrate the important effects of back support on the APMS magnitude responses, which have been widely reported only for rigid seats [48,62,65]. The results show that the peak APMS magnitudes of the subjects sitting without a back support (NB) are considerably higher than those obtained with the WB posture. This trend is similar to that observed for the rigid seat in Fig. 4.10. Sitting without a back support resulted in mean peak magnitudes of 88.9, 91.5 and 94.1 kg, respectively, under 0.25, 0.50 and 0.75 m/s^2 excitations for seat A. The corresponding magnitudes for seats B and C are 93.0, 95.3 and 96.2 kg, and 99.6, 98.8 and 97.8 kg, respectively. The mean peak magnitudes while sitting with a back support (WB) are 82.8, 81.6 and 83.1 kg, 80.3, 80.5 and 82.3 kg, and 83.2, 83.7 and 88.0 kg for seats A, B and C, respectively. The results suggest that the peak magnitudes with the WB sitting condition are about 9%, 14% and 14% lower compared to the NB condition for seats A, B and C, respectively. The results further show that the reduction in the mean peak magnitude with softer seats B and C is greater than that observed for the rigid seat (Fig. 4.10).

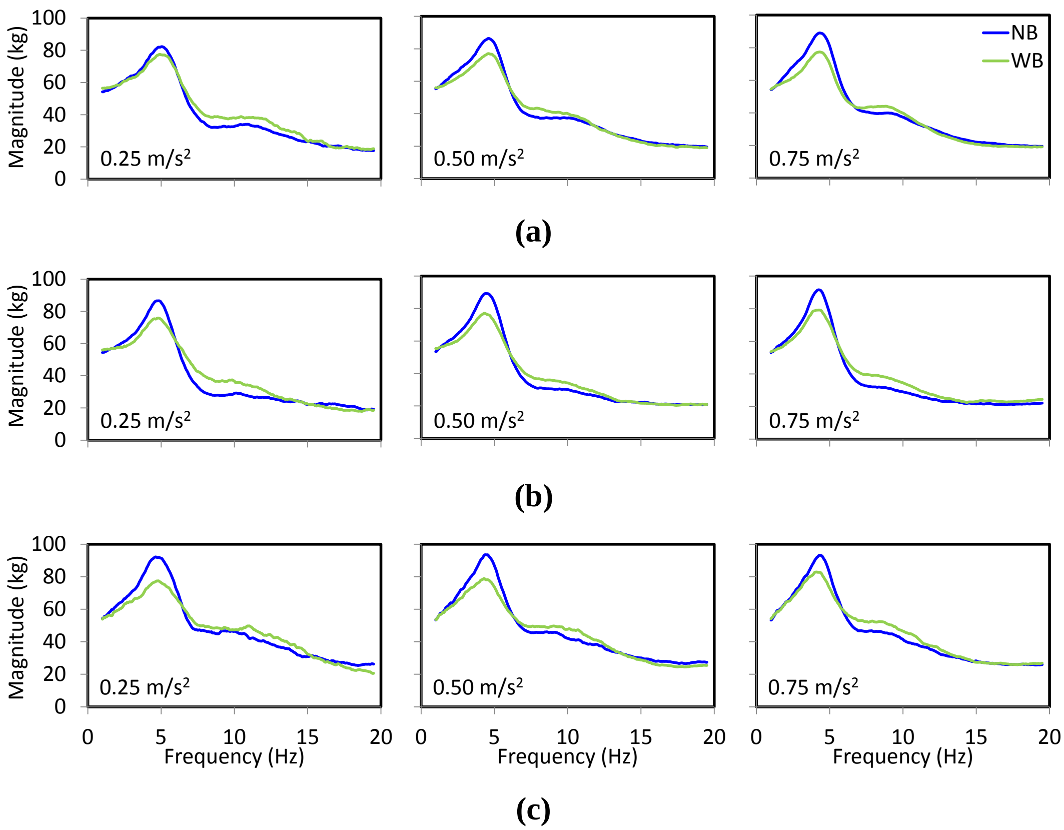


Figure 5.9: Comparisons of mean APMS magnitudes of subjects seated with (WB) and without (NB) a back support on elastic seats: (a) seat A; (b) seat B; and (c) seat C, under different vibration excitations (0.25, 0.50 and 0.75 m/s^2).

Opposite trends, however, are evident with regard to the back support effect around the secondary resonance, although the second peak in the mean response is less clear due to data averaging. The results further show that the primary resonance frequencies observed from the mean peak response with no back support are comparable with those obtained with the vertical back support (Table 5.3). For example, the primary resonance frequencies with the NB posture and seat A are 5.13, 4.70 and 4.50 Hz under 0.25, 0.50 and 0.75 m/s^2 excitations, respectively, while the corresponding frequencies for the WB posture are 5.17, 4.71 and 4.40 Hz. Similar trends are also evident for seats B and C.

5.3.4 Effect of vibration magnitude

Figure 5.10 illustrates comparisons of the mean APMS magnitude responses attained under selected excitation magnitudes for the three elastic seats and the two sitting conditions. Softening tendency of the human body with increasing excitation is evident from the results for all the seats, irrespective of the sitting conditions, as it was observed for the rigid seat (Fig. 4.8). The results, in general, show slightly higher peak magnitudes near the primary resonance frequencies with an increase in the excitation magnitude from 0.25 to 0.75 m/s^2. The softening tendency was further studied by considering changes in the primary resonance frequency with an increase in the excitation magnitude. The results, presented in Table 5.3, suggest greater softening effect of the vibration magnitude for the WB posture compared to the NB posture. For seat A, the primary resonance frequency of the mean responses shifts from 5.13 to 4.50 Hz with the NB condition, and from 5.17 to 4.40 Hz with the WB condition, when the excitation magnitude is increased from 0.25 to 0.75 m/s^2. For seat B, the resonance frequency shift occurs from 4.96 to 4.42 Hz and from 4.84 to 4.24 Hz for the NB and WB conditions, respectively. The corresponding frequency shifts for seat C are from 5.02 to 4.50 Hz and from 5.01 to 4.20 Hz for the NB and WB conditions, respectively. The results show relatively lower frequency shift for the elastic seats compared to the rigid seat (Table 5.3). The relatively stiff elastic seat (seat A) also yields greater frequency shift compared to the other seats for the NB posture, while the very lightly damped air cushion (seat C) shows greater frequency shift for the WB posture.

From Figs. 5.7 to 5.10, it is concluded that cushions have strong effects on the seated body APMS responses. The peak APMS magnitudes and the corresponding frequencies of the subjects seated on elastic seats are significantly lower than those obtained for the rigid seat ($p < 0.005$). Furthermore, the APMS responses of the subjects on the elastic seats are strongly influenced by the sitting conditions and by the excitation magnitudes.

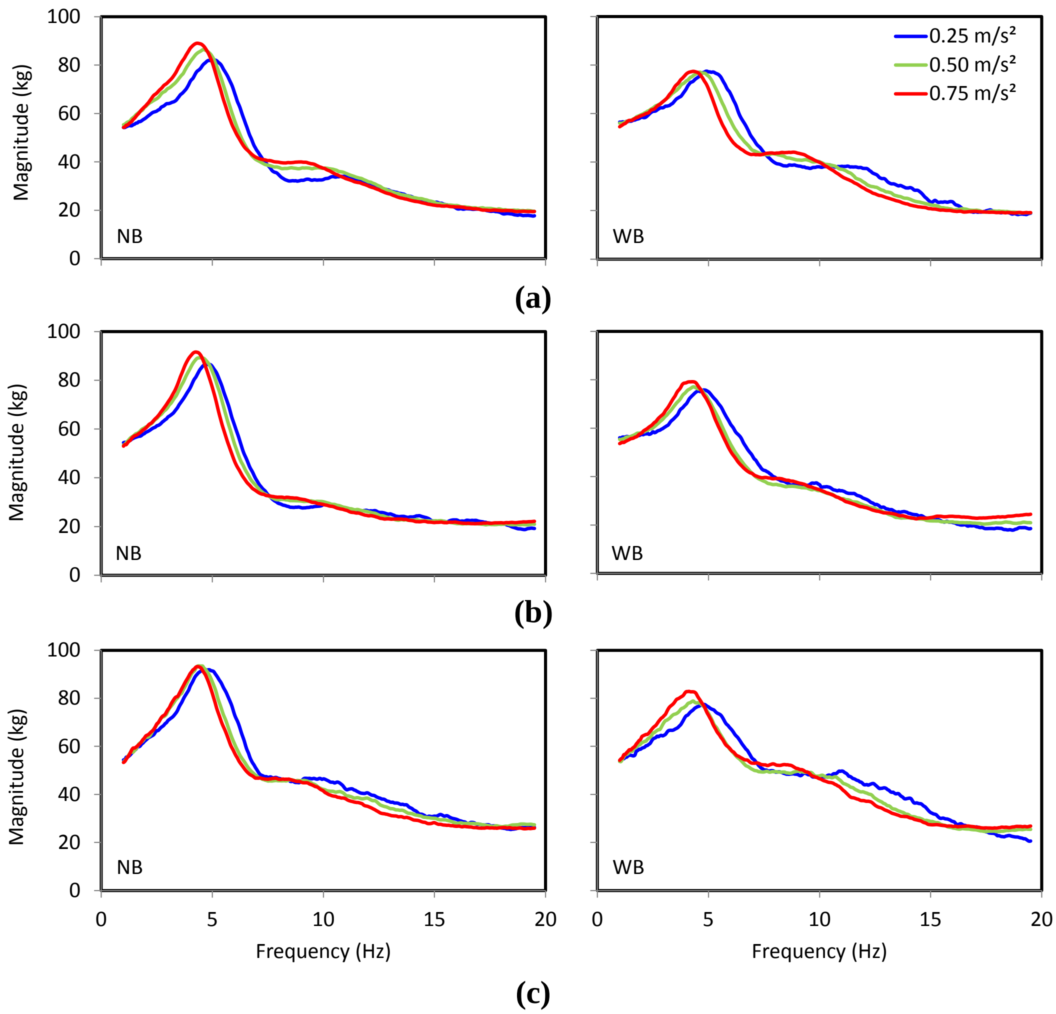
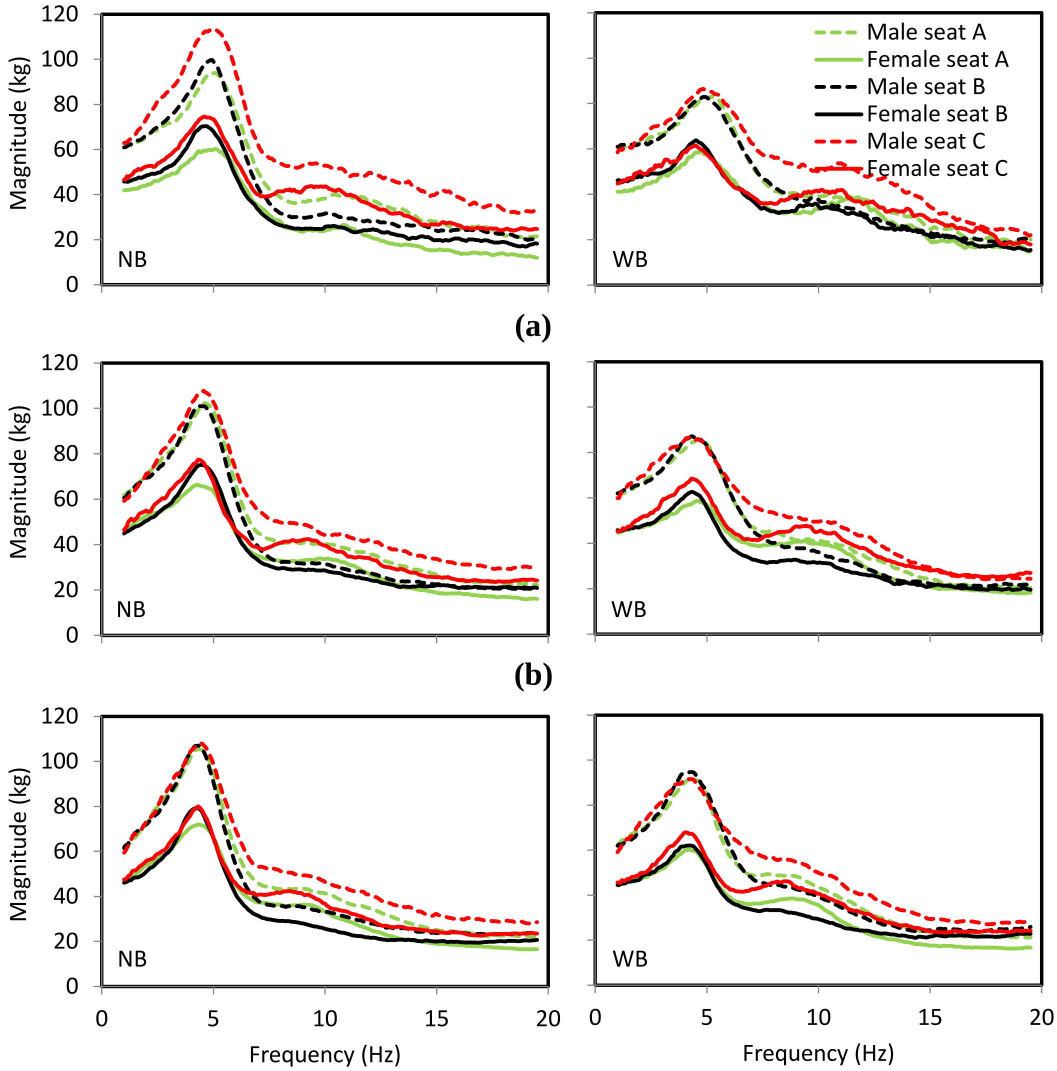


Figure 5.10: Comparisons of mean responses of subjects under different vibration magnitudes while seated with (WB) and without (NB) a back support on elastic seats: (a) seat A; (b) seat B; and (c) seat C.

5.4 Effect of gender on the APMS responses obtained with elastic seats

The mean APMS magnitude responses of the male and female subjects are compared in Fig. 5.11 for each elastic seat and sitting and excitation combination. The results show higher APMS response magnitudes of the male compared to the female subjects in most of the frequency range, irrespective of the seat, posture and excitation. The observed differences in the magnitude responses of the two genders are partly attributed to their respective mean body mass. Furthermore, near the secondary mode of vibration, the responses of the female subjects are more prominent as compared to the male subjects, for all vibration conditions and sitting postures considered. It should be noted that this second peak is less evident due to data averaging. These trends are similar to those observed for the rigid seat (Fig. 4.6). Comparisons of the APMS responses generally show relatively higher magnitudes of both genders for the air cushion seat in the entire frequency range, except at very low frequencies. Irrespective of the sitting condition and excitation magnitude, the peak APMS magnitudes for seat A are the lowest for both genders, while seat B yields the lowest magnitude near the secondary resonance frequency. The results presented in Fig. 5.11 also show that the mean primary resonance frequencies of the male subject responses are relatively greater than those of the female subject responses.



(c)

Figure 5.11: Comparisons of mean APMS magnitude responses of male and female subjects seated on elastic seats under different vibration levels: (a) 0.25 m/s^2; (b) 0.50 m/s^2; and (c) 0.75 m/s^2.

The mean peak response magnitudes and primary resonance frequencies of the two genders are summarized in Table 5.5 for the selected elastic seats, back support and excitation conditions.

The mean values presented in the table further show lower primary resonance frequencies of the female subjects compared to the male subjects. The results also show that the primary resonance frequencies of female subjects seated on an air cushion (seat C) are lowest, while the relatively stiffer seat A yields highest frequencies for both sitting conditions. Results suggest greater difference between primary resonance frequencies of male and female subjects for seat C compared to seats A and B.

Table 5.5: Mean (standard deviation) of peak APMS magnitude and primary resonance frequency for male and female subjects on different cushions for the two sitting conditions and the three levels of excitation.

Posture	NB - No back support						WB - With back support					
Seat	A - Flat PUF		B - Contoured PUF		C - Air cushion		A - Flat PUF		B - Contoured PUF		C - Air cushion	
Gender	M	F	M	F	M	F	M	F	M	F	M	F
Excitation (m/s^2)	Peak APMS magnitude (kg): mean (standard deviation)											
0.25	102.2 (26.5)	65.6 (10.9)	106.1 (31.7)	75.9 (15.0)	123.9 (36.7)	82.1 (14.2)	88.4 (18.8)	62.9 (10.1)	88.0 (21.7)	65.0 (10.9)	92.9 (27.7)	63.9 (9.7)
0.50	107.7 (29.3)	70.2 (8.2)	108.3 (32.0)	79.8 (15.7)	113.6 (37.6)	80.7 (17.2)	90.2 (20.4)	62.3 (6.9)	91.6 (20.8)	64.5 (8.8)	93.3 (26.7)	71.0 (13.1)
0.75	110.0 (33.1)	76.0 (11.4)	112.5 (29.3)	83.2 (15.4)	112.8 (35.0)	82.7 (15.3)	95.8 (22.3)	62.4 (9.8)	98.4 (22.4)	64.3 (11.6)	97.9 (25.7)	70.9 (8.1)
	Primary resonance frequency (Hz): mean (standard deviation)											
0.25	5.31 (0.59)	5.26 (1.55)	5.07 (0.51)	4.82 (0.54)	5.20 (0.69)	4.66 (0.96)	5.26 (0.57)	4.84 (0.49)	4.98 (0.51)	4.57 (0.29)	5.24 (0.84)	4.55 (0.67)
0.50	4.79 (0.39)	4.58 (0.54)	4.68 (0.46)	4.64 (0.43)	4.81 (0.59)	4.36 (0.54)	4.76 (0.54)	4.54 (0.63)	4.68 (0.60)	4.39 (0.32)	4.55 (0.65)	4.46 (0.46)
0.75	4.55 (0.49)	4.40 (0.47)	4.43 (0.44)	4.41 (0.42)	4.77 (0.60)	4.32 (0.38)	4.43 (0.56)	4.29 (0.44)	4.30 (0.41)	4.16 (0.37)	4.31 (0.56)	4.10 (0.22)

M – Male; F – Female

The results also show that the gender effect on the APMS responses is coupled with the body mass, as it was observed in the responses obtained for the rigid seat. In order to decouple the body mass effect, the datasets are grouped so as to achieve comparable body mass for both genders. Datasets acquired from subjects with body mass in the vicinity of 60 kg (55 to 65 kg) and 70 kg (65 to 75 kg), respectively denoted as G60 and G70, are subsequently selected to further analyze the gender effect for the three elastic seats, the two sitting conditions and the three excitation levels.

Figures 5.12 to 5.14 illustrate comparisons of the mean magnitude responses of male and female subjects of comparable body masses of 60 and 70 kg for the two back support and the three excitation conditions. The mean of the primary resonance frequencies and mean peak APMS magnitudes of the two body mass groups obtained with the three elastic seats, and different excitation and sitting conditions, are summarized in Table 5.6. It should be noted that the results do not include the responses of the female subjects within the G60 mass group, for seat A, for the WB condition, due to large errors in the data. The results further confirm relatively lower primary resonance frequencies for the female than for the male subjects of similar body mass, irrespective of the seat type, sitting condition and excitation level. Furthermore, the differences in the primary resonance frequencies for the male and female subjects varied for the two mass groups and the three elastic seats. The difference is observed to be greater for the G60 mass group when compared to the G70 mass group. The differences observed in the primary resonance frequency of the male and female subjects are also greater for seat C compared to seats A and B, which suggest a dependence of the APMS responses on the stiffness and damping properties of the seat. The APMS magnitudes reveal that the mean values of the peak APMS magnitude of the male subjects is comparable to those of the female subjects of similar body mass groups for all the cushion seats. However, in a few combinations of experiments on the flat PUF cushion, the differences of the peak APMS magnitude of the male subjects were more than 10% those of the female subjects.

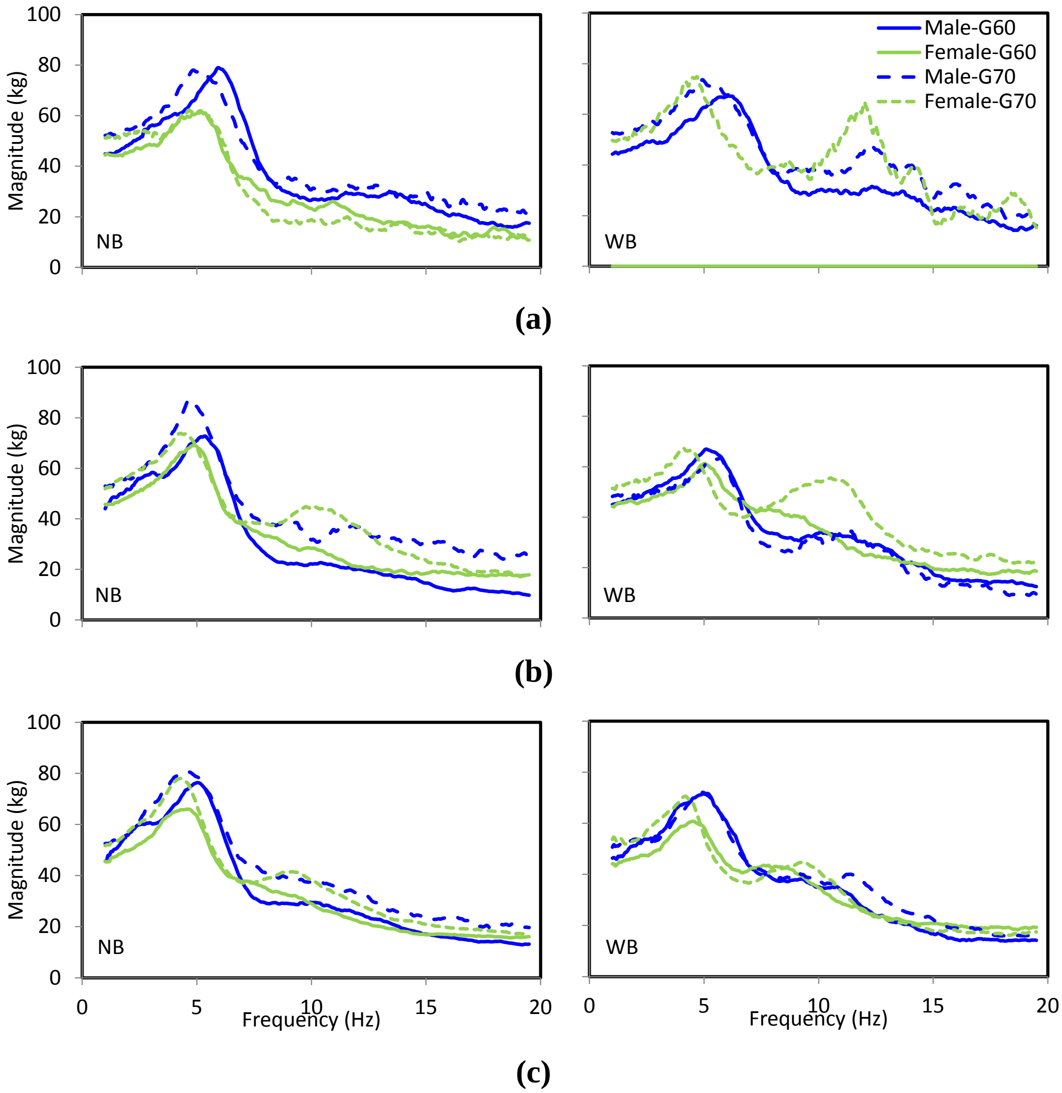


Figure 5.12: Mean APMS magnitude responses of male and female subjects within two mass groups (60 and 70 kg) seated on the flat PUF cushion (seat A) with (WB) and without (NB) a vertical back support and subjected to different excitation levels: (a) 0.25 m/s^2; (b) 0.50 m/s^2; and (c) 0.75 m/s^2.

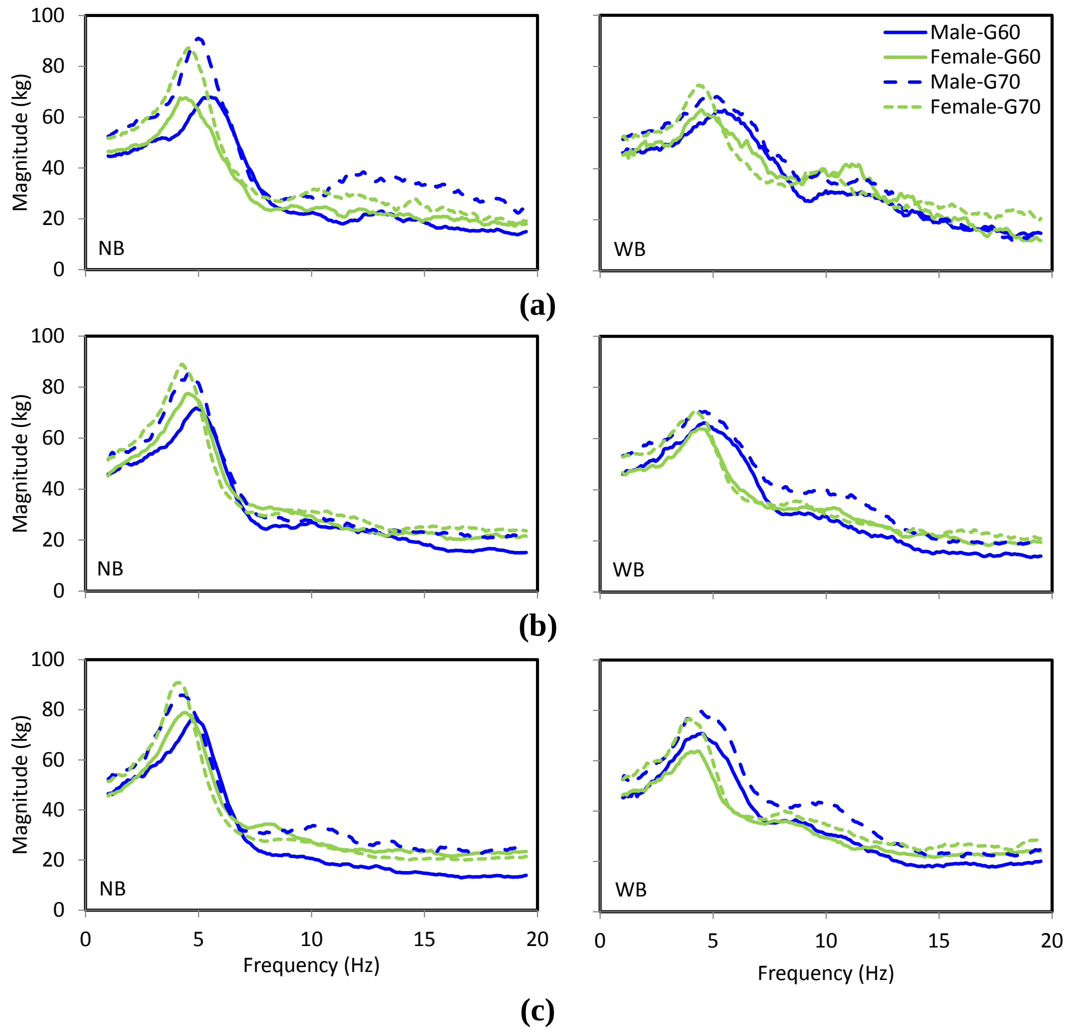


Figure 5.13: Mean APMS magnitudes of male and female subjects within two mass groups (60 and 70 kg) seated on seat B and subjected to different excitation levels: (a) 0.25 m/s^2; (b) 0.50 m/s^2; and (c) 0.75 m/s^2.

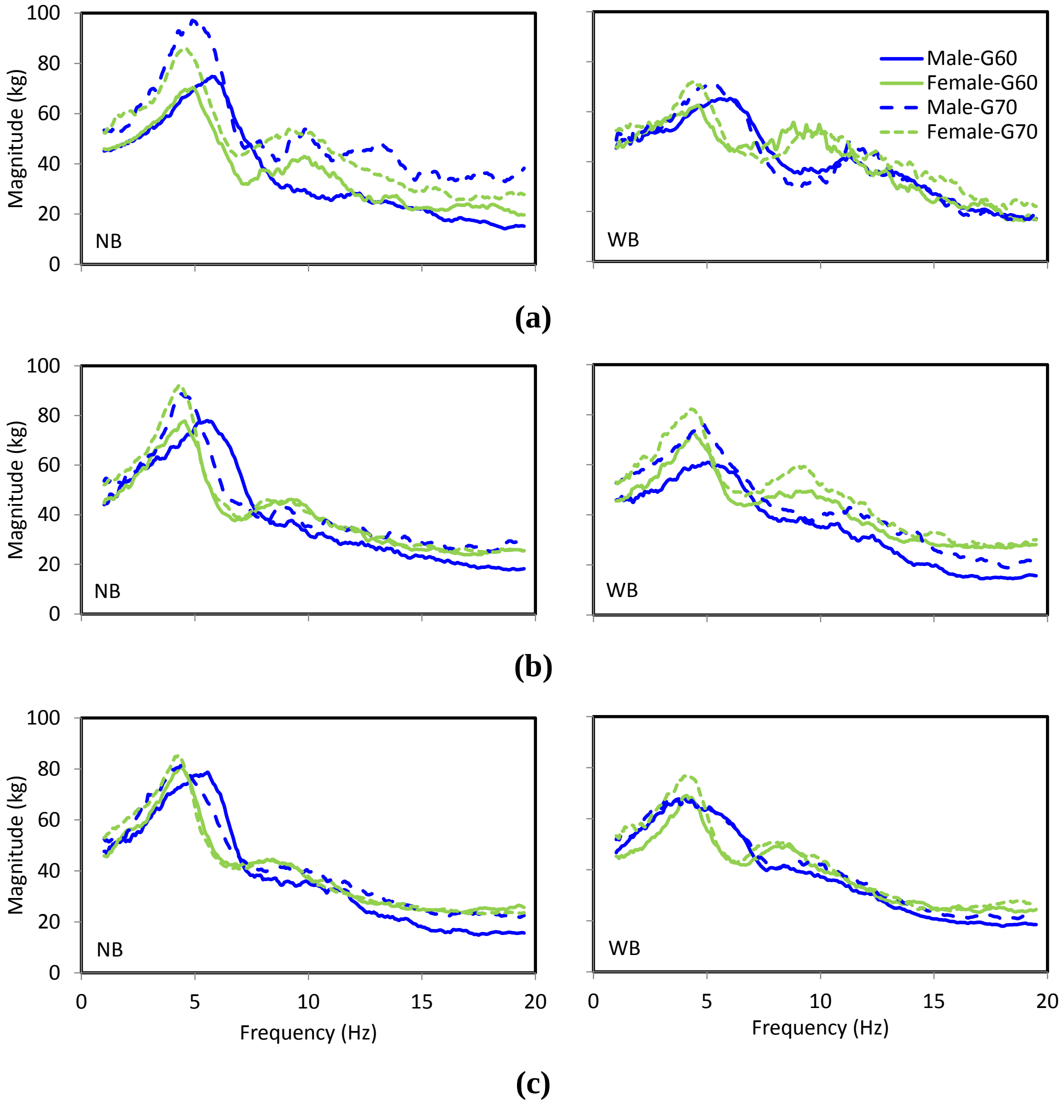


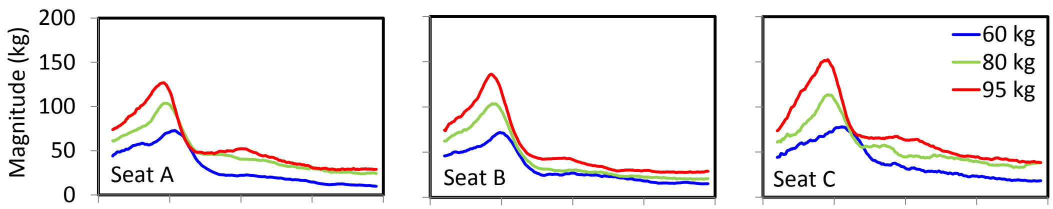
Figure 5.14: Mean APMS magnitudes of male and female subjects within two mass groups (60 and 70 kg) seated on seat C and subjected to different excitation levels: (a) 0.25 m/s^2; (b) 0.50 m/s^2; and (c) 0.75 m/s^2.

Table 5.6: Means (standard deviations) of primary resonance frequencies and peak APMS magnitudes of male and female subjects within two body mass groups seated on elastic seats and exposed to different vibration magnitudes.

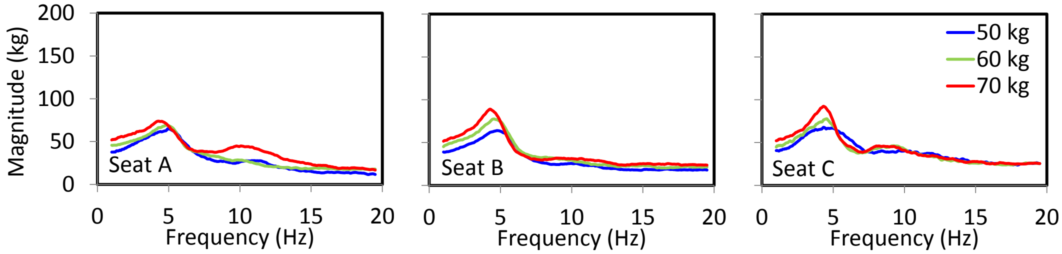
Seat	Mass groups	Body mass group – G60				Body mass group – G70			
	Back support	NB		WB		NB		WB	
	Gender	Male	Female	Male	Female	Male	Female	Male	Female
	Excitation (m/s^2)	Primary resonance frequency (Hz)							
Seat A	0.25	5.98(0.28)	4.91(0.69)	5.76(0.50)		5.40(0.51)	4.63	5.48(0.49)	4.69
	0.50	5.14(0.31)	4.92(0.45)	5.31(0.37)	5.05(0.45)	4.96(0.38)	4.56(0.40)	5.16(0.75)	4.23(0.24)
	0.75	5.06(0.38)	4.28(0.54)	4.72(0.66)	4.45(0.62)	4.58(0.92)	4.41(0.37)	4.98(0.48)	4.18(0.23)
		Peak APMS magnitude (kg)							
	0.25	79.9(6.1)	68.3(7.7)	70.5(6.9)		89.1(16.4)	62.1	75.8(11.0)	74.9
	0.50	73.3(7.0)	72.3(8.1)	68.9(11.1)	63.1(4.5)	88.1(30.4)	77.3(5.6)	64.4(4.9)	67.9(1.8)
	0.75	78.6(12.1)	71.0(9.1)	75.9(6.7)	63.5(3.0)	86.1(24.9)	80.7(7.4)	72.7(5.4)	71.4(5.4)
Seat B		Primary resonance frequency (Hz)							
	0.25	5.59(0.39)	4.60(0.62)	5.39(0.45)	4.59(0.22)	5.04(0.16)	4.70(0.34)	4.81(0.57)	4.42(0.31)
	0.50	4.95(0.40)	4.66(0.53)	5.23(0.76)	4.49(0.45)	4.83(0.43)	4.42(0.19)	4.58(0.52)	4.24(0.16)
	0.75	4.92(0.21)	4.58(0.45)	4.36(0.59)	4.14(0.29)	4.48(0.59)	4.12(0.25)	4.52(0.54)	3.97(0.15)
		APMS magnitude (kg)							
	0.25	70.9(7.0)	71.8(8.2)	65.7(5.1)	63.4(6.4)	91.8(13.4)	96.0(13.5)	73.9(7.8)	74.1(8.1)
	0.50	74.0(8.2)	75.8(8.6)	70.1(7.3)	66.5(4.7)	87.9(20.3)	89.8(17.1)	74.2(4.8)	71.6(5.8)
	0.75	77.4(1.4)	84.2(4.0)	74.7(14.2)	70.8(6.2)	91.0(16.4)	93.5(13.8)	82.8(9.0)	78.0(9.7)
Seat C		Primary resonance frequency (Hz)							
	0.25	5.86(0.60)	5.25(0.86)	5.78(0.84)	4.66(0.13)	5.44(0.53)	4.42(0.39)	5.27(0.76)	4.58(0.36)
	0.50	5.54(0.78)	4.23(0.63)	5.04(0.67)	4.46(0.38)	4.77(0.66)	4.36(0.25)	4.84(0.04)	4.34(0.19)
	0.75	5.41(0.36)	4.43(0.46)	4.46(0.78)	4.09(0.22)	4.98(0.90)	4.30(0.32)	4.48(0.88)	4.06(0.29)
		APMS magnitude (kg)							
	0.25	77.6(8.2)	75.1(4.9)	70.6(12.1)	63.8(1.7)	94.2(10.2)	87.8(10.1)	77.4(6.0)	73.9(8.5)
	0.50	82.1(2.3)	79.7(14.2)	68.1(8.8)	74.6(3.8)	90.3(28.2)	93.4(18.1)	75.9(2.7)	83.7(5.4)
	0.75	80.4(7.9)	78.6(13.7)	76.2(10.1)	72.1(7.3)	87.3(5.4)	88.3(13.0)	76.7(5.8)	77.7(3.4)

5.4.1 Effect of body mass on the APMS responses obtained with elastic seats

In order to evaluate the body mass effect on the APMS responses of male and female subjects eated on elastic seats, the datasets are grouped within three different mass ranges for each gender. These include body mass in the vicinity of 60 kg (55 to 65 kg), 80 kg (75 to 85 kg) and 95 kg (90 to 106 kg) for the male subjects and around 50 kg (45.5 to 55 kg), 60 kg (55 to 65 kg) and 70 kg (66 to 72.5 kg) for the female subjects. The mean APMS responses of subjects within each mass range are illustrated in Figs. 5.15 and 5.16, while seated with the NB and WB postures respectively, on the three elastic seats and subjected to the 0.50 m/s^2 excitation. The results show body mass effects similar to those observed in the responses obtained with the rigid seat. Relatively greater variability in the APMS magnitude is evident at lower frequencies up to the primary resonance frequency, irrespective of the sitting condition. The peak APMS magnitudes of heavier subjects are considerably larger than those of lightweight subjects for both genders, while the primary resonance frequency of the lightweight subjects is considerably higher than those of the heavier subjects.

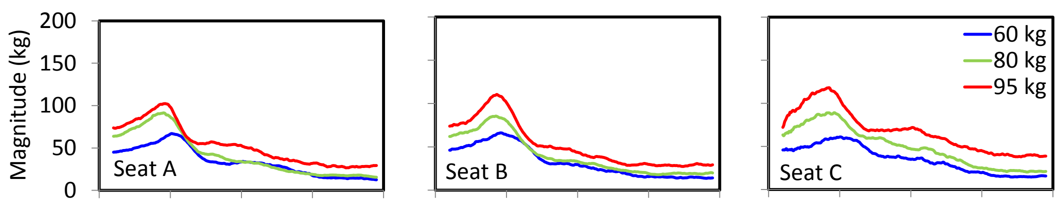


(a)

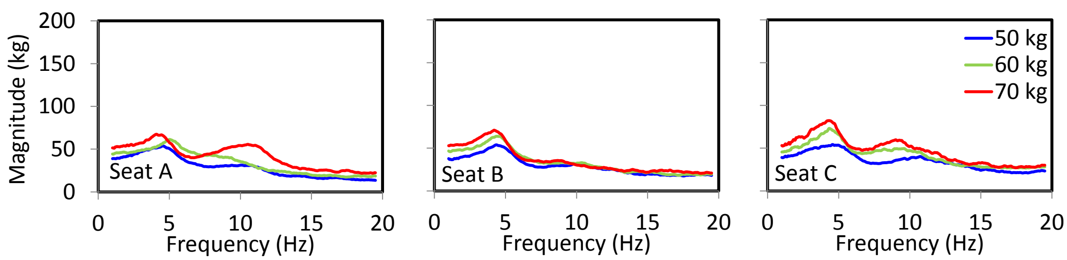


(b)

Figure 5.15: Comparisons of mean response magnitudes of male and female subjects within different mass groups seated on elastic seats: (a) male; and (b) female subjects (NB posture and 0.50 m/s^2 excitation).



(a)



(b)

Figure 5.16: Comparisons of mean APMS magnitude responses of male and female subjects within different mass groups seated on elastic seats: (a) male; and (b) female subjects (WB posture and 0.50 m/s^2 excitation).

Figure 5.17 shows further correlations between the peak APMS magnitude and the body mass for the three elastic seats, the two back support conditions and the three excitation levels. Although considerable dispersion in the peak APMS magnitude with the body mass is evident, the results suggest that the peak APMS magnitude can be positively correlated with the body mass, irrespective of the seat, the sitting condition and the level of excitation (r^2 ranging from

0.74 to 0.89). The responses obtained with the rigid seat showed relatively higher correlations between the peak APMS magnitude and the body mass (Fig. 4.17, r^2 ranging from 0.91 to 0.95). Very poor correlation, however, is observed between the primary resonance frequency and the body mass for all seat and sitting conditions considered, for the 0.50 m/s^2 excitation (Fig. 5.18).

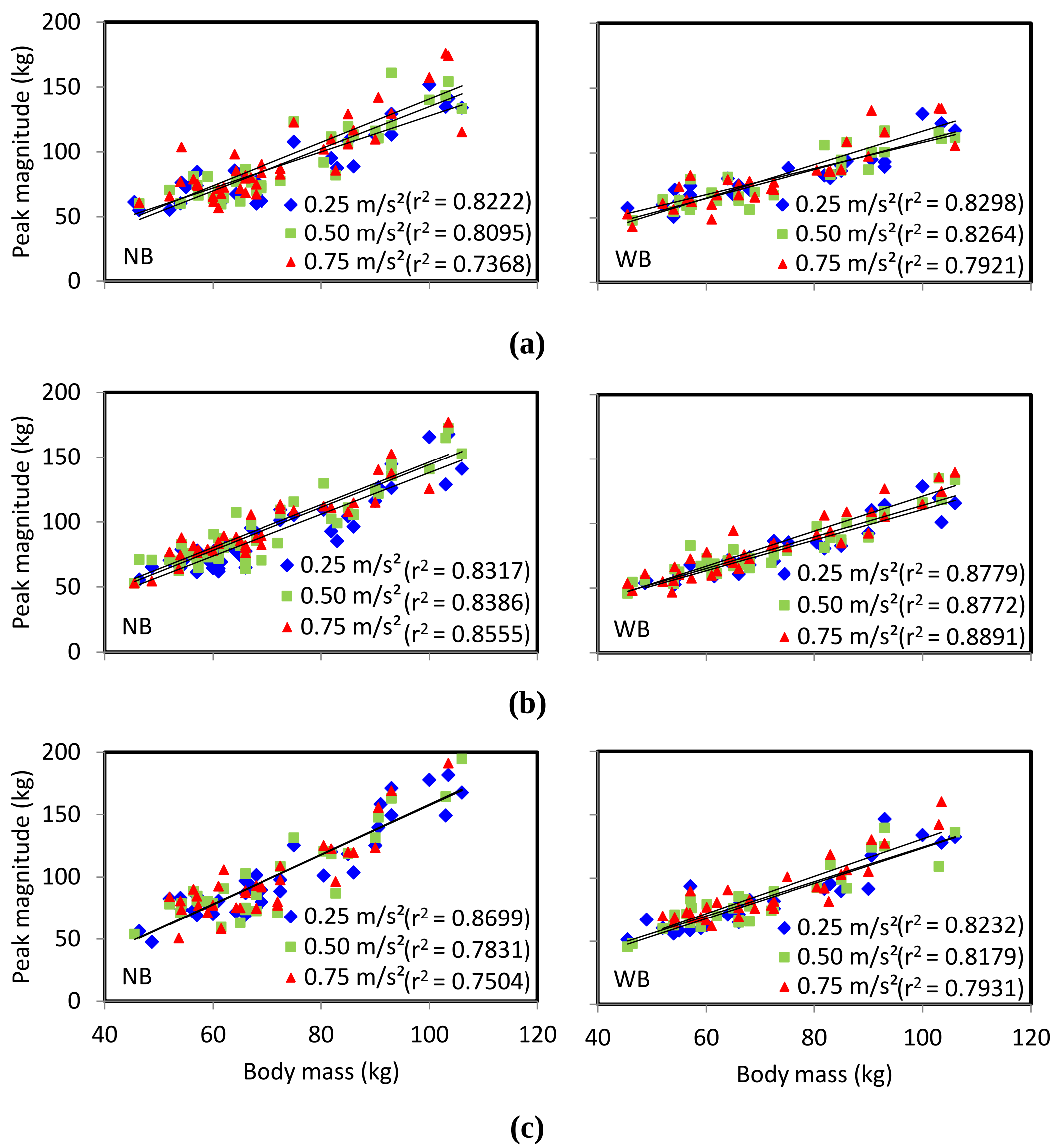


Figure 5.17: Correlations between peak APMS magnitude responses and body mass for the two sitting conditions and the three levels of excitation: (a) seat A - flat PUF; (b) seat B - contoured PUF; and (c) seat C - air cushion (both male and female subjects included).

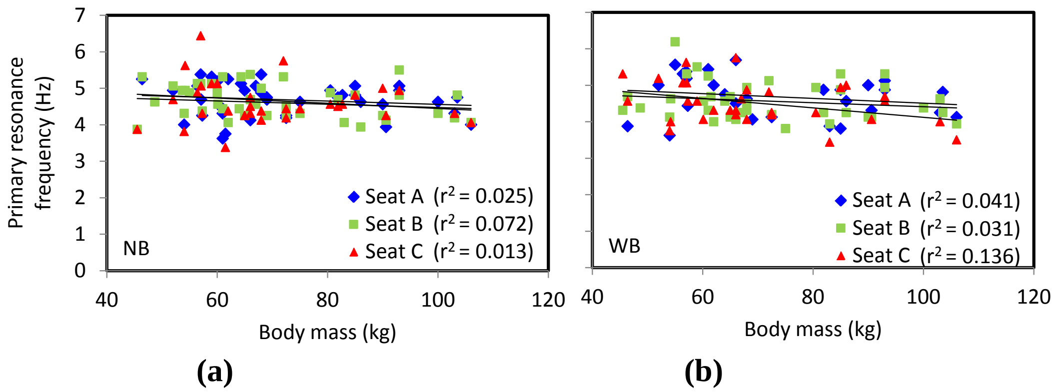


Figure 5.18: Correlations between primary resonance frequencies and body mass for the two sitting conditions and the 0.50 m/s^2 excitation: (a) NB – without a back support; and (b) WB – with a back support (both male and female subjects included).

The trends, however, suggest a negative correlation between the resonance frequency and the body mass, similar to the results attained with the rigid seat. Table 5.7 further summarizes the correlations between the peak magnitude and the body mass, in terms of r^2 values, for the two genders, together with the three elastic seats, the two sitting conditions and the three levels of excitations. The results suggest higher correlations for the male subjects compared to the female subjects for all the conditions considered. Relatively poor correlations are evident for seat A (flat PUF cushion) and seat C (air cushion) under the higher excitation of 0.75 m/s^2 compared to seat B (contoured PUF cushion).

Table 5.7: Coefficient of determination (r^2) of the peak APMS magnitude with the body mass of the subjects for the three seats, the two back support conditions and the three excitation levels.

Back support	Excitation (m/s^2)	Male			Female		
		Seat A	Seat B	Seat C	Seat A	Seat B	Seat C
NB	0.25	0.78	0.82	0.85	0.29	0.53	0.52
	0.50	0.76	0.87	0.80	0.35	0.52	0.36
	0.75	0.72	0.84	0.83	0.40	0.70	0.19
WB	0.25	0.78	0.85	0.79	0.44	0.76	0.70
	0.50	0.74	0.82	0.78	0.66	0.75	0.79
	0.75	0.67	0.82	0.77	0.61	0.67	0.39

5.5 Discussion

5.5.1 Comparison of the APMS responses of this study with reported data

The biodynamic responses of human subjects seated on a cushion seat and exposed to vertical whole-body vibration have been reported in a single study [57]. The study investigated APMS responses of 13 subjects (body mass - 79.3±24.3 kg) seated on a cushion seat with an inclined backrest (inclination angle = 17 – 28 degrees with respect to the vertical axis). The study employed three different vibration magnitudes at the seat base, while amplification/attenuation of vibration by the cushion was not considered. The white-noise random vibrations with nearly flat acceleration PSD were synthesized at the seat base to realize overall rms accelerations of 0.25, 0.80 and 1.6 m/s^2, while the rms accelerations and spectra of vibration encountered at the occupant-seat interface differed considerably. The results attained with the cushion seat thus could not be directly compared with those obtained with a rigid seat due to different levels of vibration encountered at the human-cushion interface.

In the present study, the experiments were designed so as to realize comparable vibration at the human-seat interface on both rigid and elastic seats. This facilitated direct comparisons of the responses obtained with the rigid and elastic seats. Three different excitation magnitudes with nearly constant acceleration PSD at the seat cushion were synthesized (0.25, 0.50 and 0.75 m/s^2 overall rms acceleration). The resulting acceleration at the seat base was also measured and analyzed for each seat and body mass group. The rms values of the acceleration measured at the seat base corresponding to the 0.25, 0.50 and 0.75 m/s^2 rms acceleration excitations synthesized at the seat cushion were obtained as 0.35, 0.68 and 0.98 m/s^2, respectively, which suggest notable vibration attenuation by the elastic seat. As an example, Fig. 5.19 illustrates acceleration transmissibility characteristics of the three seats coupled with an 81 kg subject and a 0.50 m/s^2 excitation at the seat cushion. These clearly show that significantly different levels of vibration would occur at the cushion, when the control is limited to the seat base vibration.

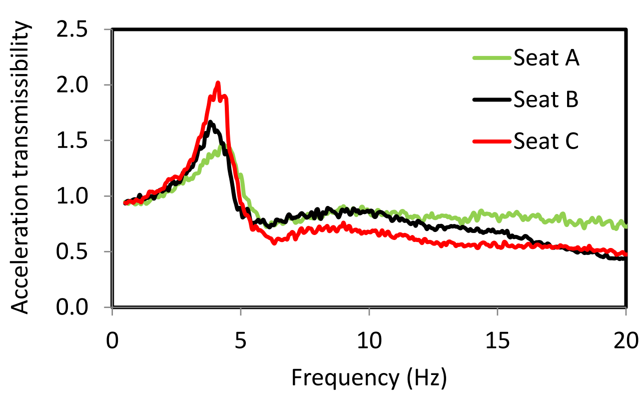
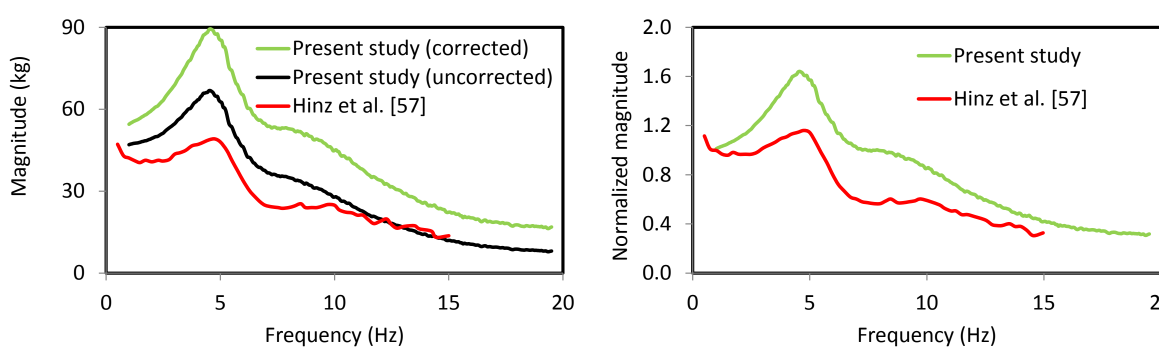


Figure 5.19: Vibration transmissibility characteristics of selected elastic seats (81 kg subject; 0.50 m/s^2 excitation at the seat cushion).

The mean APMS magnitude response of the subjects seated on the seat cushion under 0.8 m/s^2, reported in [57], is compared with that obtained in the present study for comparable mean body mass and excitation. Figure 5.20(a) compares the corrected and uncorrected mean responses obtained in this study with 31 subjects with body mass ranging from 70.3 to 73.5 kg and subjected to 0.75 m/s^2 excitation, with that reported in [57]. The reported APMS magnitudes are significantly lower than those attained in the present study, whether corrected or uncorrected, in most of the frequency range, even though the mean body mass of the subjects in the reported study was higher (79.3 kg). The reported data also show substantially lower magnitude at lower frequency, suggesting that the body mass supported by an elastic seat is significantly lower compared to that supported by a rigid seat. This may in-part be attributed to the low dynamic range of the capacitive pressure sensing mat used in the reported study. The corrected low frequency APMS magnitude in the present study corresponds to approximately 75-80% of the mean standing body mass, which is comparable with that observed for the rigid seat [62]. Furthermore, the peak APMS in the reported study is slightly below 50 kg, which is believed to be quite low for the mean body mass of 79.3 kg. This peak magnitude is even lower than the mean body mass supported by a rigid seat, which would be in the vicinity of 60 kg. Although the reported study considered an inclined back support and a contoured cushion, the observed differences cannot be entirely due to these factors.

The corrected data acquired with the 31 subjects were also normalized with respect to seated mass of the individual subjects (75% of the standing body mass). The resulting mean normalized magnitude is also compared with the reported normalized response under the same excitation in Fig. 5.20(b). It needs to be emphasized that the normalization in the reported study was based upon measured seated mass, which ranged from 46 to 61% of the total body mass. The comparison again shows substantially smaller reported normalized magnitudes in the entire frequency range compared to the data obtained in this study. Comparable values, however, are observed only at very low frequencies around 1 Hz, which is due to different normalization factors considered in the two studies.



(a) (b)

Figure 5.20: Comparison of mean APMS responses of 31 subjects (mean body mass = 71.9 kg) seated on seat A (flat PUF) with a vertical back support with mean responses of 13 subjects (mean body mass = 79.3 kg) reported by Hinz *et al.* [57]: (a) mean APMS magnitudes; and (b) mean normalized magnitudes.

Table 5.8 further compares the primary and secondary peak magnitudes and the corresponding frequencies with those reported [57]. The comparison again shows that the peak values obtained in this study are considerably larger than the reported values, for all the three seats. Furthermore, the frequencies corresponding to the primary and secondary peaks are also generally lower that those reported, except in the case of the primary frequency under the 0.75 m/s^2 excitation. This may be partly caused by differences in the stiffness of the seats and the backrest inclination between the two studies.

Table 5.8: Comparisons of the reported primary and secondary peak APMS magnitudes and the corresponding frequencies with those obtained in the current study.

	Hinz *et al.* [57]		Present study					
			Seat A		Seat B		Seat C	
Excitation (m/s^2)	0.25	0.80	0.25	0.75	0.25	0.75	0.25	0.75
Primary peak magnitude (kg)	48.0	53.3	82.9	83.1	80.3	82.3	83.2	88.0
Primary frequency (Hz)	5.25	4.08	5.17	4.40	4.84	4.24	5.01	4.20
Secondary peak mag. (kg)	29.0	29.8	43.8	48.1	36.2	40.9	53.1	58.3
Secondary frequency (Hz)	10.48	8.32	9.63	7.69	9.68	7.43	9.56	7.35

5.5.2 APMS responses of subjects seated on elastic seats

The APMS response characteristics of human subjects exposed to WBV are also dependent upon many factors, as observed from the rigid seat responses. For elastic seats, the responses seems to depend upon additional factors including the visco-elastic properties of the seat, the dynamics of the tissue beneath the ischial tuberosities and thigh, the pelvis rotation, the visceral movement and the whole body bending. These are strongly related to the visco-elastic properties of the seat, the posture, the magnitude and frequency of vibration, and the resonance frequency of the coupled human-seat system. While the results clearly show considerable differences between the human body APMS responses seated on rigid and elastic seats, the responses exhibit some comparable trends. At very low frequencies, the APMS magnitudes of subjects seated on rigid and elastic seats are quite comparable, which represent the body mass supported by the seat pan. The low frequency magnitudes for some of the subjects on elastic seats, however, were lower than those measured on the rigid seat. The differences were observed to be in excess of 15% under the lower excitation of 0.25 m/s^2. Relatively greater differences were also observed in the data acquired for the WB posture. Such large differences are attributable to low dynamic range of the pressure sensing system, together with the sitting condition and subjects build that resulted in low pressure contact zones. This suggests that the dynamic contact pressure is not only dependent on the subject body mass but also on the stature, build and gender. From the frequency response characteristics of elastic cushions, Wu *et al.* [55] reported that the peak pressure is a complex function of the subject weight, height and build.

The measured APMS responses of the subjects seated on elastic seats also showed greater degree of inter-subject variability compared to those observed with the rigid seat. The large variability in the data at lower frequencies up to 6 Hz is mostly caused by large variations in the body mass of the subjects (45.5 to 106 kg), which was also evident from the rigid seat responses. The APMS magnitudes in the mid-frequency range (from the primary to the secondary resonance frequency), however, are considerably lower with the elastic seats compared to those obtained with the rigid seat (Fig. 5.7). The variation in the APMS magnitudes obtained with the elastic and rigid seats may be caused by many contributory factors, where the human-seat interface pressure and pelvis rotations may be the major factors. The magnitude of the interface pressure is strongly related to the visco-elastic properties of the seat, the posture, the magnitude and frequency of vibration, and the resonance frequency of the coupled human-seat system [55]. Sitting on a rigid surface yields dominant pressure distribution within the ischium region with peak pressure occurring in the vicinity of the ischial tuberosities, while the pressure magnitude under the thighs is relatively small. Thus, the human-seat contact area on the rigid seat is lower compared to elastic seats. The interface pressure distribution obtained for the elastic cushions, however, is considerably different. The seated body mass is more uniformly distributed over a much larger sitting area, and the peak interface pressure is significantly lower than that encountered on a rigid seat. The maximum contact pressure, however, appears in the vicinity of the ischial tuberosities. The lower peak interface pressure on elastic seats thus may be the reason for lower APMS magnitude compared to those obtained with the rigid seat. Furthermore, sitting on a rigid seat causes negligible pelvis rotation, while relative deflections of an elastic seat would cause relatively higher pelvis rotation that may also alter the human-seat interface contact force and thus the APMS magnitude.

The APMS responses obtained with subjects seated on the selected elastic seats also show lower primary resonance frequencies compared to those observed with the rigid seat, irrespective of the back support and excitation conditions. The differences in the primary resonance frequencies of the human body seated on rigid and elastic seats is in-part caused by lower human-seat interface pressure on the elastic seats when compared to that on the rigid seat, apart from the differences in their static stiffness. Wu *et al.* [56] also reported that the ischium pressure on a rigid seat surface approaches its peak value near 5 Hz. However, the peak ischium pressure on the soft seat under vibration is in the 2.5-3.0 Hz range. The differences among the primary resonance frequencies obtained with the three elastic seats are most likely due to differences in their static stiffness and effective human-seat contact area, which affects the interface dynamic pressure and thus the dynamic driving-point force.

The pelvic rotation and the biodynamic force developed at the occupant-cushion interface are also expected to depend on the visco-elastic properties of the seat, the contouring of the seat surface, the sitting condition and the thigh contact. Considering considerable differences in the visco-elastic properties of the selected seats, the APMS responses of subjects seated on these seats are expected to differ. The static stiffness of seats A, B and C were measured as 6.07, 4.13 and 4.24 kN/m, respectively. Although the stiffness of seat C (air cushion) is lower than that of seat A (flat PUF), it yields relatively lower effective human-seat contact area due to the large size of the inflated air bubbles, as shown in Fig. 3.2. Furthermore, the air cushion seat exhibits only minimal damping, attributed to the thin PUF cover compared to seats A and B, which comprise thick PUF materials with greater damping property. Seat C thus yields higher driving-point dynamic force and higher APMS magnitude as compared to seat A. The static stiffness of seat B (contoured PUF cushion) is also comparable to seat C, but considerably lower than that of seat A. The seat B with lower stiffness coupled with the contoured geometry yields considerably larger human-seat contact area compared to seats A and C. This seat thus yields a more uniform distribution of pressure on the cushion compared to seat A, where localized high pressure concentrations were evident. Owing to its low stiffness, the foam cells may collapse under deflections at higher frequencies, and thereby limit bleed flows across the foam. The higher APMS magnitudes attained with seat B at higher frequencies, compared to seat A, may be attributed to this phenomenon.

5.5.3 Effect of back support

Support against a backrest tends to lower the peak APMS magnitude considerably compared to that obtained without a back support, while the effect on the primary resonance frequency is very small (Fig. 5.9). This suggests that a back support serves to constrain the body motion and yields a more damped response. Opposite trends, however, are evident around the secondary resonance, where the APMS magnitude is higher when seated with a back support. These patterns for the cushion seats are identical to those obtained for rigid seats in earlier studies [59,61,62]. Earlier studies have also reported that change in the sitting posture alters the proportion of body mass supported on the seat [55,62]. Furthermore, sitting with a back support also causes greater body-seat interface pressure near the tail bone. The variations in the APMS responses with different sitting postures may in-part be attributed to changes in proportion of body mass supported on the seat and differences in the human-seat interface contact area. The results of this study suggest that sitting without a back support on cushion seats yields considerably higher ischium pressure than those observed when sitting with a back support. The higher peak pressures with the NB posture, as compared to the WB posture, contribute to higher peak APMS magnitude response when sitting without a back support. In this study, it was observed that the mean peak APMS magnitudes of subjects seated with a vertical back support were about 9%, 14% and 14% lower for seats A, B and C, respectively, compared to those obtained without a back support. The differences in peak APMS magnitudes obtained with the three seats are primarily due to differences in their stiffness and contouring.

5.5.4 Effect of vibration magnitude

Softening tendency of the human body is evident from the responses obtained with the three cushions, irrespective of the back support condition. The results show a decrease in the primary resonance frequency with an increase in the magnitude of the excitation (Fig. 5.10). Such a softening tendency has been widely reported in many studies on the characterization of the biodynamic responses of human subjects seated on rigid seats and exposed to WBV [40,59,62,68,72]. Hinz *et al.* [57] have also reported such softening tendency of the human body seated on a cushion seat. The results in the present study, however, suggest that the softening behavior of the body on elastic seats differs from that reported for rigid seats (Table 5.3). The variation in the softening tendency of the human body seated on different seats may be due to the coupled effect between the sitting condition and the stiffness of the seats. Sitting without a back support would cause stiff and tense abdominal muscles, while the muscles are relaxed when the trunk is supported against a backrest. Matsumoto and Griffin [89] reported that increasing voluntary muscle tension in the abdominal muscles reduces the extent of the softening non-linearity in the APMS responses. Mansfield and Griffin [90] also observed relatively smaller softening effects in the APMS response when sitting with a back support on a rigid seat compared to the no-back posture.

The three elastic seats considered in this study revealed different degree of softening tendency, which may be again attributed to differences in their stiffness and damping properties. For the NB posture, the seat A (flat PUF), owing to its high stiffness (6.07 kN/m), showed higher softening tendency (0.63 Hz), when the excitation magnitude was increased from 0.25 to 0.75 m/s^2. Seats B and C, with comparable stiffness, resulted in similar softening effect (0.54 Hz for seat B; and 0.52 Hz for seat C). The results also suggest that changes in the human-seat interface contact area, observed for the WB posture, may also contribute significantly to the softening tendency of the human body under increasing excitation magnitudes. Seat B showed the lowest softening effect (0.60 Hz) with the WB posture, which may be attributed to a higher contact area with its contoured cushion and its lower stiffness. On the other hand, seat A, with its highest stiffness and relatively small contact area, showed considerably higher softening effects (0.77 Hz). Seat C with an air cushion, however, showed greatest softening effects (0.81 Hz), which were attributed to its lowest contact area due to large air bubbles.

The effect of excitation magnitude on the APMS responses obtained with elastic seats generally showed a larger increase in the peak APMS for an increase in excitation magnitude, while a few exceptions were also observed. This pattern in the APMS responses was not observed for the rigid seat. The larger increase in peak APMS magnitude on elastic seats with an increase in the magnitude of the excitation may be due to an increase in the peak human-seat interface pressure. Wu *et al.* [56] also observed a considerably higher increase in the maximum ischium pressure on a soft seat with an increase in the magnitude of the vibration excitation.

5.5.5 Effect of gender

A few studies have investigated the gender effect on the biodynamic responses of subjects seated on rigid seats and exposed to vertical vibration, while the reported findings are somewhat contradictory, as discussed earlier in section 4.3.1. The gender effect on the vibration transmissibility of typical automotive seats has been attempted in a single reported study [73]. The study measured seat-to-head acceleration transmissibility (STHT) characteristics of male and female subjects seated on an elastic seat and exposed to vertical vibration, as opposed to APMS, and concluded that the vibration transmissibility of a seat is strongly influenced by the gender, which may in part be caused by differences in the body mass of the two genders.

In the present study, the APMS responses obtained with elastic seats showed coupled effects of body mass and gender, as in the case of rigid seat (Fig. 5.11 and Table 5.5). The peak APMS magnitude and the corresponding frequency of the two genders were significantly different ($p<0.005$). Comparison of the two genders within similar body mass groups showed that the APMS responses of female subjects are lower than those of male subjects (Figs. 5.12 to 5.14). However, the differences between the male and female subjects were observed to differ between rigid and elastic seats. The differences in the primary resonance frequencies also varied for both mass groups and for different seats (Table 5.6). The observed differences in the APMS responses of male and female subjects seated on rigid and elastic seats are most likely caused by differences in various seat- and anthropometry-related factors. These may include visco-elastic properties of the seats, contact pressure distributions, as well as body shape and build, which are attributed to well-established anatomic differences between the male and female subjects. Females possess higher body fat (adipose tissue) and broader pelvis compared to males. The male pelvis, however, is taller, narrower and more compact. It is found that most of the body fat in females is deposited in the pelvis and the thighs. From the anthropometric measurements of recruited subjects, it was observed that female subjects have higher hip circumference (101.1 and 103.9 cm for the G60 and G70 groups, respectively) as compared to male subjects with comparable body mass (93.2 and 99.0 cm for the G60 and G70 groups, respectively). Higher contact area (578 and 587 cm^2, for G60 and G70 groups, respectively) might be the reason for lower interface peak contact pressure for the female subjects as compared to the male subjects with significantly lower contact area (355 and 407 cm^2, for G60 and G70 groups, respectively). The variations in the interface contact pressure might be one of the reasons for lower primary resonance frequency and slightly lower peak APMS magnitude for the female subjects than those of the male subjects.

Another reason for differences in the primary resonance frequencies of the two genders may be due to their different proportions of muscle and fat mass. Females generally possess lower muscle mass and thus lower lean body mass compared to males. Higher ratio of body fat mass to lean body mass could yield lower stiffness-to-mass ratio [70], suggesting lower stiffness of the female body compared to the male body. Furthermore, the dynamic properties of the muscles and body fat differ substantially [87]. Body muscles are visco-elastic materials, which show thixotropic behavior, i.e. viscosity is shear rate-dependent (viscosity decreases when stress is applied), whereas the body fat (adipose tissue) is anti-thixotropic material, i.e. viscosity increases with increase in shear rate [87]. The primary resonance frequency of female subjects may thus be expected to be lower than those of male subjects.

Gender difference was also found from the APMS responses near the secondary resonance frequency. A few researchers have attempted to identify the cause of the secondary resonance and suggested that it may be due to motions of the pelvic and visceral mass [84-86]. The female subjects showed prominent and higher magnitude of APMS response near the secondary resonance as compared to the male subjects within the same mass groups. The higher APMS magnitude at the secondary resonance frequency for the female subjects may be due to the relatively higher pelvis mass of the female subjects than the male subjects of same standing body mass. The APMS responses of subjects seated on different elastic seats also revealed that the differences between the primary resonance frequencies of male and female subjects are greater for the air cushion (seat C) followed by the flat PUF cushion (seat A) and by the contoured PUF cushion (seat B). These are again attributable to visco-elastic properties of the seats and anatomical differences between the two genders.

5.5.6 Effect of body mass

Studies on the biodynamic responses of subjects seated on rigid seats have invariably shown that heavier subjects yield considerably higher APMS magnitude, but lower primary resonance frequency compared to the lighter subjects [43,59,62,65]. The results obtained in the present study with elastic seats also showed the same pattern (Figs. 5.15 and 5.16). Furthermore, the subject body mass and peak APMS magnitude were positively correlated to the data obtained with the rigid seat. However, the r^2 values for the elastic seats (0.74 to 0.89) were slightly lower than those for the rigid seats (0.91 to 0.95). The coefficients of determination were further lowered when the subjects were grouped in accordance with the gender (males: 0.67 to 0.87; females: 0.19 to 0.79). Poor correlations may be attributed to a variety of factors, apart from the limited dynamic range of the measurement system: (1) non-linear characteristics of elastic seats, (2) non-linear behavior of human subjects which may change the dynamics of the tissues beneath the ischial tuberosities and thighs, and (3) selection of subjects with a wide range of anthropometric parameters (body mass: 45.5 to 106 kg; BMI: 15.78 to 34.99 kg/m^2; body fat, 8.8 to 39.0 kg). It is thus inferred that the coupled behavior of non-linear seat and non-linear human body is very complex. Further studies done with a careful selection of subjects within well-defined ranges of anthropometric parameters would be desirable to gain more insight on the biodynamic responses of subjects coupled with elastic seats.

5.6 Limitations of the study

The methodology developed in this study for the measurement of the APMS responses of human subjects seated on elastic seats and exposed to whole-body vertical vibration provides important guidelines for future studies. The results obtained with three elastic seats, two sitting conditions and three excitation levels controlled at the body-seat interface provide essential preliminary data with regard to the responses of the coupled human-seat system for both genders. The study, however, presents a number of limitations related to the measurement system and the experiment design, which might have affected the results.

The primary limitation of the study arises from the pressure sensing system (Tekscan Inc.) used to measure the dynamic force at the human-seat interface. It is shown that the peak ischium pressure of the subjects (body mass ranging from 45.5 to 106 kg) sitting on the elastic seats varies from 25 to 45 kPa, while the peak pressure is substantially higher when seated on a rigid seat [55]. Although the pressure sensing mats with peak pressure ranging from 36 to 207 kPa were available, the study employed a high pressure mat (207 kPa) in order to accurately measure the contact forces of the participants seated on both rigid and elastic seats. The seated body yields pressure concentrations near the ischial tuberosities and near the thighs, when supported by a seat. The pressure values around the extremities of the contact region, however, are very small and may be below the sensel resolution (0.83 kPa) and its dynamic range, particularly under low vibration levels. It is thus believed that the limited dynamic range of the high pressure mat may have caused some errors in the measured dynamic force. The degree of error could be reduced by selecting the high pressure range mat in conjunction with scaled sensitivity factors of the sensors (such scaling capability of the measurement system was not possible at the time of this study but is now available within the Tekscan software). The measurement system also revealed serious limitations with regard to the rate of data acquisition. Although the preliminary experiments with rigid seat loads were conducted using different sampling frequencies (64, 128 and 256 Hz), the results showed substantially lower dynamic force at frequencies above 3 Hz, irrespective of the sampling frequency used. This suggests limitations of the hardware in acquiring dynamic pressures accurately. The recommended two-point method of calibration together with the power law relationship may also contribute to some measurement errors. A multi-point calibration of the measurement system would help improve the measurement accuracy.

Secondly, the synthesis of the desired vibration magnitudes at the human-seat interface may have caused some measurement errors. The study employed two micro-accelerometers (14×14×1.4 mm), installed on the elastic seat surface around the ischial tuberosities, to serve as a feedback to the vibration controller (Vibration Research 8500) and to measure the acceleration at the human-cushion interface. The curved profile of human buttocks together with the seat motion would alter the orientations of the accelerometers leading to some error in the measured vibration levels. The estimation of the instantaneous orientations of the accelerometers through measurements along the three-axis would help reduce such error [91].

Thirdly, the correction function derived on the basis of the measurements obtained only with the rigid seat present another major limitation of the study. The APMS responses of the subjects seated on the rigid seat obtained from the two measurement systems showed that the correction functions derived for a rigid load differ from those derived for human subjects. The correction functions varied between individual subjects, and with the excitation magnitude and sitting posture. Such correction functions derived for the rigid seat may also yield errors when applied to the elastic seats. However, a reference response for elastic seats is not yet available for verifying the correction functions derived in this study. The results reported by Hinz *et al.* [57] show substantially lower APMS magnitudes in the entire frequency range, which could not be considered as an adequate reference for this study. A measurement system with enhanced dynamic range and frequency response, however, would provide the essential reference values for a verification of the results of this study.

6. CONCLUSIONS AND RECOMMENDATIONS

The study addressed two major challenges associated with the characterization of the biodynamic responses of human subjects seated on typical elastic seats and exposed to vertical whole body vibration: (i) synthesis of desired vibration spectra at the interface of the body and the elastic seat; and (ii) measurement of the biodynamic force at the human-seat interface. The seat pad accelerometer, recommended for measurement of vibration on elastic seats, could not be applied in this study, since its large size would alter the body-seat contact pressure distribution. It is shown that micro-accelerometers, applied in the vicinity of the ischial tuberosities, could provide an accurate measurement of the vibration at the seat comparable to the standardized seat accelerometer, and serve as feedback accelerometers for the synthesis of vibration spectra at the seat. Owing to nonlinear and load-dependent visco-elastic properties of vehicular seats, it was concluded that the desired vibration spectra need to be synthesized for each seat and specific body mass ranges.

The application of a thin-film seat pressure sensing system for the measurement of the biodynamic force developed at the elastic human-seat interface revealed many challenges and complexities. The seat pressure system provided reasonably accurate measurements of the seated body weight in the absence of vibration but large errors under vibration. Attenuation of the measured force was evident at frequencies above 3 Hz. The apparent mass (APMS) magnitudes obtained from the seat pressure measurement system applied to the rigid seat were substantially lower than those obtained from the conventionally used force plate. Furthermore, the seat mat resulted in lower APMS magnitude at low frequencies (0.5 to 1 Hz) under the low magnitude excitation (0.25 m/s^2), which was attributed to the limited dynamic range of the measurement system. The ratio of the APMS magnitude obtained from the force plate to that from the seat mat increased linearly with frequency. This was attributed to limited frequency response of the sensors and the measurement system hardware, and poor resolution of the sensing system. This magnitude ratio was considered as a correction function to be applied to the APMS in order to account for limited frequency response of the seat pressure measurement system. Different correction functions, however, were derived for different body masses and excitations levels (0.25, 0.50 and 0.75 m/s^2) considered in the study. Applications of these correction functions resulted in APMS responses comparable with those derived from the force plate for all of the 58 subjects (31 male and 27 female) seated on the rigid seat. It was thus concluded that the seat pressure measurement system together with the proposed correction function could be used for the characterization of the biodynamic force developed at the rigid body-seat interface.

It was further hypothesized that the proposed correction functions could also be applied for measurements on the elastic seats. The seated body APMS derived from the corrected body-seat interface force revealed trends similar to those observed in the responses obtained with the rigid seat. The magnitudes of APMS at low frequencies were similar to the static body mass supported by the seat for the majority of the subjects, which confirmed the validity of the measurement system and of the correction function in the low frequency range. Under the low magnitude vibration (0.25 m/s^2), however, the measured responses revealed relatively larger error between the low frequency APMS magnitude and the static body mass supported by the seat. This was mostly attributed to the poor resolution of the measurement system. Depending upon the build, individual subjects may yield localized low pressure zones, specifically around the outer periphery of the body-seat contact area, which would contribute to relatively greater errors due to the limited dynamic range of the measurement system. This was clearly evident from the data acquired under low vibration (0.25 m/s^2). The low frequency APMS magnitudes for many subjects were observed to be lower than the expected values (75-80% of the standing body mass). The datasets showing deviations in excess of 15% were excluded from the analyses.

The results clearly showed that the biodynamic responses of human subjects seated on elastic seats and exposed to vertical vibration significantly differ from those acquired with a rigid seat. This is attributed to human body coupling with the elastic seat that not only alters the nature of the vibration transmitted to the seated body, but also substantially changes the body-seat contact, the sitting posture and the body weight distribution on the seat [55, 56]. The widely reported and standardized (ISO 5982) APMS responses of the seated body would thus be expected to yield substantial errors, when applied to seating design and analyses, and the design of anthropodynamic manikins for assessment of vibration isolation performance of suspension seats. The results further showed that the APMS responses of subjects are not only strongly dependent upon the visco-elastic properties of the seat, but are also coupled with the gender and anthropometry of the subjects in a highly complex manner. Elastic seats tend to shift the primary resonance of the body towards a lower frequency, while reducing the resonance peak, irrespective of the back support and excitation conditions. This may be attributed to the visco-elastic properties of the seats. The results also suggest that design of seats and suspensions must take into consideration the resonance of the coupled human-seat system, as opposed to the widely reported uncoupled primary resonance of the human body near 5 Hz.

The APMS responses obtained with polyurethane (PUF) cushions were lower than those obtained with the air cushion seat in most of the frequency range, irrespective of the sitting condition and excitation magnitude. This suggests that the human response to vibration is dependent upon the stiffness and damping properties of the seat, and that the human body will most-likely absorb lower vibration energy with well-damped seats. The peak APMS response of subjects seated on elastic seats generally increased with an increase in vibration magnitude, while the primary resonance frequency decreased. While the softening tendency of the body with an increase in vibration has also been reported for rigid seats, the increase in peak magnitude has not been observed with rigid seats. Furthermore, the elastic seats showed reduced softening of the body with an increase in vibration magnitude.

The results also revealed significant gender effects on the measured biodynamic responses, which is strongly coupled with the body mass and a number of anthropometric parameters such as body fat content and buttock circumference. A clear gender effect could thus be established when male and female subjects of comparable body mass are considered. The APMS responses of male and female subjects of comparable body mass showed important gender effect suggesting that the vibration energy absorption of the two genders differ. Female subjects showed higher APMS magnitudes near the secondary resonance but lower magnitudes near the primary resonance compared to the male subjects, irrespective of the back support condition and excitation magnitude. The peak magnitudes for both genders of similar body mass were, however, comparable. Irrespective of the vibration magnitude and back support condition, the peak APMS magnitude was positively correlated (r^2>0.7) with the body mass. Furthermore, the use of a back support resulted in considerably lower peak APMS response. The results also showed linear positive correlations of the peak APMS (r^2>0.7) with body mass index, body fat and hip circumference for both genders. However, the correlations were moderate with lean body mass and body fat, and poor with stature and contact area. Furthermore, the peak APMS magnitude of the male subjects was higher compared to the female subjects of comparable anthropometric values.

From the results, it is concluded that the application of the pressure measurement system considered in this study poses many complexities, when a range of seats and excitation magnitudes are considered. The measurement system together with the methodology and the proposed correction function can be effectively applied to characterize the biodynamic force developed at the interface between the body and the visco-elastic vehicular seats and thus, it can be effectively applied to characterize the APMS under vertical vibration. The results in this study, however, can only be treated as preliminary, demonstrating the validity of the measurement system. Further studies with representative seats and vibration conditions are vital for defining target biodynamic responses and thereby biodynamic models applicable to realistic vehicle seats. The target responses and the models would serve as valuable tools for seating design and designs of anthropodynamic manikins. These are also expected to lead to revisions of the standardized APMS responses of the seated body (ISO 5982). Further studies are also desirable to study the contributions of inclined back supports and elastic back supports. A measurement system with improved resolution and dynamic range, however, would be most beneficial to conduct the above-mentioned studies in an efficient manner. For this purpose, it is also important to undertake systematic characterizations of the measurement system in terms of its linear range, frequency response and resolution. Additional efforts are also needed in developing hardware and software to simultaneously acquire the biodynamic force and vibration signals so as to minimize the potential errors due to time delays between the two signals.

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