CHARACTERIZATION OF APPARENT MASS OF HUMAN BODY SEATED ON RIGID AND ELASTIC SEATS UNDER VERTICAL VIBRATION

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ABSTRACT

CHARACTERIZATION OF APPARENT MASS OF HUMAN BODY SEATED ON RIGID AND ELASTIC SEATS UNDER VERTICAL VIBRATION

Arman Shahmir

Characterization of biodynamic responses of seated body exposed to whole-body vibration forms an essential basis for understanding of mechanical-equivalent properties of the body and potential injury mechanisms, and developments in frequency-weightings and enhanced design tools for the coupled human-seat system. Such responses are strongly dependent upon human anthropometric, gender, sitting posture and vibration condition in a highly complex and coupled manner, while only limited knowledge exists on effects of these factors. Furthermore, such responses are mostly evaluated for body on a rigid seat due to complexities associated with measurement of forces developed at an elastic human-seat interface under vibration. An elastic seat greatly alters human-seat interface contact force and contact area. The biodynamic responses with an elastic seat are thus expected to differ. This dissertation research concerns with development of a methodology for measurement of apparent mass (APMS) responses of human body seated on an elastic seat and exposed to vertical vibration. A force-sensing resistive pressure measurement system was initially used to capture responses of 58 human subjects (31 male and 27 female) seated on a rigid seat with and without a vertical back support, and exposed to three different magnitudes of broad band random vibration in the 0.5 to 20 Hz range (overall rms acceleration = 0.25, 0.50 and 0.75 m/s^2). The APMS responses were also obtained using the conventional force plate. The responses acquired from the force plate were thoroughly analyzed to study effects of gender, and mass-related (body mass, body mass index, body fat, lean body mass), stature-related (standing height, sitting height, C7-height) and build-related (buttock circumference, contact area) anthropometric dimensions. The results showed strong coupling between the gender and the body mass, while a strong correlation of the peak APMS was evident with body mass, body mass index, body fat and hip circumference. The data were subsequently grouped within three different body mass ranges in order to decouple the effect. The gender effect was observed in the vicinity of secondary peak where female subjects revealed higher APMS magnitude, while the male subjects showed relatively higher primary peak frequency than females. Comparisons of APMS responses with those derived from the pressure sensing mat revealed large differences. APMS magnitudes derived from the pressure sensing mat were considerably lower than those obtained from the conventionally used force plate in the entire frequency range. The differences were attributed to low resolution of the sensor and limited acquisition rate of the hardware. A correction function was subsequently derived from the ratio of response functions obtained from the two measurement systems, which revealed nearly linear decreasing trend with frequency. The application of correction functions resulted in comparable responses from the two measurement systems. It was then hypothesized that the proposed correction function, mostly attributed to limited acquisition rate, would be equally applicable for cushion seats. Subsequent measurements were performed to derive APMS of subjects seated on a cushion seat. Comparisons of APMS magnitudes obtained for the cushion seat with those obtained with the rigid seat revealed that response magnitudes and the primary resonance frequency of subjects when seated on a cushion seat are generally lower. The effects of selected anthropometric factors, sitting posture and vibration magnitudes, however, were very similar to those observed for the rigid seat.

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CONTENTS

CHAPTER 1
INTRODUCTION AND SCOPE OF DISSERTATION

CHAPTER 2

EXPERIMENTAL AND DATA ANALYSES METHODS

CHAPTER 3

EFFECTS OF ANTHROPOMETRIC FACTORS ON APPARENT MASS RESPONSES

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

APMS	Apparent Mass
BMI	Body Mass Index
C7	Seventh Cervical Vertebrae
DPMI	Driving-Point Mechanical Impedance
ISO	International Standard Organization
LBP	Lower Back Pain
NB	No Back Support
PSD	Power Spectral Density
PUF	Poly Urethane Foam
rms	Root-Mean Square
SD	Standard Deviation
WB	With Back Support
WBV	Whole-Body Vibration
WBVS	Whole-Body Vibration Simulator

CHAPTER 1
INTRODUCTION AND SCOPE OF DISSERTATION

1.1 Introduction

The ride vibration environment of a ground vehicle constitutes among the significant factors affecting the occupant comfort. While the ride vibration in a vehicle may arise from many sources such as surface irregularities, aero-dynamic forces, engine and driveline vibrations, and imbalances of tire assembly [1], the tire/track interactions with surface irregularities yield most significant low frequency vibration. The magnitudes of such vibration are generally large in work vehicles operating on relatively rough terrains. Exposure to such vibration coupled with relatively long exposure duration has been associated with a number of health disorders among the drivers and reduced work efficiency apart from discomfort [2-4]. Several epidemiological studies on drivers of different vehicles have suggested strong association between occupational whole-body vibration (WBV) exposure and low back pain (LBP), disc degeneration, spinal muscle fatigue and altered spinal proprioception [2,5-8]

Some studies have suggested that the current knowledge on human responses to WBV and the epidemiological data are limited to identify a reliable exposure-response relationship for assessing potential health risks [2,5,9]. This is mostly attributed to many other contributory factors that have not been adequately studied. Characterization of human responses to vibration is thus vital for enhancing the knowledge. The biodynamic responses of seated human subjects exposed to WBV have thus been widely studied in the laboratories under different sitting and vibration conditions [10-12]. The reported responses in terms of apparent mass (APMS) have been applied to derive biodynamic models for design of seats [11,13- 17] and anthropodynamic manikins [18-22], identify resonances and deflection modes, and to develop frequency-weightings for assessment of exposure risks [2,5,9]. The applications of biodynamic models for seating design and assessments, however, have met limited success [14,17]. This is partly attributable to lack of knowledge on various sitting conditions and human anthropometry, and in-part to lack of consideration of the human occupant coupling with the elastic seat.

The reported studies have invariably, with only one exception, have measured APMS of humans seated on a rigid seat while exposed to vibration [16,23-25]. The human body coupling with elastic seats could significantly alter the contact force distribution, contact area and pelvic orientation, and thus affect the APMS responses. The measurement of biodynamic force on the interface of human body and an elastic seat, however, poses considerable challenges. Thus far, only a single study has attempted measurements of APMS responses of human subjects seated on cushion seats and exposed to vertical vibration [26]. The interface force in the study was measured using a flexible seat pressure mat composing an array of pressure sensors. The poor resolution and limited acquisition rate of the measurement hardware, however, resulted in significantly lower APMS in the entire frequency range. Considering the important influence of elastic properties of a seat cushion, it is desirable to develop a more effective measurement methodology. Furthermore, the reported studies have suggested important effects of gender and various anthropometric factors on the biodynamic responses. While the studies have reported contradictory gender effects [27- 29], the effect of various anthropometric factors could not be quantified. This could be mostly attributed to consideration limited samples of subjects with widely different body mass and dimensions, and coupled effects of anthropometric variables. A few studies have shown negligible gender effect on the APMS responses under vertical vibration [27- 29], while others have suggested important gender effect [30-32]. Wang et al. [33], on the other hand, established that the gender effect is strongly coupled with body mass.

This dissertation research aims at: (i) a thorough study of various anthropometric factors, including the gender effect, on apparent mass responses of human subjects seated on a rigid seat and exposed to vertical vibration; and (ii) development of a methodology for measurement of apparent mass responses of subjects seated on a cushion seat. The results obtained are expected to provide additional knowledge on characterization of vertical biodynamic properties of seated body for application in seating design, biodynamic modeling, design of anthropodynamic manikins for assessment of seats and improved frequency weightings for exposure assessments.

1.2 Review of Relevant Literature

The reported studies on biodynamic response characterization of seated body are critically reviewed to gain essential knowledge on methods and various contributory factors. The studies, grouped in a logical manner, are briefly discussed in following subsections so as to build the scope of this dissertation work.

1.2.1 Biodynamic measures and measurement methods

The ride vibration environment of a vehicle directly affects the comfort performance of the vehicle. Apart from discomfort many epidemiologic studies have established strong correlations between the exposures to whole-body vibration of work vehicles with various health risks among the occupational drivers [2,6,34]. The health effects have been described in a few review articles, which include the low back pain, disc degeneration and spinal, muscle fatigue effects [2, 5-8]. Consequently, the characterization of responses of seated human body to WBV is considered vital to identify resonances and vibration modes of the body, and the transmission of seat vibration to the body. These have mostly focused on biodynamic behavior of the body under vibration, which have been applied for deriving biodynamic models for applications in seating design and dynamics [11,13-17]. It has been shown that visco-elastic properties of the seated body strongly affect the vibration performance of the seat. Figure 1.1 compares of acceleration transmissibility of a suspension seat loaded with a human subject and an equivalent rigid mass. The comparison clearly shows that the human body significantly alters the seat vibration performance through absorption of vibration energy.

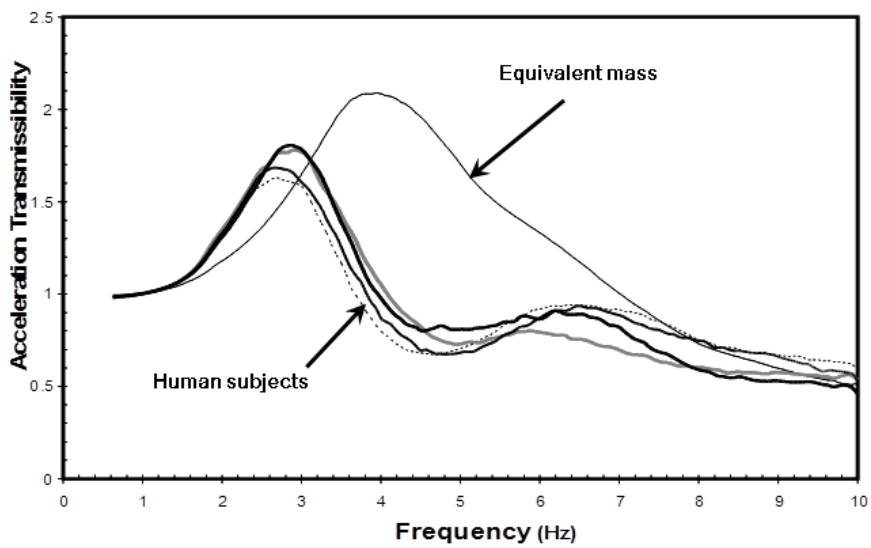


Figure 1.1: Comparisons of acceleration transmissibility of a high natural frequency suspension seat loaded with human subjects and an equivalent rigid mass [35]

The design of vehicle seats thus necessitates consideration of the human driver by integrating a human body model in the design process. Characterization of seated body biodynamic responses is thus essential not only for deriving biodynamic models, but also for developing anthropodynamic manikins for effective assessments of seats [33,36-39]. Furthermore, the biodynamic responses have been applied for deriving frequency-weighting for assessing exposure risks [40-44].

The responses of seated human body to WBV have been widely investigated using to-the-body and through-the-body biodynamic response functions. The to-the-body response function relates the driving-point biodynamic force to the motion at the driving point (human-seat interface). Though-the–body relates the motions transmitted to a body segment to the motion at the driving-point. This measure has been mostly studied in terms of vibration transmission to the subjects' head and is referred as seat-to-head vibration transmissibility (STHT) [12,43,45].

To-the-body biodynamic responses function of the seated subjects under vibration have been expressed in terms of driving point mechanical impedance (DPMI) or the apparent mass (APMS), given by:

$$Z(j\omega) = \frac{F(j\omega)}{v(j\omega)} \; ; and \; M(j\omega) = \frac{F(j\omega)}{a(j\omega)} \tag{1.1}$$

Where $Z(j\omega)$ and $M(j\omega)$ are the complex mechanical impedance and apparent mass functions, respectively, relating the human-seat interface force $F(j\omega)$ with velocity $v(j\omega)$ and acceleration $a(j\omega)$ at the driving point, respectively, corresponding to rotational frequency ω.

DPMI and APMS are also related such that $Z(j\omega) = j\omega M(j\omega)$. Under random vibration these two functions are expressed as one sided power spectral density functions, such that [46]:

$$Z(j\omega) = \frac{S_{Fv}(j\omega)}{S_v(j\omega)} \; ; and \; M(j\omega) = \frac{S_{Fa}(j\omega)}{S_a(j\omega)} \tag{1.2}$$

Where $S_{vF}(j\omega)$ and $S_{aF}(j\omega)$ are the cross spectral densities of the force and velocity and force and acceleration, respectively, and $S_v(j\omega)$ and $S_a(j\omega)$ are auto spectral densities

In a similar manner, the STHT biodynamic response of the seated subject is evaluated from:

$$H(j\omega) = \frac{S_{a_H a}(j\omega)}{S_a(j\omega)} \quad (1.3)$$

Where $H(j\omega)$ defines the seat-to-head vibration transmissibility and $S_{aa_H}(j\omega)$ is cross spectral density of the acceleration at the head a_H and the driving point acceleration a.

The biodynamic responses are normally measured in the laboratory under controlled vibration and postural conditions. The experiments generally involve human subject seated on a rigid seat platform supported on a dynamic force measurement system and subject to controlled vibration over a frequency band of interest (generally up to 20 Hz). The total force measured during the experiment is corrected for inertia of the seat platform, and applied to derive 'to-the-body' response function in terms of either DPMI or APMS. The correlation between the vibration signal and measured force is monitored during the experiments through the coherence function γ^2, given by [46]:

$$\gamma^2(\omega) = \frac{|S_{Fa}(j\omega)|^2}{S_a(j\omega)S_F(j\omega)} \quad (1.4)$$

The coherence ranges from 0 to 1, and a higher value ensures greater correlation between the measured signals.

Earlier studies on seated body responses to whole body vibration generally reported DPMI [e.g. 11,47-50], while later studies have reported APMS, since it is relatively easier to measure and perform inertia correction. Furthermore, the APMS magnitude at a very low frequency represents the body mass supported by the seat, while the corresponding DPMI magnitude nearly zero. The APMS also yields relatively less variations in the primary resonance frequency compared to the DPMI.

Owing to strong dependence of APMS on the body mass, the measured responses are generally normalized with respect to either the static seated body mass [24,33,51,52] or the APMS magnitude at a low frequency, ranging from 0.5 to 2 Hz [28,53,54]. The seat tends to support 73 to 89% of the total body mass depending upon the seat height, seat geometry and back support condition. Lundstörm et al. [55] reported that 77% and 76% of the total body mass is supported by the seat for the female and male subjects, respectively, when sitting upright without a back support. Increasing in the height of seat pan causes greater body weight on the seat. Wang et al. [33] reported that increasing seat height form 410 to 510 mm resulted in proportion of body mass on the seat to increase from 73.4% to 85% when sitting without a back support. This can be attributed to greater thigh contact with the pan of a higher seat and relatively lesser load on the legs. Inclination of the seat pan and the backrest, as seen in automotive seats, could lead to approximately 88.7% of the body weight on the seat [33]. Furthermore placing the hands on a steering wheel (driving-like posture), as opposed to hands on thighs (passenger-like posture) causes the body mass supported by the seat to decrease by approximately 3.3%.

1.2.2 Factors affecting biodynamic response

The biodynamic responses of seated body under WBV are strongly affected by a large number of factors. The factors affecting the APMS may be grouped in body-related, seat-related and vibration-related factors. The body mass and build together with seating support conditions yields important nonlinear effects on the APMS responses [33,36-39]. The seat geometry and support properties further alter the human-seat contact force and area and thus to-the-body response function [56,57]. The human body APMS responses also vary significantly with varying vibration magnitude and frequency [24,29,33,36,58-59]. The reported to-the-body and through-the-body biodynamic responses, despite the large inter-subject variabilities, exhibit primary magnitude peak in the 4 to 7 Hz range, which is often termed as the whole-body vertical mode [28,32,58,61]. Many studies have related this prominent mode to deformations of the spine [38,41,43,61,62]. A secondary vibration mode in the 8 to15 Hz range has also been reported, although a peak in this range is not quite clear for many subjects [28,29,32,33]. Kitazaki and Griffin [38] and Pranesh [63] identified the pelvic pitching modes near 8.1 and 8.7 Hz, and second visceral mode near 9.3 Hz, which were related to the secondary mode in APMS response. Owing to complex contributions of various factors, the reported APMS responses exhibit large inter subject variability, which is particularly large in through-the-body measures. While the nonlinear effects of vibration magnitude and the effects of body mass have been widely reported [24,29,33,36,58,59], the effect of human anthropometry and support conditions have been addressed in a relatively fewer studies [33,36-39].

Visco-elastic properties of the seat also alter the contact force distributions and the contact area, and thus the APMS. The reported biodynamic responses, however, have been invariably measured for subjects seated on a rigid seat. Although, a few studies have measured APMS of subjects seated on cushion seats and exposed to horizontal or vertical vibration, the driving-point was measured only at the seat base not at the human-seat interface [64- 66]. The reported results thus cannot be considered to describe biodynamic responses of the seated body but those of the coupled human-seat system. The APMS of subjects seated on a cushion seat, however, have been attempted in a single study through measurement of the driving-point force at the seat surface [26]. The effects of selected important factors on the APMS responses are discussed in detail in the following sections.

1.2.3 Body mass and anthropometric parameters

The body mass exhibits greatest influence on the APMS and DPMI responses of seated human subjects particularly in the lower frequency range. A larger body mass could yield to greater contact area and more uniform contact force at the seat-human interface and thus alter the biodynamic responses of seated subject [67]. Wu et al. [56,57] measured the body-seat contact force, peak contact pressure and contact area of subjects of different body masses seated on rigid as well as cushion seats. The study concluded that the peak human-seat interface pressure reduces with increasing body mass due to greater contact area.

The variation in body mass causes large scatter in the APMS data, particularly in the lower frequency range [24,29,33,68]. This can be directly related to variation in the body mass supported by the seat. A few studies have thus suggested describing the APMS of subjects within narrow ranges of body mass [29,33,69,70]. Patra et al. [70] measured the APMS responses of subjects within three different mass groups (55±3.3, 75±3.9 and 98±5.5 kg) using 9 subjects for each group. Figure 1.2 (a) illustrates the APMS magnitudes of the three groups, which clearly show vast differences in the lower frequency range. The figure also illustrates the mean response, which can hardly be considered representative of responses of lower (55 kg) or higher (98 kg) body mass subjects.

The scatter in the APMS magnitude is excessive in the low frequency range, while the responses tend to converge above 10 Hz. The measured APMS responses are frequently normalized with either the magnitude at a low frequently (ranging from 0.5 to 2 Hz, assuming that the body behaves close to a rigid mass up to 2 Hz) or with respect to body mass supported by the seat [28,36,53,71]. While the low frequency scatter diminishes through normalization, the trends with respect to body mass are significantly altered in higher frequency range, as seen in Figure 1.2

(b). The lower body mass subjects exhibit considerably higher magnitude at frequencies above 6 Hz, while the APMS magnitudes of heavier subjects are lowest at frequencies above 5 Hz. These trends are opposite to those observed in Figure 1.2 (a). The peak APMS magnitude is positively correlated with the body mass, as illustrated in Figure 1.3 [25,29,33,72]. Few studies have also investigated a correlation between the primary resonance frequency and the body mass. While the trend suggest a negative correlation with the body mass, the correlation was observed to be weak, as seen in Figure 1.3 [29,73]. Another study concluded that the APMS magnitude up to 12 Hz is linearly correlated with the body mass, irrespective of the body support and hand position, while at higher frequency the APMS is less sensitive to body mass [33].

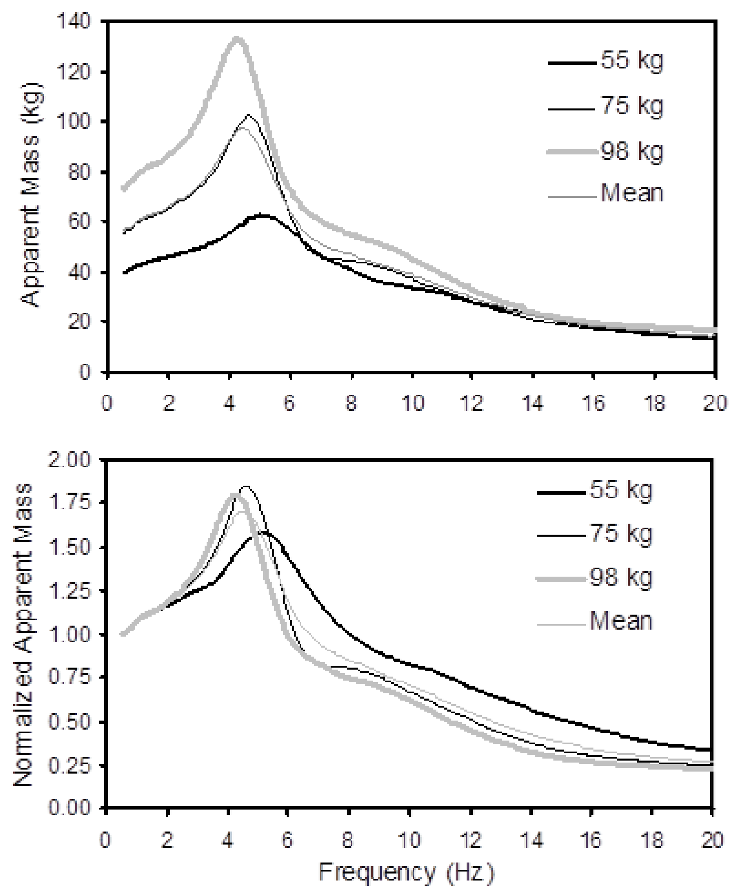


Figure 1.2: (a) APMS magnitudes of subjects within three different body mass ranges and the mean magnitude; and (b) normalized APM response of three mass groups [70]

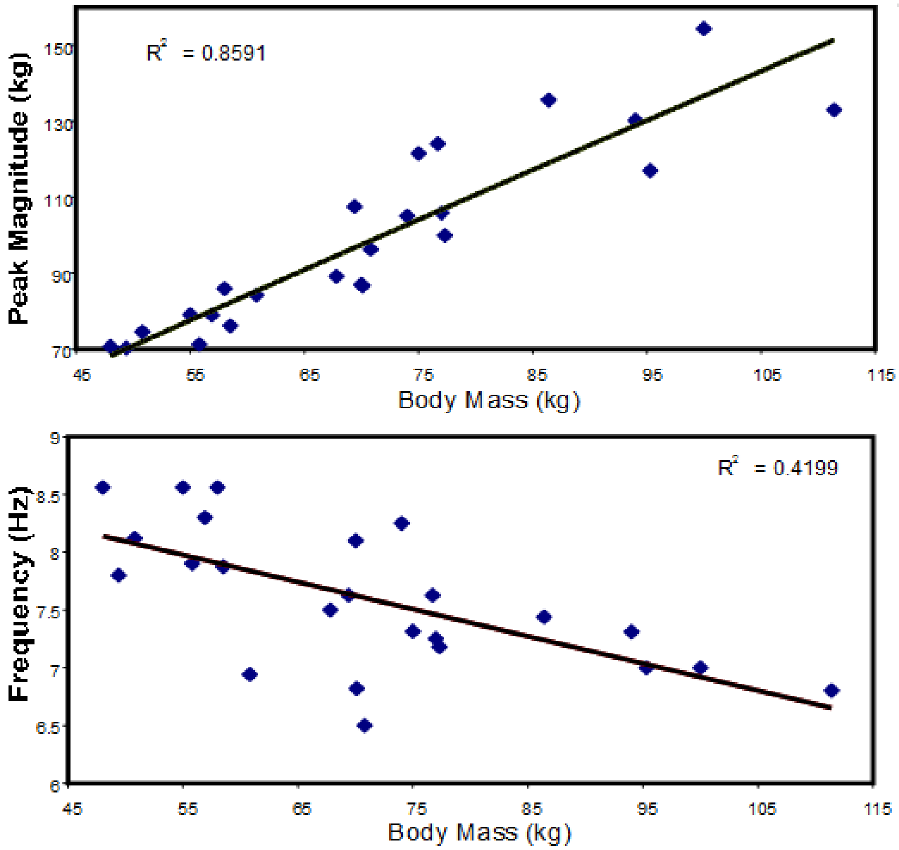


Figure 1.3: Correlation of the vertical apparent mass magnitude and corresponding frequency with body mass

Apart from the body mass, the APMS responses are also influenced by various anthropometric dimensions, although only a few studies have explored relations between APMS and anthropometry. These have attempted correlations between APMS magnitude and selected anthropometric parameters such as standing height, body mass index (BMI) and body fat percentage. Wang et al. [73] analyzed the APMS responses of 12 subjects considering four different postures in an attempt to study correlations with body mass, BMI, standing height and body fat. The postures included sitting with and without a back support coupled with hands on thighs and on a steering wheel. The linear regressions of the measured data suggested positive correlation of the APMS with body mass and BMI, while a poor correlation was observed with standing height and body fat. In a similar manner, Toward and Griffin [52] investigated the effects of age and selected anthropometric parameters on the APMS responses, and showed strongest correlation with body mass in the vicinity of 0.6 Hz, primary resonance frequency and 12 Hz. The APMS responses also revealed positive correlations with age and BMI only near the principal resonance frequency, while the effect of BMI was not significant. Few studies have shown the influence of human anthropometry on through-the-body response function [39,52,72]. The APMS responses of the seated body are likely influenced by many other stature- and mass-related parameters such as lean body mass, percent body fat, hip circumference and torso height, which have not been addressed in the reported studies.

1.2.4 Gender effect

The reported studies primarily focus on the effects of body mass on the measured biodynamic responses. Apart from the body mass and other anthropometric factors, the APMS may also be affected by gender. Female anatomy differs from the male anatomy, and the body fat content of females is considerably different from the males [74,75]. The APMS responses of the two genders are thus expected to differ. The gender effect on the APMS, however, has been addressed in only a few studies, which report contradictory findings. Fairley and Griffin [28] measured APMS responses of 24 male, 24 female and 12 children subjects and observed insignificant gender effect. Holmlund et al. [76], on the other hand, noted higher 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. The study concluded significant gender effect and suggested an alternate weighting for assessing WBV exposure of female workers. Insignificant gender effect, however, was observed on the DPMI phase responses. Another study on the basis of normalized APMS responses reported important gender effect around 10 Hz [32]. Toward and Griffin [52] the 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.

The contradictory findings in the above studies were most likely caused by consideration of male and female subjects of different body masses. Wang et al. [33] has shown that the gender effect is strongly coupled with the body mass. This study attempted to decouple the gender effect from the body mass effect through analyses of responses of male and female in a comparable body mass range. The analyses of data acquired with 5 male (71.7±3 kg) and 5 female (71.4±7.4) subjects revealed a more clear second peak for the female than the male subjects. A statistical analysis of the data, however, revealed that the gender effect is significant at frequencies above 15 Hz. Owing to the contradictory findings of few studies reporting gender effect, it is desirable to investigate the effect considering a larger subject populations of comparable body masses.

1.2.5 Effect of back support

Geometry of the seat pan and the back support can alter the muscle tension and postural stress, and thus the biodynamic response to vibration. The vast majority of the studies have characterized biodynamic responses of subjects seated upright without a back support and hands resting in the lap or on thighs. Such a posture cannot be considered representative of a vehicle driving posture. The International Standards Organization has defined idealized ranges of DPMI and APMS responses of subjects seated without a back support and hands in lap, and exposed to vertical vibration up to 5 m/s^2 [77]. Relatively fewer studies have considered either a vertical or an inclined back support [25,33,70].

Studies, conducted under vertical and horizontal vibration, have invariably reported most significant effects of a back support. An inclined backrest can support a greater proportion of the trunk weight, which can reduce the compressive force between the trunk and the pelvis and the intra-discal pressure [78, 79, 80]. The body support against a backrest tends to reduce the peak vertical apparent mass magnitude considerably compared to that obtained with no back support, while the effect on the primary frequency is very small [25,33,70]. A back support condition, however, yields relatively higher apparent mass magnitude at frequencies above 5.5 Hz and larger bandwidth suggesting increase in energy dissipation property of the body [33]. Mansfield and Maeda [23] reported that the peak vertical apparent mass with a vertical back support was 6% lower than that without a back support, while effect on the median primary frequency was small. Boileau and Rakheja [13] investigated APMS responses of subjects seated on a seat with 14^{o} inclination of the backrest. The results showed that the DPMI response magnitudes for the no back support were higher, while the resonance frequency was lower than that obtained with inclined back support. The reported studies have also revealed that a back support tends to reduce the inter-subject variability, which is attributed to a more stable upper body supported against a backrest [43,76,81,82]. The lower peak magnitude with a back support was also attributed to considerably lower peak pressure at the human-seat interface compared to that measured when sitting without a back support [57].

A back support also serves as an additional source of vibration transmitted to the torso, especially when the backrest is inclined. A seat with a back support thus constitutes two driving-points formed by the buttocks-seat pan and upper body-backrest interfaces[33]. The reported studies, however, characterize the biodynamic responses considering a single driving-point formed by the buttocks-seat pan interface, with only few exceptions. Rakheja et al. [69] and

Wang et al. [33] measured the APMS responses of seated subjects at the two driving-points by introducing force plates at the seat pan and the back rest. The backrest APMS was considered to describe dynamic interactions of the body with the backrest. The studies considered a seat geometry representative of automobile and commercial vehicle seats with inclined backrest. It was concluded that the body imposes substantial dynamic forces at the backrest that should be integrated in the biodynamic modeling process.

1.2.6 Effect of cushion

The biodynamic responses of seated body under vibration have been invariably characterized using rigid seats. A recent study by Hinz et al. [26] is the only exception, which measured the responses of subjects seated on cushion seats. A rigid seat permits convenient measurements of the human responses decoupled from the visco-elastic properties of the seat. This condition, however, is not at all representative of vehicle seats since an elastic seat cushion substantially alters the body-seat contact, sitting posture and the seated body weight distribution on the seat [11,56,57,83]. The reported biodynamic models, when applied for seating design and dynamic analyses, have thus met only limited success [14,17]. The measurement of biodynamic force at the elastic-human seat interface, however, is extremely challenging. Contouring of the seat surface would further contribute to complexity associated with measurements.

A few studies have employed thin and flexible pressure sensing grids to measure body contact area and force on elastic seats under static conditions [11,56,57,83]. These include the force-sensing resistance grids and foam-capacitor sensing mat [11,26,56,57,83]. These studies have effectively measured static body mass supported by the seat, body-seat interface pressure, contact area and ischium pressure, and effects of selected human anthropometric parameters, seat posture and seat geometry [11,56,57,83]. These have generally observed that interface pressure on an elastic cushion seat is more evenly distributed over a larger effective contact area compared to rigid seats where nearly 80% of the seated weight is distributed around the ischial tuberosities (IT) [57,83]. The peak pressure that occurs around the IT is significantly lower for a cushion seat compared with that measured on rigid seats. The mean pressure and the force at the human-seat interface, however, are dependent upon the seat height and the subject posture [11,56,57,83]. Heavier subjects tend to induce low ischium pressure due to increased effective contact area. Furthermore, seating on soft flexible seat causes relative motion across the legs and pelvic motion, which is absent when siting on a rigid seat [84].

Wu et al. [11] applied the capacitive seat pressure measurement system for measurement of body-seat contact properties in the presence of vertical vibration. Owing to hardware data acquisition limitations, the measurements were limited to discrete harmonic excitations up to 10 Hz. The study showed that the dynamic contact pressure at the seat could be significantly larger than the static pressure. The magnitudes of contact pressure and contact area were further dependent upon the seat elasticity and build of the subjects. Hinz et al. [26] applied the same measurement system to measure the total contact force at the human-seat interface under random vertical vibration in the 0.5 to 15 Hz band. The measured force was subsequently applied to obtain APMS responses of subject seated on cushion seats. Study employed 13 subjects seated on a rigid seat without a back support and cushion seat with inclined back support. The biodynamic force developed at the cushion seat was derived from pressure sensing mat placed on the cushion, while that for the rigid seat it was directly obtained from the force plate placed on the seat pan. The study also reported static body mass supported by the elastic seat, which was relatively low and ranged from 46 to 63% of the total body mass. Wu et al. [11] and Tarczay [81] reported static body mass supported by the seat in the 73 to 80% range, which were also acquired by the same measurement system. The magnitude of APMS, reported by Hinz et al. [26], was thus significantly lower in the entire frequency range compared to those reported for the rigid seats.

A cushion seat also alters the nature of vibration transmitted to the human-seat interface. The APMS or DPMI responses of human subjects seated on rigid seats have been generally measured under harmonic or white noise random vibration with nearly flat acceleration power spectral density. The measurements with a cushion seat thus impose an additional challenge in controlling the vibration at the human-seat interface. Hinz et al. [26] applied controlled vibration at the seat platform, while the levels of vibration encountered at the cushion seat was not controlled. The study employed three different levels of excitations with overall rms acceleration around 0.25, 0.8 and 1.6 m/s^2 for both the rigid and cushion seats. The vibration was controlled only at the platform, which resulted in considerably different vibration at the human-cushion interface. Owing to nonlinear dependence of the APMS on the magnitude and frequency of vibration [10,29,43], the measured APMS responses could not be compared with the available data for the rigid seats. The results of study concluded that the primary frequency of APMS of subjects seated on a cushion seats was comparable with that measured on the rigid seat. The frequency corresponding to the secondary peak, however, differed with difference up to 0.89 Hz.

1.2.7 Effect of vibration magnitude

Different work vehicles imposed widely different magnitude, direction and frequency of vibration of vehicle depending upon the type of vehicle, nature of task, terrain and operating conditions. The reported studies have been mostly concluded under single-axis vibration, either vertical or horizontal. Only a few recent studies have characterized biodynamic responses under three-axis vibration [23,85]. These studies suggest nearly negligible effects of multi-axis vibration, which may in-part be caused by uncorrelated nature of vibration used in laboratory experiments [85]. Mandapuram et al. [16] applied an alternate method of analysis of APMS under uncorrelated multi-axis vibration and showed notable contributions of response components attributed to cross-axis vibration. Furthermore, the vast majority of studies have considered either harmonic or white noise random vibration in frequency ranges up to 20 Hz. The magnitudes and frequency ranges of vibration used in different studies have been summarized in a recent article on synthesis of reported APMS responses to single-axis vibration [76].

The effect of vibration magnitude on APMS responses has been most widely studied [24,29,33,36,58,59]. These studies have invariably concluded upon nonlinear dependency of APMS responses on the magnitude of vibration. This nonlinear dependency has been attributed to many factors such as body support and postural condition, muscle thixotropy and time varying properties of muscles. All of the studies report a softening effect of the body with increasing vibration magnitude. The effect, however, diminishes when the magnitude of vibration becomes very large [51]. Increasing the vibration magnitude, however, yields only a small effect on the peak APMS and DPMI response magnitudes, while sitting upright without a back support [13,24,28,32,33,36,69,70,87]. A few studies have also shown an increase [25,88] or a decrease [54,58] in peak APMS and DPMI magnitudes with increasing vibration magnitude. It has also been suggested that sitting with a back support with hands on a steering wheel can eliminate the effect of increasing vibration magnitude on the peak APMS and DPMI magnitudes [33,69,70].

1.3 Scope and Objective of the Dissertation Research

From the review of literature, it is evident that the biodynamic responses of human subjects seated on a rigid seat and exposed to vertical vibration have been widely investigated. A rigid seat, however, is not representative of vehicle seating that invariably employs elastic cushion seats with or without a suspension. From the reported studies, it also became evident that characterization of APMS responses of subjects seated on cushion seats is vital for developing biodynamic models that can be effectively applied for seating design and dynamic analyses. It is thus important to develop methodologies for characterization of human body vibration biodynamic when seated on visco-elastic seats. Furthermore, only limited knowledge seems to exist on the effects of human anthropometry, while the reported studies contradict with regard to the gender effect.

The overall goal of this thesis research is formulated so as to seek the effects of selected anthropometric dimensions on the human body biodynamic responses to vertical vibration and a method for characterizing APMS responses of the body seated on a cushion seat. The specific objectives of the dissertation research are summarized below:

- Experimentally characterize apparent mass responses of human body seated on rigid seat considering a large subject population comprising male and female subjects of varying body mass and anthropometric dimensions so as to facilitate a study of effects of these factors on measured responses;
- Analyze the measured responses in an attempt to identify the influences of gender and various anthropometric factors on the APMS for different back supports and vibration magnitudes; and

- Explore a measurement system for characterizing the biodynamic force developed at the interface of the body and an elastic seat cushion, and its potential applicability for characterizing apparent mass responses of subjects seated on cushion seats and exposed to vertical vibration.

1.4 Organization of the Dissertation

This thesis research is organized in five chapters, where the initial chapter summarizes the highlights of the reported studies so as to formulate and justify the goals of this work. The subsequent chapter 2 presents detailed experiment design, and test and data analysis methodology for characterizing the apparent mass (APMS) responses of seated subjects under vertical vibration. Two different methods are presented for measurement of biodynamic force developed at the driving-point formed by the human buttocks and the seat pan. The first methodology employs a conventionally used force plate that can be applied for characterizing responses of body seated only on a rigid seat. An alternate flexible pressure sensing system is described for measurements of the force developed at the elastic human-seat interface. The chapter also describes the limitations of the measurement system and proposes a correction function to account for its poor resolution and limited acquisition rate.

Analyses of the data acquired with a rigid seat are presented in chapter 3. The effect of gender, and mass-, stature- and build-related anthropometric variables on the measured APMS responses are thoroughly evaluated and discussed. In chapter 4, the proposed correction function is applied to the data acquired with a cushion seat. The validity of the pressure sensing system and the proposed correction function is demonstrated by comparing the APMS responses of the subjects seated on a rigid seat obtained from the two measurement methods. The APMS responses of subjects seated on cushion seats are further obtained through applications of the proposed correction function. The results are discussed to highlight the contributions due to a cushion seat and the effects of selected anthropometric factors. The major conclusions of the study are finally summarized in chapter 5 together with a few suggestions on the further work.

CHAPTER 2
EXPERIMENTAL AND DATA ANALYSES METHODS

2.1 Introduction

Characterization of biodynamic properties of seated body under whole body vibration (WBV) is vital for identifying resonant frequencies of the biological system, deriving frequency-weightings for assessment of exposure risk and for developing biodynamic models for applications in seating design. Such properties, however, have been characterized for the human body seated on a rigid surface, as opposed to a viscos-elastic seating surface [28,33,43,53,59,67,70,89]. This is primarily due to lack of a measurement system for acquiring body-seat interface force on a flexible cushion. Considering that an elastic seat cushion substantially alters the body-seat contact, sitting posture and the seated body weight distribution on the seat [11,56,57,81], 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 thus extremely vital to seek alternate measurement systems for characterizing the biodynamic response of the body seated on an elastic seat and exposed to WBV. This would permit developments in identifying improved frequency-weightings for assessing exposure risks, anthropodynamic manikins for design and assessment of seats, and more realistic biodynamic models of the human derives for vehicle ride assessments and suspension designs. The measurement of biodynamic forces at the elastic body-seat interface, however, this involves numerous difficult challenges, particularly for contoured seat cushions.

Only, 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 [11,26,56,57,81]. 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 [11,56,57,81]. The body-seat pressure distribution in the presence of vertical vibration has been reported in a single study [57]. The study measured variation in the contact force and contact area under harmonic vibrations at frequencies up to 10 Hz. 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. The biodynamic properties of the body seated on an elastic seat cushion and exposed to vertical vibration have been characterized in a single recent study [26] where a capacitive pressure sensing seat mat, developed by Novel Electronics, was used to measure the body-seat cushion interface force under three different magnitudes of broad-band vibration and subsequently derived the apparent mass (APMS) characteristics of the seated body. The study 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.

A visco-elastic seat cushion also substantially alters the nature of vibration transmitted to the seated body [90]. Considering that APMS characteristics exhibit strong nonlinearities with vibration magnitude, it is vital to ensure similar vibration exposure, irrespective to the cushion properties. This may involve additional challenges in such studies. In this dissertation research, two micro-accelerometers were applied to the seat cushion in the vicinity of the seated body's ischial tuberosities to serve as the feedback sensors for the vibration control so as to achieve comparable vibration exposures for the rigid as well as elastic seats. A measurement system comprising a resistive pressure sensing mat is explored for measurements of interface force and thus the APMS responses of subjects seated on rigid and elastic seats. In this chapter the measurement system is described together with the experimental setup, measurement methods, and data acquisition and analysis methods for acquiring the APMS characteristic. The primary limitations of the measurement system were also identified through systematic analysis of the measured data.

2.2 Measurement System and Methods

A pressure sensing seat mat together with the signal processing, developed by Tekscan Inc., was used for measurement of 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. Each sensel is a tiny load cell, which applied force on it leads to resistance change of sensel. The total thickness of pressure sensing mat is 0.33 mm. Figure 2.1 illustrates a schematic of the measurement system. The sensing area of the mat is 487.7mm long and 426.7mm wide, while the pitch of the columns and rows is 10.2mm. The grid is comprised of 2016 sensels with density of 1 sensel/cm^2.

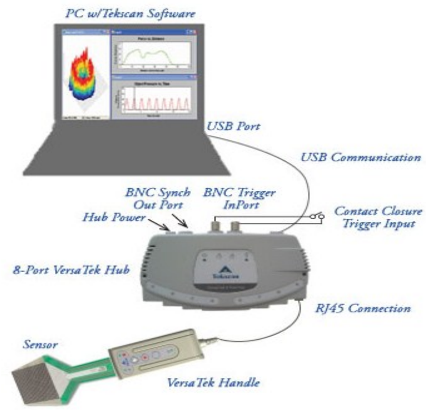


Figure 2.1: Schematic of the seat pressure sensing system, developed by Tekscan [91]

The sensing mats were selected for different ranges of pressures. It has been shown that the peak ischium pressure may vary from 25 to 202 kPa, while sitting on a rigid seat and from 2 to 45 kPa, on elastic seat [11,56,57]. Sensing mat with pressure range of 207 kPa was thus selected for application to rigid seats. A lower pressure rang (36 kPa) was also acquired for acquisition of interface force on soft cushions. Preliminary measurements revealed overloading of some sensels when applied to a very soft cushion. Consequently the higher pressure rang (207 kPa) mat was also used for soft cushions. 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 the variations in digital outputs of different sensels. When subject to uniform pressure loading, the I-Scan software establishes a scale factor for each sensel by normalizing the digital output of the same sensel by average output of the entire sensor. The smoothing process was repeated under multiple loads, as suggested by Tekscan [91]. The calibration process involved placement of sensing mat in the calibrator and application of constant pressures in the 0.08 to 2 bar range in fixed increments (0.08, 0.15, 0.20, 0.25, 0.50, 0.75, 1.00, 1.50 and 2 bar). The software permits 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:

$$P = ax^b \tag{2.1}$$

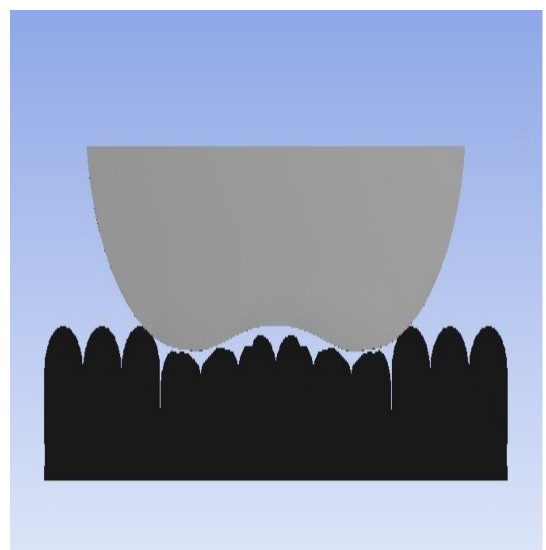
Where a and b are calibration constants, P is applied pressure and x is the raw output of each sensel. Two-point method, recommended by Tekscan, was subsequently used to define the power relationship. In this method, the calibration process involved measurements of raw digital output under only two pressures (0.08 and 1.5 bar), while each pressure was maintained for nearly 150s.

2.2.1 Measurement system verifications 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 revealed very good agreements between the applied load and the load estimated by the measurement system software through integration of the sensels 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 study. The standing body mass of the subjects is presented in Table 2.1, which ranged from 45.5 to 103 kg (mean mass = 72.1 kg). A rigid seat structure was designed so as to accommodate different cushions. Three different cushions were considered for the study. These included: (A) a flat cushion comprising a 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 (Figure 2.2 (a)). The stiffness properties of three cushions were measured in the laboratory in accordance with the method recommended in SAE J 1013 [92]. The measured data revealed static stiffness of 6.07, 4.13 and 4.24 kN/m of cushions A, B, and C, respectively. The results suggest that contoured cushion (B) is significantly softer than the flat PUF cushion (A), and air-bubble cushion (C) stiffness is nearly identical to that of contoured cushion, however, provided relatively flat sitting surface, although it could cause localized presence peak and valleys around each bubble, as seen in Figure 2.2 (b). The charging valve of the air cushion was carefully sealed so as to ensure the same charge pressure in all the subsequent tests.

(a)



(b)

Figure 2.2: (a) Schematic of air bubble cushion; (b) peaks and valleys around each bubble

Table 2.1: 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

Each cushion was placed on a rigid seat structure, shown in Figure 2.3 (a). The seat with the cushion was positioned on a weighing platform (Western Scale Co.; resolution 0.1 kg), as illustrated in Figure 2.3 (b). Each subject was advised to sit on the seat while his/her feet were supported on a footrest placed put side the weighing platform. The reading of the platform loaded with the seat and cushion prior to subject seating was set as zero. This setup permitted for measurement of body weight supported by the seat and the cushion. 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 vertical lower legs (knee angle 90^o) and thighs horizontal. The measurements were performed for each subject sitting with and without a vertical back support on rigid as well as cushioned seat, while each measurement was repeated three times. The study involved 24 measurements for each subject. The digital pressure mat signals for each subject-seat combination trial for a duration 60 s. The total forces on the seat together with the weighing platform readings were subsequently recorded. The repeated measurements of each combination revealed very good degree of repeatability. Furthermore, mean force measured by pressure mat agreed very well with the mean weighting platform readings, irrespective of the sitting posture (NB no back support, WB with back support) and the seat surface (rigid, and cushions A,B and C).

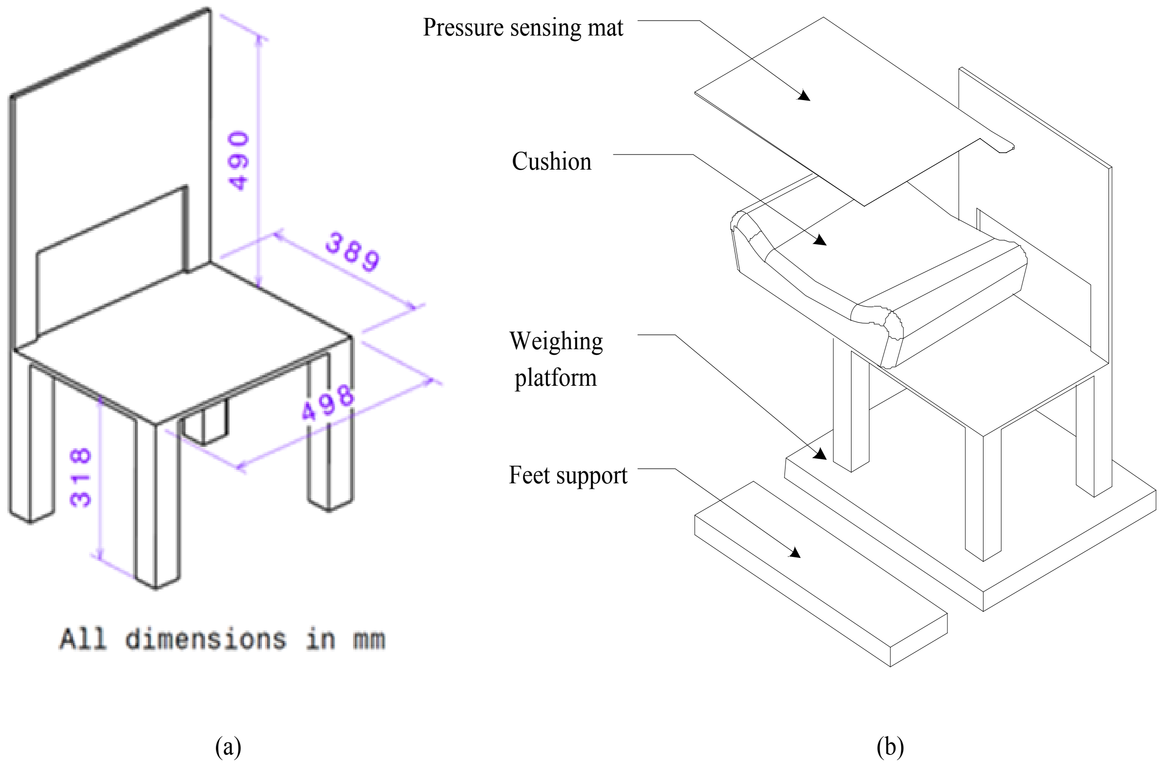
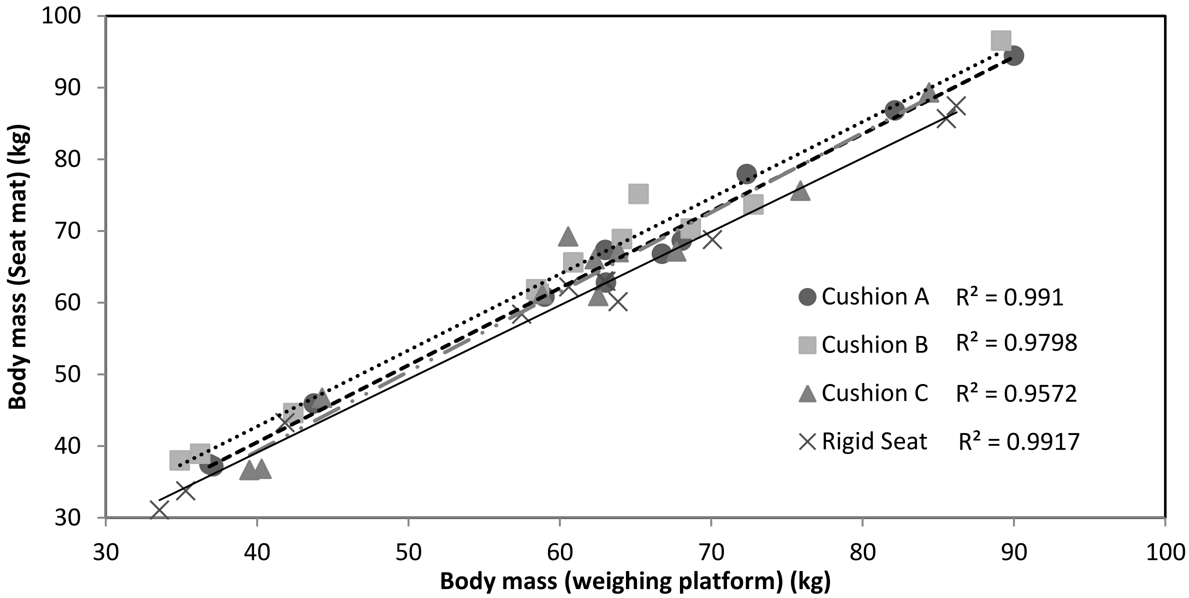
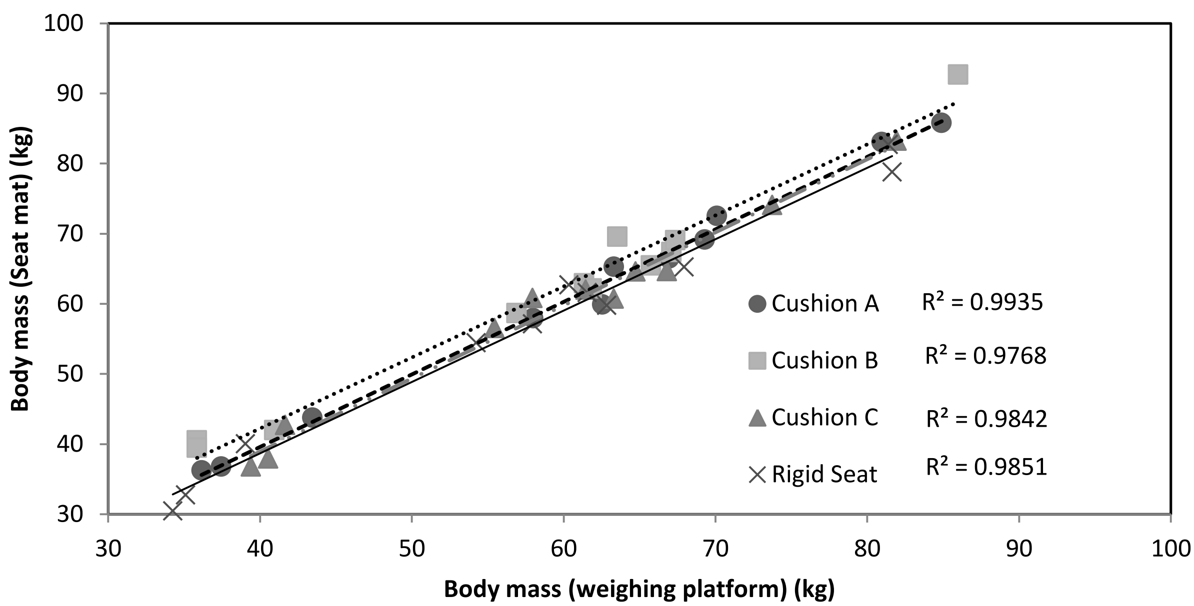


Figure 2.3: (a) Schematic of the rigid seat; and (b) rigid seat with a contoured seat cushion and the pressure mat

Figure 2.4 illustrates correlations between the pressure mat and weighting platform readings for the four seats and two backrests. The figures show the measured data together with linear regressions. 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 nearly perfect 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%. From the results in Figure 2.4, it is concluded that the seat pressure measurement system can accurately measure the static seated body mass for the range of cushions considered.



(a)



(b)

Figure 2.4: Correlations between the mean body mass measured by the seat mat and the weighting platform: (a) back not supported posture (NB); (b) back supported against a vertical back support (WB) (cushion A: flat PUF; cushion B: contoured PUF; and cushion C: air-bubble)

2.2.2 Dynamic measurements setup - rigid seat

The measurement system was subsequently applied for acquisition of body-seat interface force in the presence of vertical whole body vibration. For this purpose, the seat was installed on the whole body vibration simulator (WBVS) in the Concave laboratory. The WBVS consists of a platform supported on two servo-controlled hydraulic actuators that can produce vertical motion up to ±10cm. A steering column is also installed on the platform to create a driving-like sitting posture, as shown in Figures 2.5 and 2.6. In order to perform experiments in a safe manner, the actuators are equipped with various safety control loops, while the peak acceleration is limited to 2 m/s^2. Furthermore, emergency stop switches are provided to both the operator and the subject. Activation of any of these switches will cause the system to shut down in a ramp-down manner.

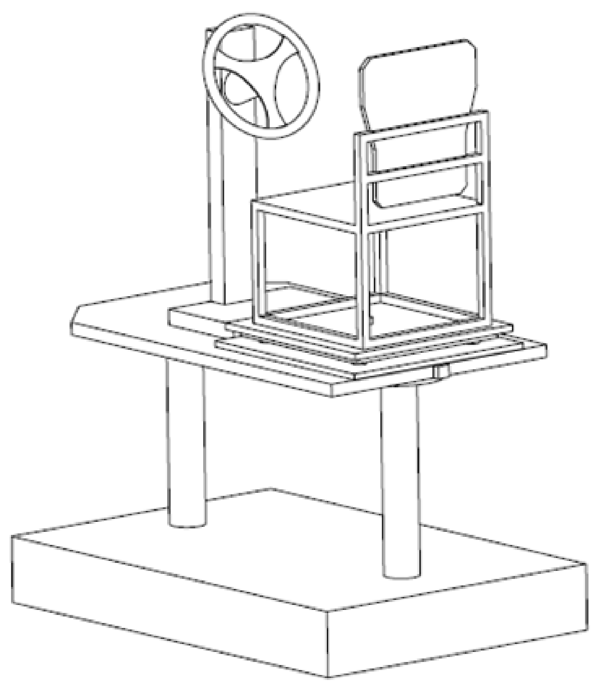


Figure 2.5: Schematic of the whole body vertical vibration simulator

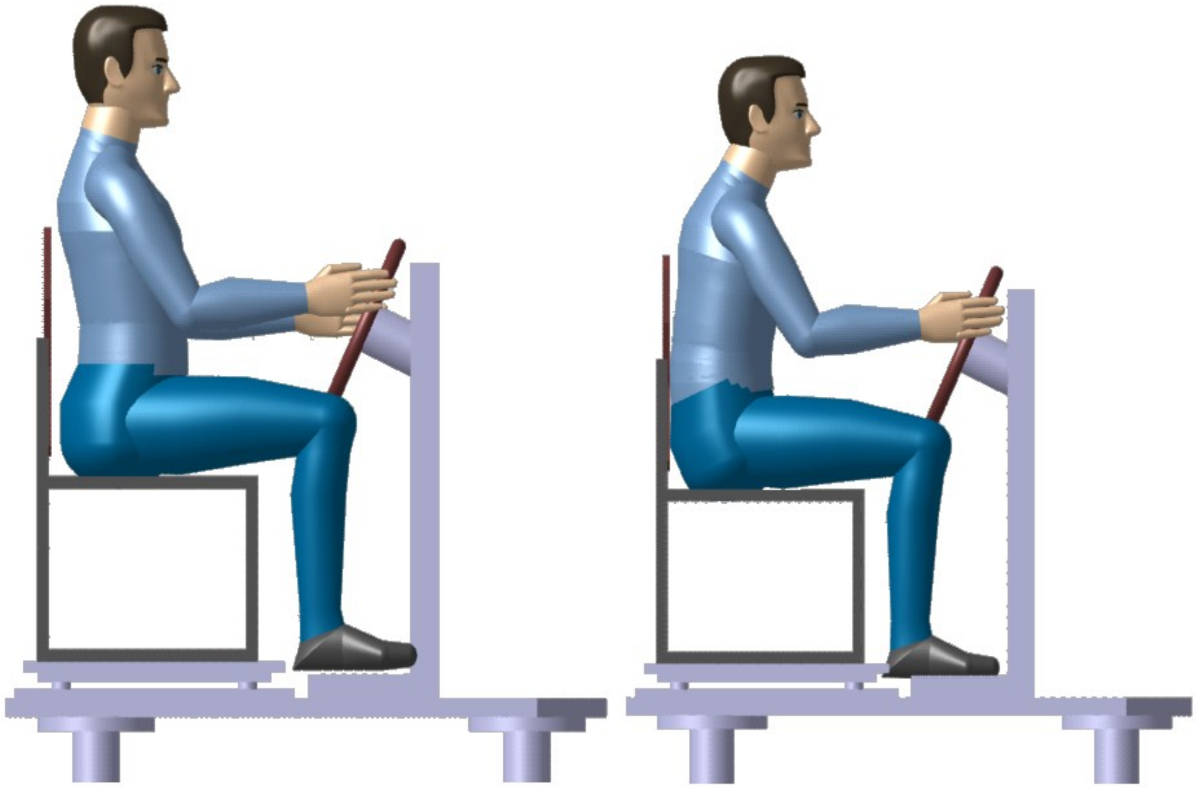


Figure 2.6: Schematics illustrating two sitting postures.

A rigid seat with vertical back support and 449 × 456 mm pan was installed on a single-axis 560 × 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 (Brurel & Kjær-4370) was installed on the force plate to measure the vertical acceleration at the seat base, while the total force developed by the seat structure and subject was measured using the force-plate. The seat pressure sensing mat was placed on the seat pan to measure the biodynamic force due to the seated body under vibration. The measurements were performed for each subject assuming two different sitting postures as illustrated in Figure 2.6.

The variations in the sitting posture were realized by different back support conditions: (i) seating with no back support (NB); and (ii) seating against a vertical back support (WB). In both cases the subjects were asked to place their hands on the steering wheel, as seen in Figure 2.6. The force-plate and the acceleration signals were acquired in a multi-channel vibration analysis system for deriving the apparent mass (APMS) responses. The computed APMS was inertia corrected to account for the seat and seat structure mass [33]. The resulting corrected APMS served as the reference for verification of biodynamic responses derived from the force measured by the Tekscan seat mat.

The seat acceleration signal also served as the feedback for the vibration controller (Vibration Research Co. 8500). The controller was programed 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, 0.5 and 0.75 m/s^2. Figure 2.7 illustrates PSD of the measured acceleration signals corresponding to the selected random excitations. It should be noted that the chosen vibration levels are relatively lower compared to those used in many reported studies, which have employed rms accelerations up to 2 m/s^2 [11,58,61,70,85]. This study, however, involved synthesis of chosen vibration magnitudes at the body-cushion interface, apart from the rigid seat. Owing to the 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 [93]

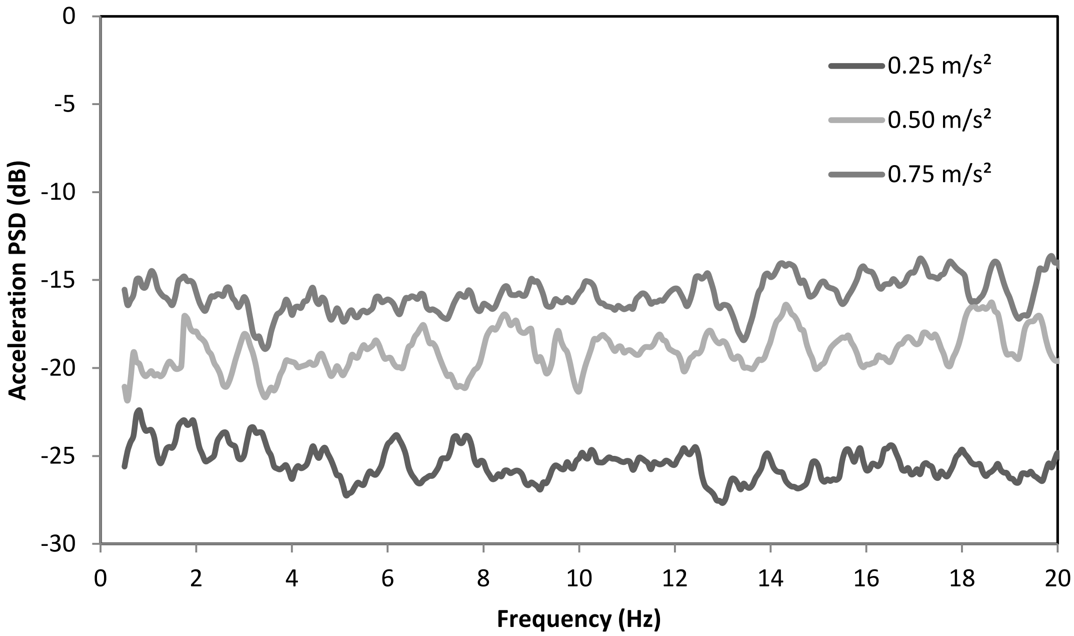


Figure 2.7: Acceleration power spectral density of the synthesized random vibration signals

The pressure sensing mat could also be placed either directly on the seat pan or on one of the selected cushion. While the force plate and acceleration signals were acquired in the multi-channel vibration analyzer (Pulse labshop), the measured seat mat force and seat base acceleration data were for subsequent acquiring using a National Instruments data acquisition analyses. Figure 2.8 schematically illustrates the measurement and data acquisition systems used in the experiments.

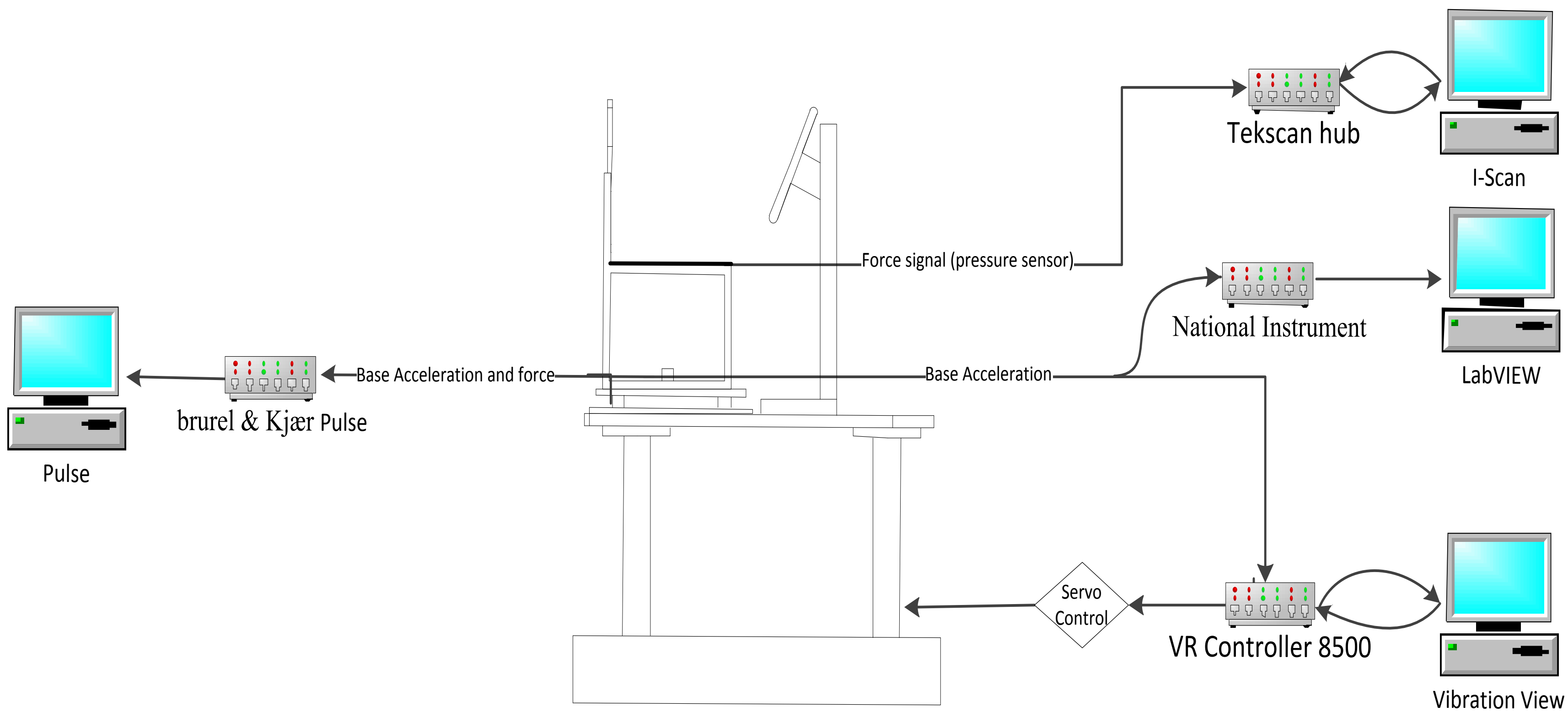


Figure 2.8: A schematic illustration of the WBVS with vibration controller and data acquisition system for the rigid seat study

2.2.3 Dynamic measurements setup - cushion seat

The rigid seat used in the previous setup was modified to accommodate the selected cushion (A). In particular, the height of the seat pan 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 cushion (A) could be placed on the rigid seat pan, as illustrated in Figure 2.9. In order to realize the same levels of vertical vibration, it was necessary to install the feedback accelerometer on the cushion. This poses a difficult challenge, since the accelerometer could not be installed on the flexible cushion surface. Consequently, two micro-accelerometers (ADXL 330, each weighing 2 g) were fixed on the cushion surface, as shown in Figure 2.4. Each accelerometer was 4×4 mm and 1.4 mm thick. These were installed around the ischial tuberosities of subjects to ensure adequate contact of the accelerometers with the seat.

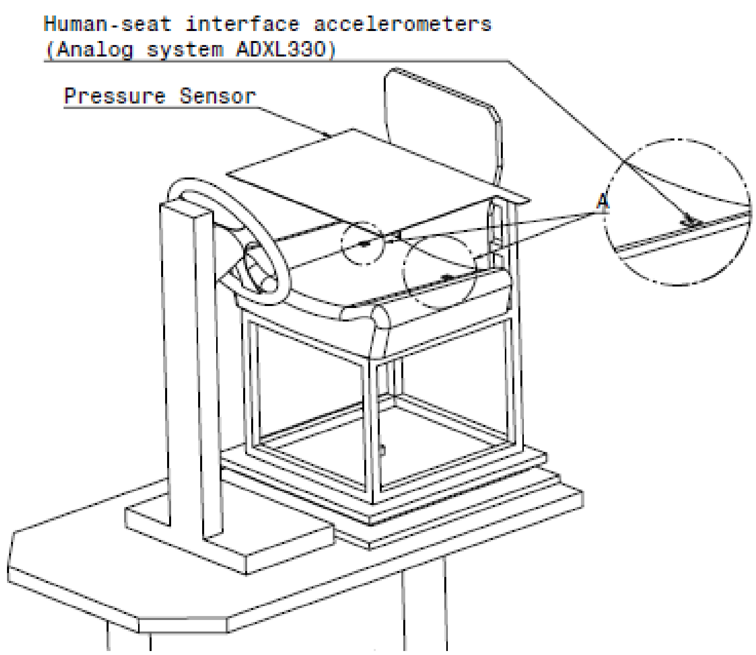


Figure 2.9: Mounting accelerometers and pressure sensor on the cushion seat

In order to verify the validity of the micro-accelerometers, a seat pad accelerometer, recommended in ISO 2631 and ISO 7096 [94,95] was also placed on the cushion, while an 81 kg subject was asked to sit on the cushion. The mean of the two micro-accelerometer signals was used as the feedback to the vibration controller to synthesize the derived vibration spectra. Figure 2.10 illustrates the measurement setup. The signals from both micro-accelerometers together with the seat pad and base accelerometers were acquired in the multi-channel vibration analyser. The transmissibility of the seat base to human-cushion interface derived for each from the accelerometers signals were computed using H1 function. The transmissibility of base acceleration to the three acceleration signals from the human-cushion interface was observed to be nearly identical (Figure 2.11). The measured responses show that the two micro-accelerometers yield nearly identical measurements. The micro-accelerometers were subsequently used to synthesize desired vibration spectra and to measure the human-seat interface acceleration, while the large size seat pad accelerometer was removed. The force sensing seat mat was placed on the cushion for measurement of human-seat interface force.

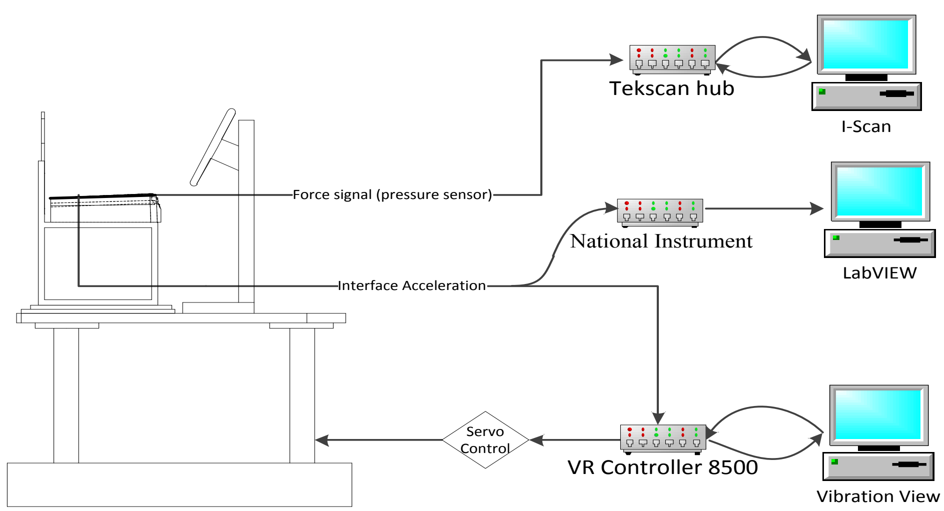


Figure 2.10 A schematic illustration of the WBVS with vibration controller and data acquisition system for cushion seats

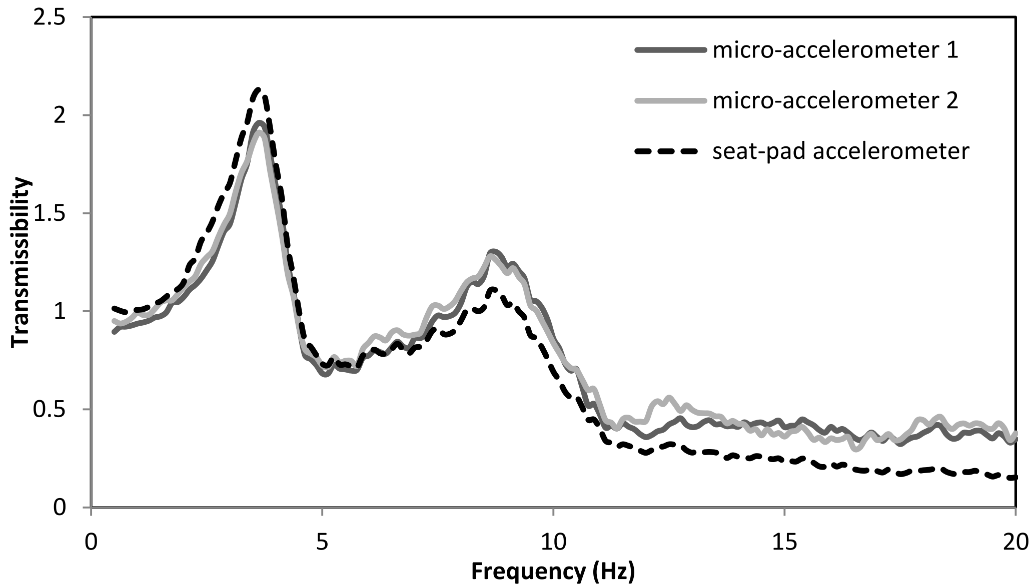


Figure 2.11: Comparisons of a seat transmissibility, derived from two micro-accelerometers and ISO-recommended seat- pat-accelerometer (81 kg subject exposed to base excitation of 0.5 m/s^2 rms)

Owing to nonlinear dependence of the seat cushion vibration isolation properties on the seated body mass, the vibration signals were synthesized for 3 different subjects with body mass of 55, 81 and 90 kg. The nature of 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 the cushion. This involved the generation of a total of 27 drive files for realizing acceleration spectra with 0.25, 0.5 and 0.75 m/s^2 rms acceleration for each of the 3 subjects. For this purpose each subject was advised to sit on a selected seat cushion assuming postures as in the case of rigid seat (NB and WB), while holding the steering wheel. The WBVS and vibration controller were subsequently operated to achieve desired vibration spectra and the corresponding drive files. As an example, Figure 2.12 illustrates the spectra of vibration generated at the platform and the human–seat interface for the cushion and an 81 kg subject.

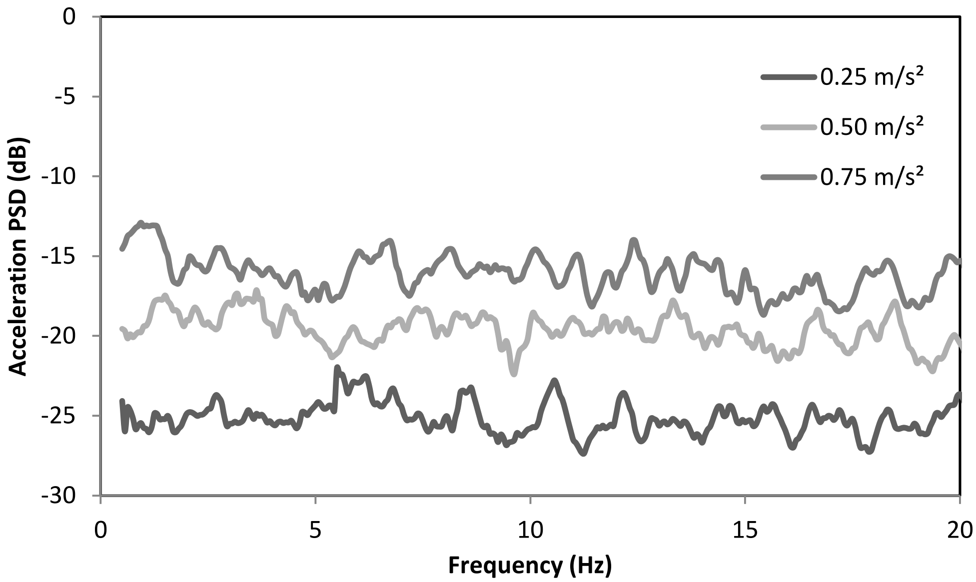


Figure 2.12: Acceleration power spectral density of the synthesized random vibration signals for cushion seat

The seat mat force and micro-accelerometer signals were acquired for each subject-cushion vibration level combination in the multi-channel National Instruments data acquisition system. Each trial was repeated three times. The measured signals were later analysed to derive the APMS of the seated human subject.

2.3 Subjects

A total of 31 male and 27 female healthy adult subjects were recruited for the study. 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 prior back injury. Prior to the experiments, each subject was informed about the purpose of the study and safety controls of the WBVS through both verbal and written instruction. Each subject was asked to approve the protocol that had been approved by the Human Research Ethics committee of Concordia University.

The selected anthropometric body dimensions of the subjects were also measured, which included body mass, stature, sitting height, hip circumference, etc. There are summarized in Table 2.2. The table presents the mean, standard deviation, minimum and maximum values of the measured parameters for male and female subjects. 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 2.2: 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 (cm)	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^2)	103.6	7.4	116.0	88.0	99.9	5.5	109.0	89.5
Body contact area on seat pan (cm^2)	575	195	1050	211	515	175	890	250

The participants were grouped in two different categories in order to study the effects of gender and the body mass on the measured apparent mass. For the study of body mass dependency on the biodynamic responses the subjects were grouped in three different body mass ranges for each gender group. 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. Each subgroup included 9 subjects. The mean and range of body mass as summarized in Table 2.3.

Table 2.3: The 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	50.35	54.2	3.3
	60 kg	9	56.4	60.96	65	2.8
	72 kg	9	66	69.11	72.5	2.7
Male	60 kg	9	55	60.9	66	4.3
	80 kg	9	75	81.58	76	4.1
	96 kg	9	90	96.67	106	6.4

Owing to the coupled effects of the body mass and the gender, further attempts were made to identify the 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 2.4.

Table 2.4: Grouping of male and female subjects with comparable body mass.

Gender	Group	Number of subjects	Mass(kg)	
			Mean	SD
Female	G1	7	61.0	2.6
	G2	7	69.6	2.7
Male	G1	7	60.4	4.2
	G2	7	70.3	3.7

2.4 Data Acquisition and Analysis

Three different data acquisition systems were employed for acquiring the biodynamic responses of the human subjects seated on cushion and rigid seat. A multi-channel (Brurel & Kjaer Pulse v. 15) system was used to measure the acceleration and force signals at the base seat. The data in this case was acquired and analyzed considering a bandwidth of 50 Hz. The Tekscan system were used to measure and record force signals at the human-seat interface (Pressure sensing mat) for both rigid and cushion seats using a sampling frequency of 128 Hz for duration of 60s. The recorded force signals were exported to a multi-channel National Instrument data acquisition system, while LabVIEW 2009 was used to record the acceleration signals (seat base for rigid seat and body-seat interface for cushion seats). The recorded force mat and acclamation signals were then analyzed using the LabVIEW 2009 software.

2.4.1 Data analysis

The biodynamic responses of the subjects seated on the rigid seat were characterized on the basis of two different measurement systems. The first approach involved determination of APMS from the force plate and the seat base acceleration signals. The complex APMS of the subjects was computed using the H1 function available in the Pulse LabShop, such that [46]:

$$\bar{M}_b(j\omega) = S_{F_b\ddot{z}_b}(j\omega)/S_{\ddot{z}_b}(j\omega) \tag{2.1}$$

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

The APMS in Eq. (2.2) relates the total force due to subject and the seat structure and seat acceleration. The APMS of the subject alone could be derived upon subtracting the APMS of the seat structure alone. The APMS of the seat alone (without a human subject) was thus measured for each vibration condition, and applied as a correction to Eq. (2.2), in the following manner [33,70]:

$$M_b(j\omega) = \bar{M}_b(j\omega) - M_0(j\omega) \tag{2.2}$$

Where $M_0(j\omega)$ is the measured APMS of the seat alone, which is generally a constant value equal to the seat mass. Figure 2.13 illustrates magnitude of the measured APMS of the seat alone under different vibration levels. The results show a nearly constant value up to 10 Hz and a slight increase thereafter. $M_b(j\omega)$ is represent the complex APMS of the seated subject, derived from the force and acceleration measured at the seat base.

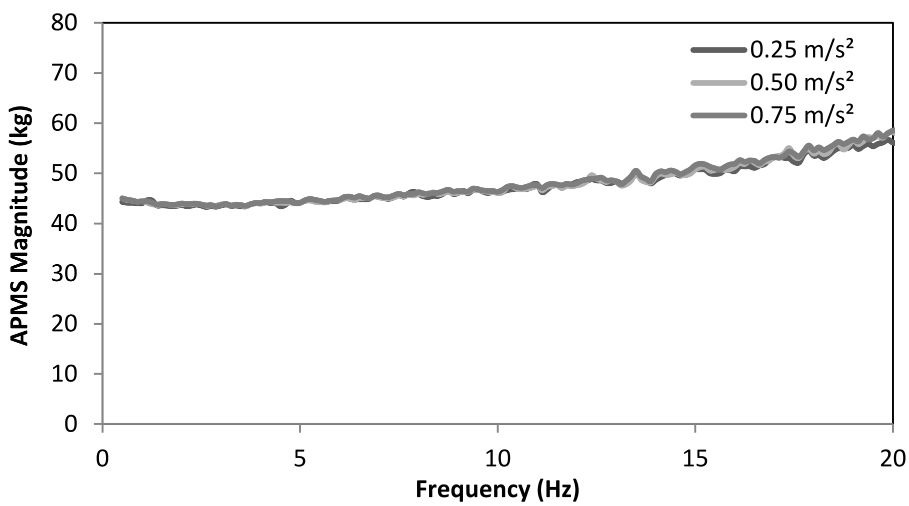


Figure 2.13: The measured apparent mass of the rigid seat and its supporting structure

The measured data were acquired with a sampling frequency of 128 Hz for a duration of 60 s. The cross- and auto-spectra were computed over a bandwidth of 50Hz using 12 averages, Hanning window and 75% data overlap. The coherency of the force and acceleration signals was constantly monitored, and a trail was rejected when coherence was below 0.9. The complex

APMS data were exported to an Excel spread sheet for furthers analysis on the contributory factors.

In the second approach, the APMS was determined from the pressure sensing mat force and the acceleration signals using the Lab VIEW 2009 package. The measured pressure distribution was initially analysed in the I-Scan software. The pressure signals over the contact area were used to derive the total body force through integration of the pressure distributed over the contact area. The resulting time history of the force was subsequently acquired in the Lab VIEW 2009. The data were sampled at 128 Hz, and the analysis software was configured to perform FFT analyses using Hanning windows, 75% overlap and 12 averages, as in the first approach. The coherency of the force and acceleration signals was also monitored. Owing to a possible time lag between the force and acceleration, the APMS were computed using the H1 and H2 frequency response functions, such that:

$$M_1(j\omega) = S_{F_p\ddot{z}_b}(j\omega)/S_{\ddot{z}_b}(j\omega) \tag{2.3}$$

$$M_2(j\omega) = S_{F_p}(j\omega)/S_{\ddot{z}_b}(j\omega) \tag{2.4}$$

Where $M_1(j\omega)$ and $M_2(j\omega)$ are the APMS computed using H1 and H2 functions, respectively. $S_{F_p}(j\omega)$ and $S_{\ddot{z}_b}(j\omega)$ are the auto-spectral densities of the force measured at the seat pan and seat base acceleration, respectively, and $S_{F_p\ddot{z}_b}(j\omega)$ is the spectral density of F_p and $\ddot{z}_b$.

Both the functions revealed comparable APMS magnitudes, while the H2 function does not yield the phase information. H1 function was retained to compute 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. The APMS responses of the subject seated on the cushion seat was determined in a same manner of second approach, while the acceleration at the human-cushion interface $\ddot{z}_i$ was substituted with acceleration at the base $\ddot{z}_b$.

2.4.2 Verification of the measurement system

Considering the lack of data available for cushioned seats, the validity of the pressure mat measurement system was examined for rigid seat alone. For this purpose, the APMS responses measured using the force plate and pressure sensing mat were compared. The seat was initially loaded with different rigid loads, ranging from 10 to 64 kg and force signals from the force plate and the pressure sensing 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 contributions of the seat structure mass, as described in Eq. (2.4). The resulting corrected APMS magnitude was compared with that derived from the pressure sensing force signal to examine its validity. The comparisons revealed large differences between the two in the entire frequency range, irrespective of the seat load and the excitation level. The differences, however, were somewhat comparable for all seat mass and excitation levels. As an example, Figure 2.14 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 0.5 m/s^2 rms acceleration excitation.

The results obtained from the force plate show APMS magnitude of nearly 44 kg at very low frequency, which is identical to the seat load mass. The APMS magnitudes, however, tends to increase with increasing frequency and is substantially high at frequency above 10 Hz, this was attributed to hopping of the unrestrained rigid load on the seat. The APMS magnitude, derived from the seat mat, also exhibits similar trends. Although, the APMS magnitude at low frequencies is comparable with that derived from the force plate, the magnitude at frequency above 3 Hz is considerably lower compared to the APMS magnitude derived from the force plate. The results thus suggest that pressure sensing mat and measurement system would yield considerable error in the biodynamic responses measured with human subjects.

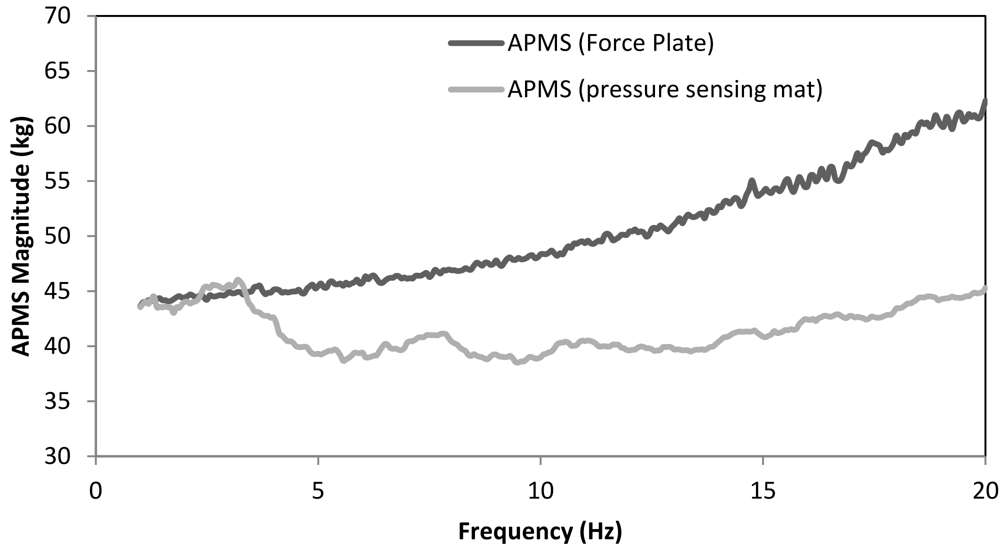


Figure 2.14: Comparisons of the APMS magnitude responses of 44 kg rigid load derived from the force plate and the pressure sensing mat

Similar degree of error was also observed with the measurements obtained with human subjects. As an example, Figure 2.15 compares APMS magnitude responses obtained for an 83 kg subject using both the measurement systems, while subject to 0.5 m/s^2 excitation. The results are presented for subject sitting without a back support. The results show considerable differences between the APMS magnitude responses acquired using the force plate and the pressure sensing pressure sensing mat over the entire frequency rang. Similar trends were observed with all the subject and vibration conditions, where the APMS magnitude measured from the pressure sensing mat is considerably lower than that measured from the force plate.

The observed differences in the measurements from the pressure sensing mat are attributed to two primary factors: (i) limited acquisition rate of the measurement hardware; and (ii) the relatively poor resolution of the pressure sensels.

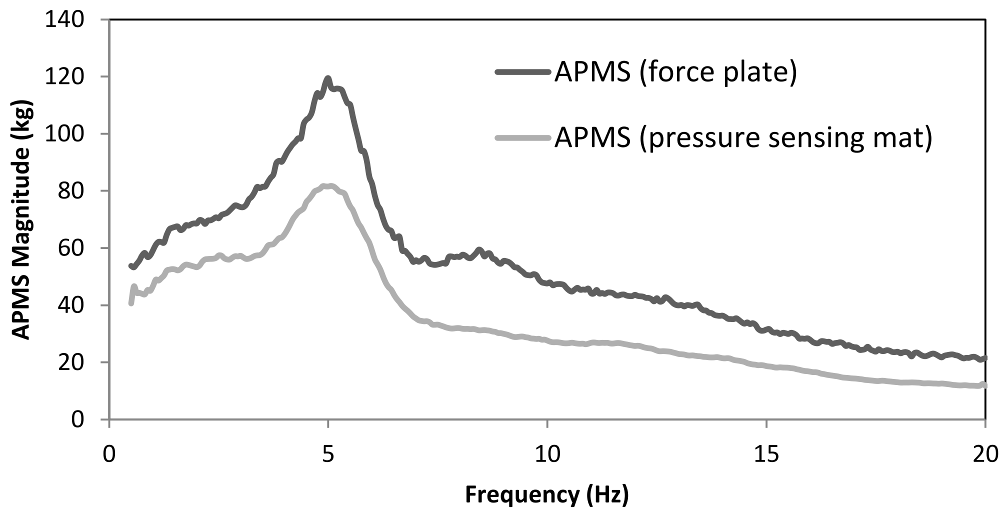


Figure 2.15: Comparisons of the APMS magnitude responses of 83kg subject derived from the force plate and the pressure sensing mat.

Figure 2.16 illustrates the ratio of APMS magnitude of the 44 kg load measured from the force plate to that from the pressure sensing mat. The ratio increases nearly linearly with the frequency this suggests a poor acquisition rate of the pressure measurement system for acquiring dynamic force. The experiments were subsequently repeated using different sampling frequencies of 64 and 256 Hz. The APMS response, derived from the pressure sensing mat, however, was observed to be identical, irrespective of sampling rate. It was thus concluded that the hardware was designed with limited acquisition rate, which could acquire a dynamic force accurately only up to 3 Hz. The magnitude ratio was thus considered as a correction function, as a function of the excitation frequency, to compensate for the limited acquisition rate. The corrected APMS magnitude was calculated from:

$$|M_s(j\omega)| = CF\left|\frac{S_{\ddot{Z}_bF_p}(j\omega)}{S_{\ddot{Z}_b}(j\omega)}\right| \tag{2.5}$$

Where $CF = a_1 f + a_2$ is the correction function, a_1 and a_2 are constant coefficients, f is frequency in terms of Hz and M_s is the APMS measure at the human-seat interface using the pressure sensing mat.

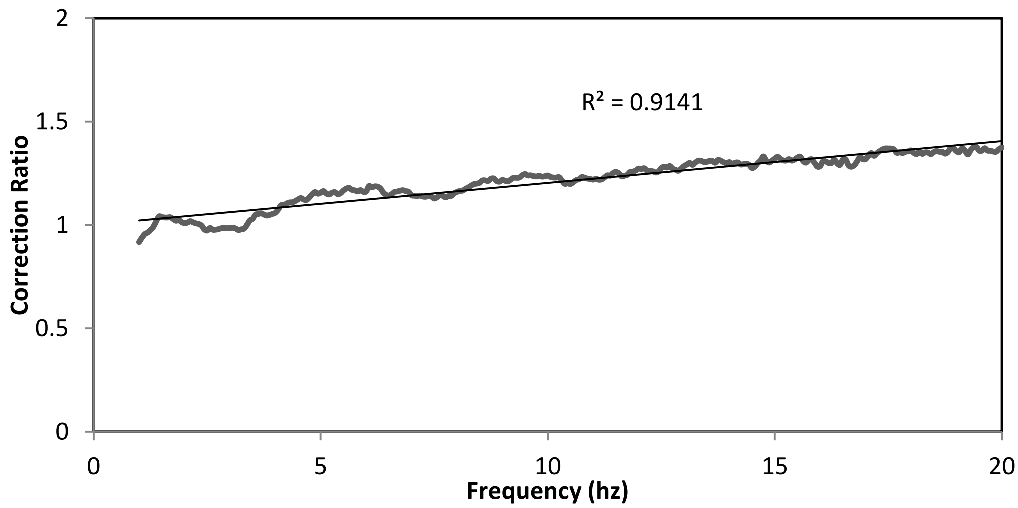


Figure 2.16: Ratio of magnitudes of APMS measured from the force plate to that from the pressure sensing mat (seat load: 44 kg).

Figure 2.17 illustrates the ratio of the APMS magnitude of the seated human subject (body mass= 83 kg) measured using the force plate to that using the pressure sensing mat. The results were obtained under 0.5 m/s^2 excitation and NB sitting posture. The results again show a nearly linear increase in the magnitude ratio with the frequency, as observed for the rigid seat load. This again is attributed to the limited acquisition rate of the measurement system. The response also exhibits a magnitude ratio in the order of 1.3 at low frequency of 0.5 Hz, which was observed to be 1 in case of rigid load. This discrepancy is attributed to poor resolution of the sensels.

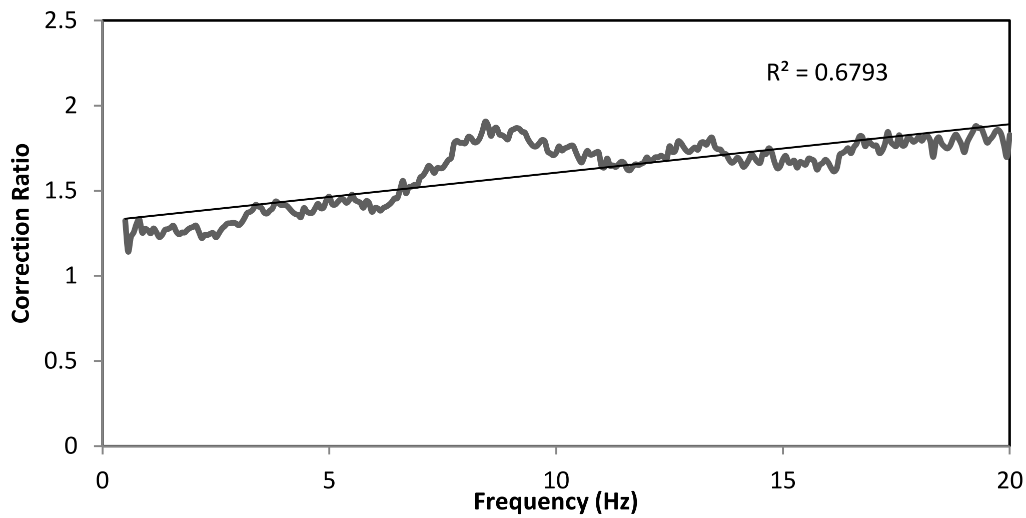
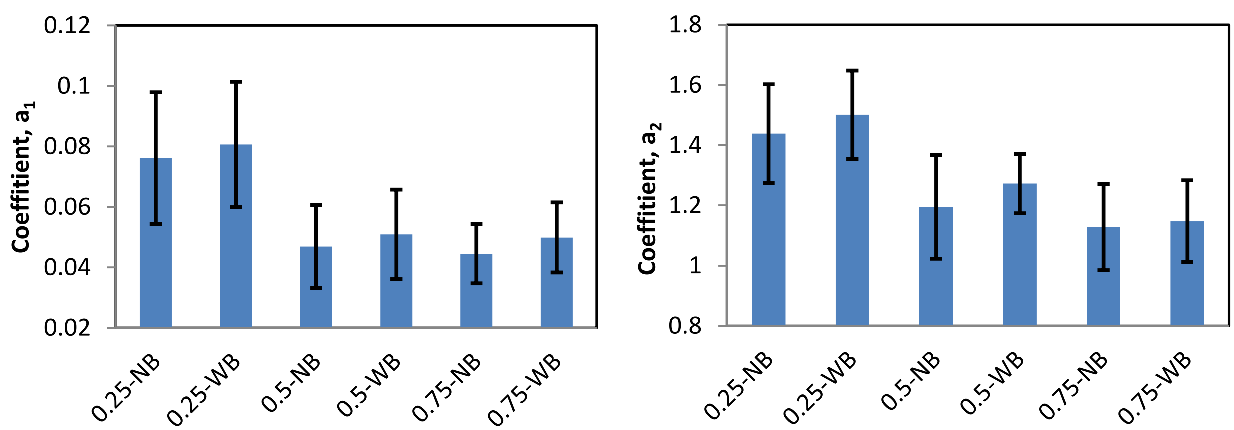


Figure 2.17: Ratio of magnitudes of APMS measured from the force plate to that from the pressure sensing mat (seat load: 83 kg human subject)

The resolution of the sensel was considered as a critical factor since study used a relatively high pressure range mat (207 kPa). The resolution of the sensel was specified as 0.83 kPa. While the localized pressure values for human subject may occur around or below this value, the pressure values under the concentrated rigid load were well above the sensel resolution.

The seated body yields pressure concentrations near the ischial tuberosities and near the thighs when supported on the seat. The pressure values around the extremities of the contact region, however, are very small. These pressure values 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 limited rate of acquisition but also for the poor resolution. Furthermore, the pressure values would depend upon the seated body mass, vibration level and the buttock contact. The correction functions (CF) were thus derived for each subject and vibration level condition, which could be applied to obtain the APMS responses more accurately.

The CF derived for all the subjects and excitation conditions revealed very similar trends. While the frequency dependence (coefficient a_1) was quite comparable for all the subjects and excitation conditions, the low frequency offset (coefficient a_2), mostly attributed to resolution, varied with the subject mass and the excitation level. The effect of vibration magnitude on a_2 was relatively small under 0.5 and 0.75 m/s^2 rms excitations but the difference in a_2 was considerably large for 0.25 m/s^2 rms excitation, which was attributed to relatively poor resolution of the acquisition system. Figure 2.18 illustrates mean and standard deviation of the coefficients a_1 and a_2 derived from data acquired with all subjects, and excitation and back support combinations. The results suggest relatively smaller differences in the coefficient values under 0.5 and 0.75 m/s^2 excitations, but the difference is larger when compared with those derived under 0.25 m/s^2 excitation. The variations in the coefficients with respect to back support are observed to be small. Consequently, different correction functions were derived corresponds to 0.25 and 0.5 m/s^2 excitations for each individual subject, which were considered applicable for both back support conditions. It is further hypothesized that same correction functions would be equally applicable for measurements on elastic seat



(a) (b)

Figure 2.18: Mean and standard deviation of (a) a_1; and (b) a_2 coefficients under each posture and excitation magnitude.

2.5 Summary

This chapter presents the methodology and experimental setup for acquisition of biodynamic responses of human subjects seated on either rigid or elastic cushion seats. A seat pressure measurement system is described for acquisition of biodynamic force at the human-cushion interface. The validity of the measurement system is demonstrated for measurement of static body mass supported by the seat cushion. The method of measurement of APMS of subject sitting on a rigid seat pan using conventional force plate is described together the inertial correction to account for contribution of the seat structure mass. A total of 58 subjects, including 31 male and 27 female adults, were recruited for measurement of APMS responses. The anthropometric dimensions of each subject were recorded in order to study the dependence of APMS on these parameters.

The seat pressure measurement system was also applied to measure the APMS responses of subjects seated on the rigid or cushion seat, the biodynamic force, obtained through interaction of interface pressure, was used to derive the APMS response of subjects in the LabVIEW software. For this purpose, the vibration controller was programed to produce identical vibration levels (0.25, 0.50 and 0.75 m/s^2 rms acceleration) at cushion surface. Two micro-accelerometers, positioned on the cushion surface, served as the feedback for controller. The data analysis methods were described and major limitations of the seat pressure measurement system were identified. Those included the poor acquisition rate of the measurement system hardware and poor resolution of the pressure sensels. It was concluded that the measurement system could provide accurate measurement of biodynamic force only up to 3 Hz, while the poor resolution contributed to considerable errors. Correction functions were subsequently derived to compensate for the poor resolution and acquisition rate. The correction function, derived for each individual subject are subsequently applied to obtain the APMS responses of the subject seated on rigid as well as cushion seat, which are discussed in chapter 4. The validity of the correction function was also demonstrated.

CHAPTER 3
EFFECTS OF ANTHROPOMETRIC FACTORS ON APPARENT MASS RESPONSES

3.1 Introduction

Biodynamic responses of the seated body exposed to whole-body vibration refer to the biomechanical responses to impressed oscillatory forces or motions. Such responses form an essential basis for understanding of the mechanical-equivalent properties of the body and the potential injury mechanism, developments in frequency-weightings and enhanced design tools of the system coupled with the human anthropometry gender, sitting posture and the vibration condition in a highly complex manner [28,33,36-39,70,85]. Furthermore, a flexible seating support such as a seat cushion greatly alters the body seat interface forces and sitting posture, and thus the biodynamic responses. While only little knowledge exist on the effects of visco-elastic cushions on the biodynamic responses of the seated body, the biodynamic response to vibration while sitting on a hard seat have been extensively reported [28,33,43,53,59,67,70,89]. The reported data invariably show strong and highly complex and nonlinear effect of majority of the contributory factors, such as body mass, seating supports and magnitude of vibrations.

Since the reported studies have been conducted under widely varying sitting and vibration conditions, these often conclude on conflicting effect of some of the factor. For instance, some studies [27-29] reported insignificant gender effect on the biodynamic response of seated subjects under vertical vibration, while others suggest otherwise [30,32,33,54,55,76]. Lundström et al. [30] showed considerable differences in APMS responses of male and female subjects and proposed that different injury criteria should be used for the two genders. International standard, ISO 5982 [77] Identified the range of idealized values of the APMS for body masses in the 49 to 93 kg, and it provides 55, 75 and 90 kg as reference values for three body masses, which are derived from the mechanical-equivalent biodynamic model proposed by Boileau et al. [10]. But these body masses are male representative.

Males and females human bodies are different in structure and their dimensions. Normally females have lower stature, sitting height and body mass as compared to males. Furthermore, the muscle mass and muscle mass to body mass ratio is lower for females, while the fat mass to body mass ratio is greater when compared those of the male population [74]. The different biodynamic responses of male and female subjects may thus be expected to differ. Most of the studies, involving the gender effect on biodynamic response, have invariably recruited the male and female subjects of different body masses. Consequently the result may have shown strong dependence of the body mass than the gender effect.

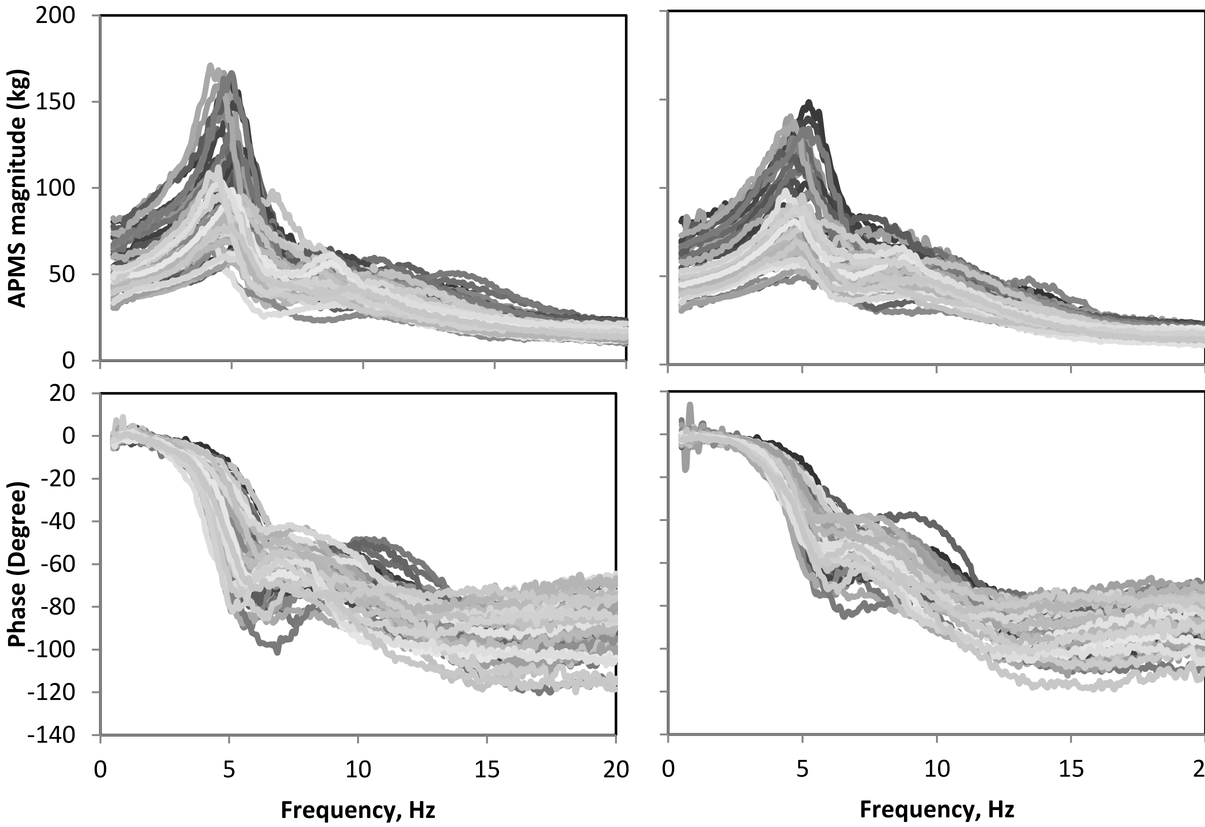
Many studies have also shown that the seated body when exposed to whole body vibration can be approximated by rigid masses representing head, thorax, pelvis, etc. coupled through elastic and dissipative elements representing various ligaments, muscles and intervertebral discs. Therefore, the biodynamic response would be expected to depend upon anthropometric factors like sitting height, body mass, body fat, lean body mass, stature, body mass index (BMI), body circumference, etc. Among these, the body mass effect has been mostly stressed in the reported studies, while the effects of other anthropometric variables have not been adherently explained. Many studies have shown that the biodynamic response of the seated body is influenced largely by important anthropometric parameters. The reported studies have mostly explained the effect of body mass, which affects the responses substantially at low frequencies [24,29,33,68,70]. These studies suggest that a higher body mass yields higher peak magnitude response and lower corresponding frequency. Owing to the substantial body mass effect, the measured apparent mass (APMS) is frequently normalized with respect to the static sitting mass or APMS magnitude at a low frequency (0.5 Hz) [28,53]. However, some studies have shown that the normalization could not eliminate the effect of body mass on the APMS response [33,70].

Wang et al. [33] investigated the gender effect by grouping the responses of male and female subjects of comparable body masses so as to eliminate the body mass effect. The study involving 5 male and 5 female subjects illustrate the differences in responses at higher frequencies. Donati and Bonthoux [72] investigated the correlations between the biodynamic measures such as DPMI, absorbed power and vibration transmissibility with various anthropometric factors like body mass, body mass on seat pan, stature, trunk height, trunk to head height, and chest circumference. In a similar manner, Wang et al. [45] studied the effect of percentage body fat, stature and BMI on the measured absorbed power. Toward and Griffin [52] measured APMS responses with respect to age, stature and BMI. However, the gender effects have not been conducted thoroughly considering the coupled effects of various anthropometric parameters such as fat body mass, lean body mass, hip circumference, body contact area on seat pan and sitting height. It is thus desirable to investigate the gender effect on the APMS of seated body exposed to vertical vibration in addition to the important anthropometric parameter.

In this chapter the APMS responses of 31 male and 27 female subjects seated on a rigid seat under two postural conditions involving no back support and a vertical back support, and exposed three different levels of random vibration (0.25, 0.50 and 0.75 m/s^2 rms), are systematically analyzed to examine the gender effect and the effects of selected anthropometric factors. The results are limited to the rigid seat sitting alone, while the analyses are presented for two sitting postures and three vibration conditions.

3.2 APMS Response Characteristics

The measured APMS responses of the subjects are initially compared to assess the degree of inter-subject variability in a qualitative sense. As an example, Figure 3.1 illustrates variations in the APMS magnitude and phase responses of all the subjects exposed to 0.50 m/s^2 rms acceleration excitation. The results are presented for the two seating conditions i.e. without and with a back support. The results show large differences in both the magnitude and phase responses, while the predominant magnitude peaks occur within narrow frequency bands. The responses obtained for no back support posture exhibit peak APMS magnitude in 4.1 to 6.6 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. The measured data show considerable scatter, irrespective to 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 no back support posture, the coefficient of variation (CoV) ranged from 25% to 34% within this frequency range. Within same range of frequencies, the results for the vertical back support posture revealed slightly lower CoV in the 23% to 30% range. However, an opposite trend was observed in the corresponding scatter in the phase responses. Lower frequencies may thus be reduced by normalization of the APMS magnitude with respect to the static sitting mass.



(a) (b)

Figure 3.1: Apparent mass magnitude and phase responses of 58 subjects with (a) no back support and; (b) a vertical back support (excitation: 0.50 m/s^2)

Figure 3.2 illustrates the normalized APMS magnitude responses of 58 subjects for the two sitting conditions and 0.5 m/s^2 excitation. Although the normalized responses exhibit considerably lower scatter at lower frequencies, the scatter at higher frequencies tends to increase. The peak values of CoV of the normalized data were obtained near 29% for the no back support posture and 22% for the back support posture. The results suggest that the scatter in the data cannot be eliminated through normalization with respect to the body mass alone.

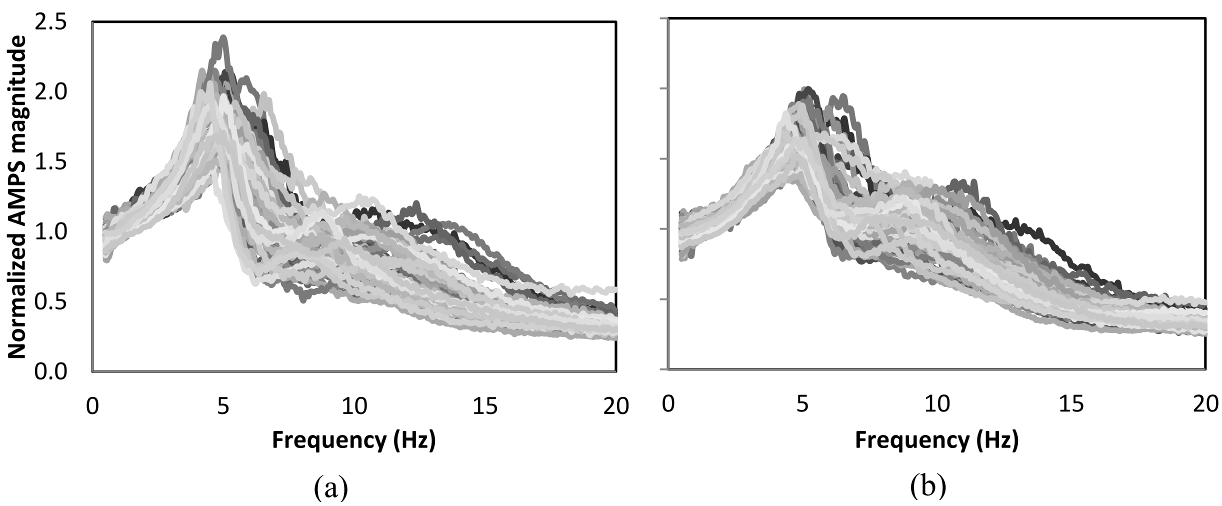


Figure 3.2: Normalized apparent mass magnitude responses of 58 subjects sitting with (a) no back support; and (b) a vertical back support (excitation: 0.50 m/s^2)

3.3 Effect of Gender on the APMS Responses

It has been widely suggested that the scatter in the magnitude response is mostly attributed to variation in the body mass of the subjects considered. In order to study the gender effect, the measured magnitude and phase responses were grouped for the 33 male and 27 female subjects. The mean responses of the two groups were subsequently derived and compared to identify the gender effects. Figures 3.3 to 3.5 illustrate comparison of measured APMS magnitude and phase responses for the three vibration exposures, and two sitting conditions. The results show that the APMS response magnitudes of male subjects are higher than those of the female subjects in the entire frequency range. Near the secondary mode of vibration, the responses of the female subjects are more prominent as compared to the male subjects, for all the vibration conditions and sitting postures considered. It should be noted that the second peak is less clear due to data averaging. The mean phase responses of the two genders, however, appear to be comparable except in 5.5 to 10.3 Hz frequency range for the vertical back support posture and in the 5.5 to 9.5 Hz rang with no back support.

The differences in the magnitude responses of the two genders could also be attributed to their respective mean mass. The mean mass of the male and female participants of the study were 79.8 and 60.1 kg, respectively. The means of normalized magnitude responses of the two groups were subsequently obtained, which are presented in Figure 3.6. 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 Figures 3.3 to 3.6 also show that mean primary peak frequency of the male subjects responses (5.06 Hz with no back support and 5.35 Hz with vertical back support) is relatively greater than that observed from the female subjects responses (4.69 Hz with no back supports and 5.00 Hz with vertical back support).

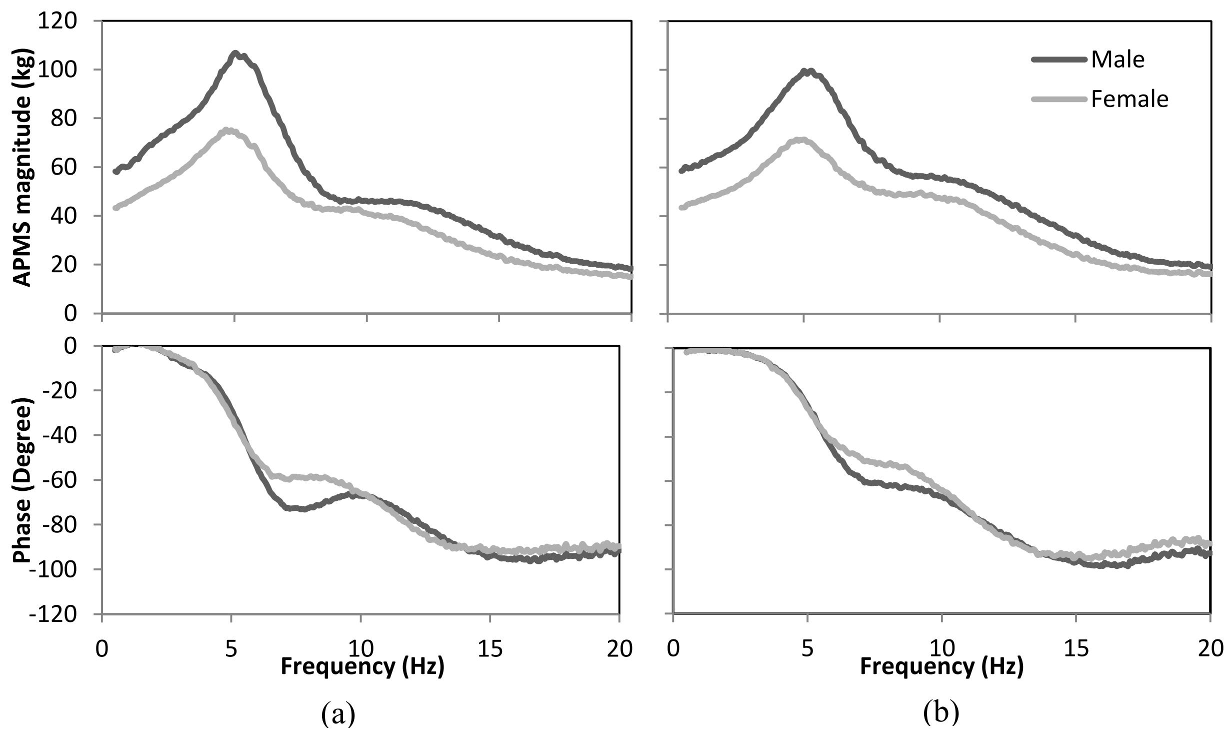
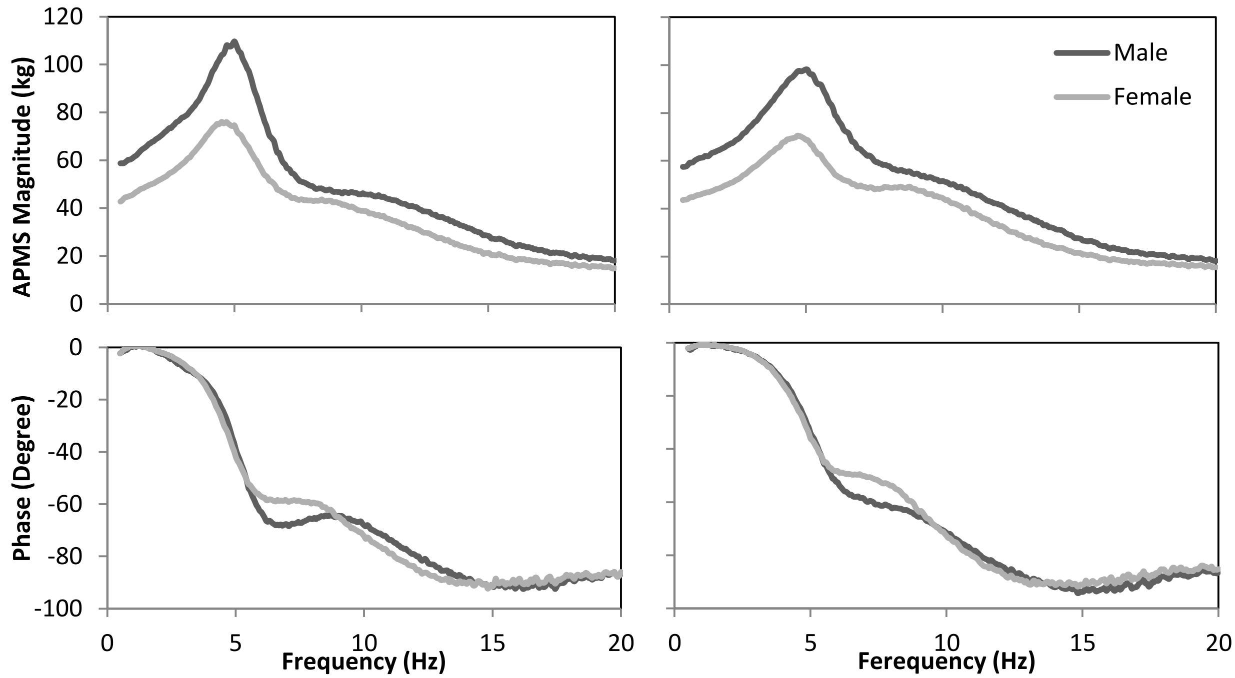
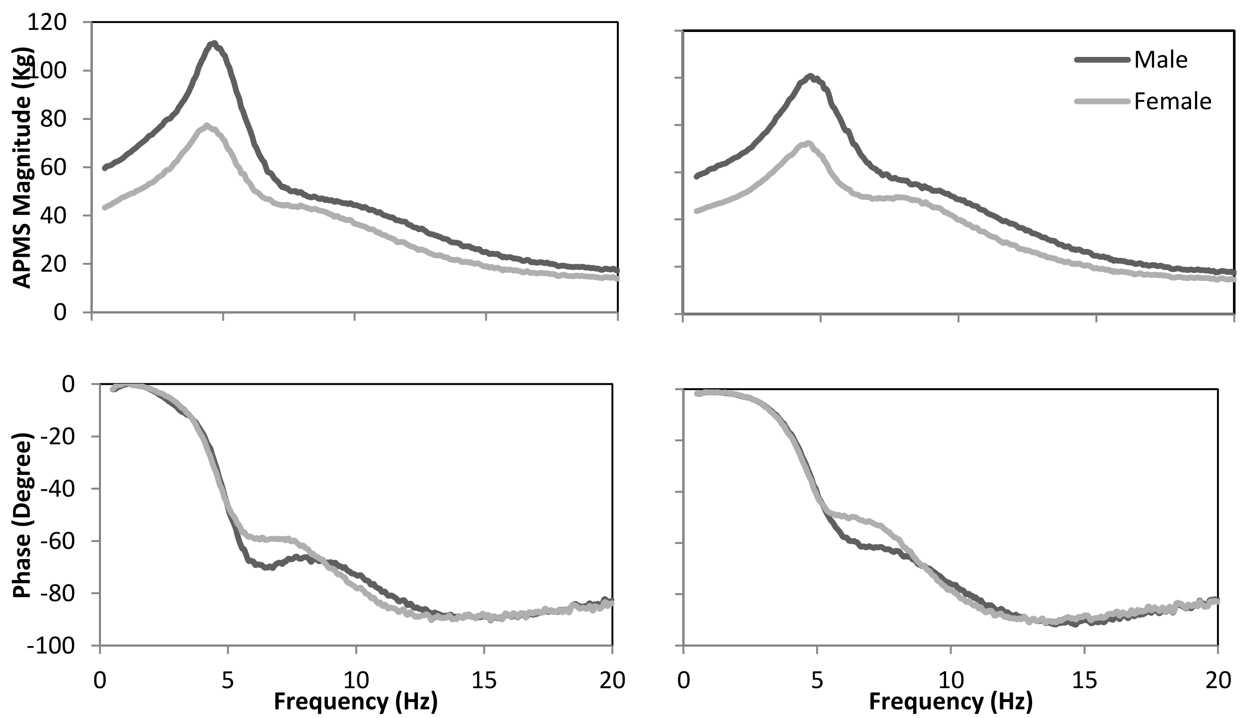


Figure 3.3: Comparisons of mean APMS magnitude and phase responses of 31 male and 27 female subjects seated with: (a) no back support; and (b) a vertical back support (0.25 m/s^2 excitation)



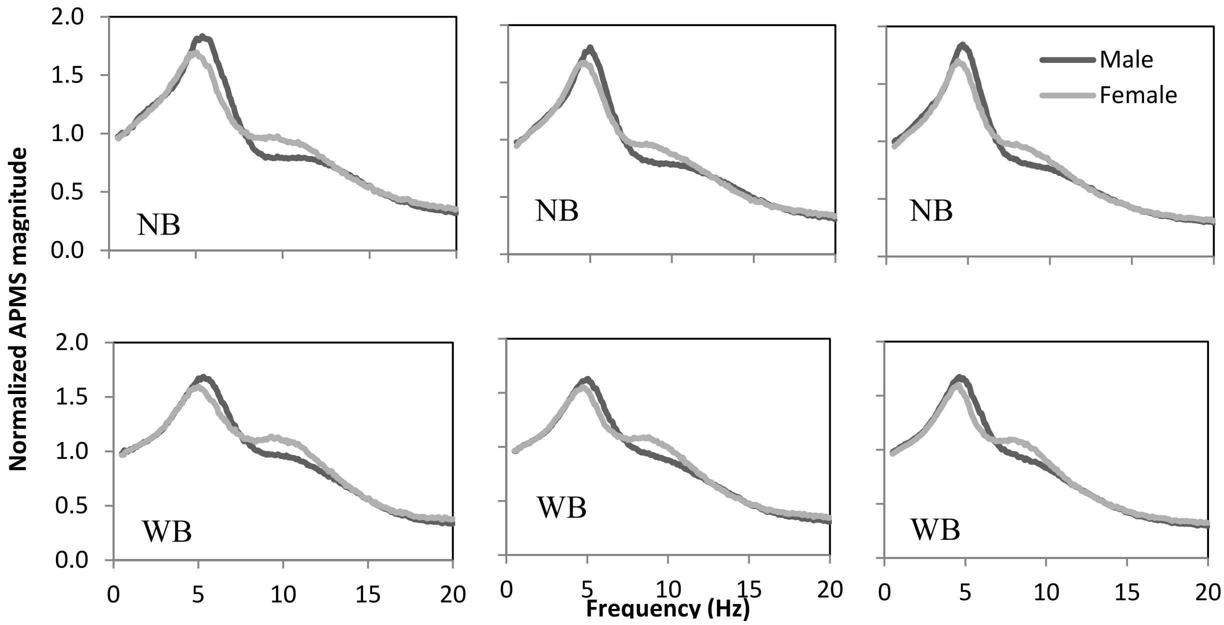
(a) (b)

Figure 3.4: Comparisons of mean APMS magnitude and phase responses of 31 male and 27 female subjects seated with: (a) no back support; and (b) a vertical back support (0.50 m/s² excitation)



(a) (b)

Figure 3.5: Comparisons of mean APMS magnitude and phase responses of 31 male and 27 female subjects seated with: (a) no back support; and (b) a vertical back support (0.75 m/s² excitation)



(a) (b) (c)

Figure 3.6: Comparisons of mean normalized APMS magnitude responses of 31 male and 27 female subjects for different sitting posture, and vibration magnitudes: (a) 0.25 m/s^2; (b) 0.50 m/s^2; and (c) 0.75 m/s^2 excitation.

Form the results, it can be deduced that both the body mass and 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 [29,33, 70,73]. This could facilitate the study of other contributory factors.

In this study, attempts were made to group the acquired data for different mass ranges and the two genders. This task however, was quite challenging considering relatively higher body mass of male group compared to the female group. The data for subject mass in the vicinity of 60 and 70 kg, alone could be considered for study of gender effects. The study participants included 7 female and 7 male subjects around 60 kg (55 to 65 kg) and 70 kg (65 to 75 kg) body mass. The data for these subjects were consequently extracted and analyzed to derive the respective mean magnitude responses. These mean responses are considered to yield the gender effect, if any, decoupled from the body mass effect. Figure 3.7 illustrates comparison of the mean magnitude responses of the male and female subjects of comparable body masses of 60 and 70 kg. The results are presented for the two back support condition and three vibration conditions (0.25, 0.50 and 0.75 m/s^2 rms).

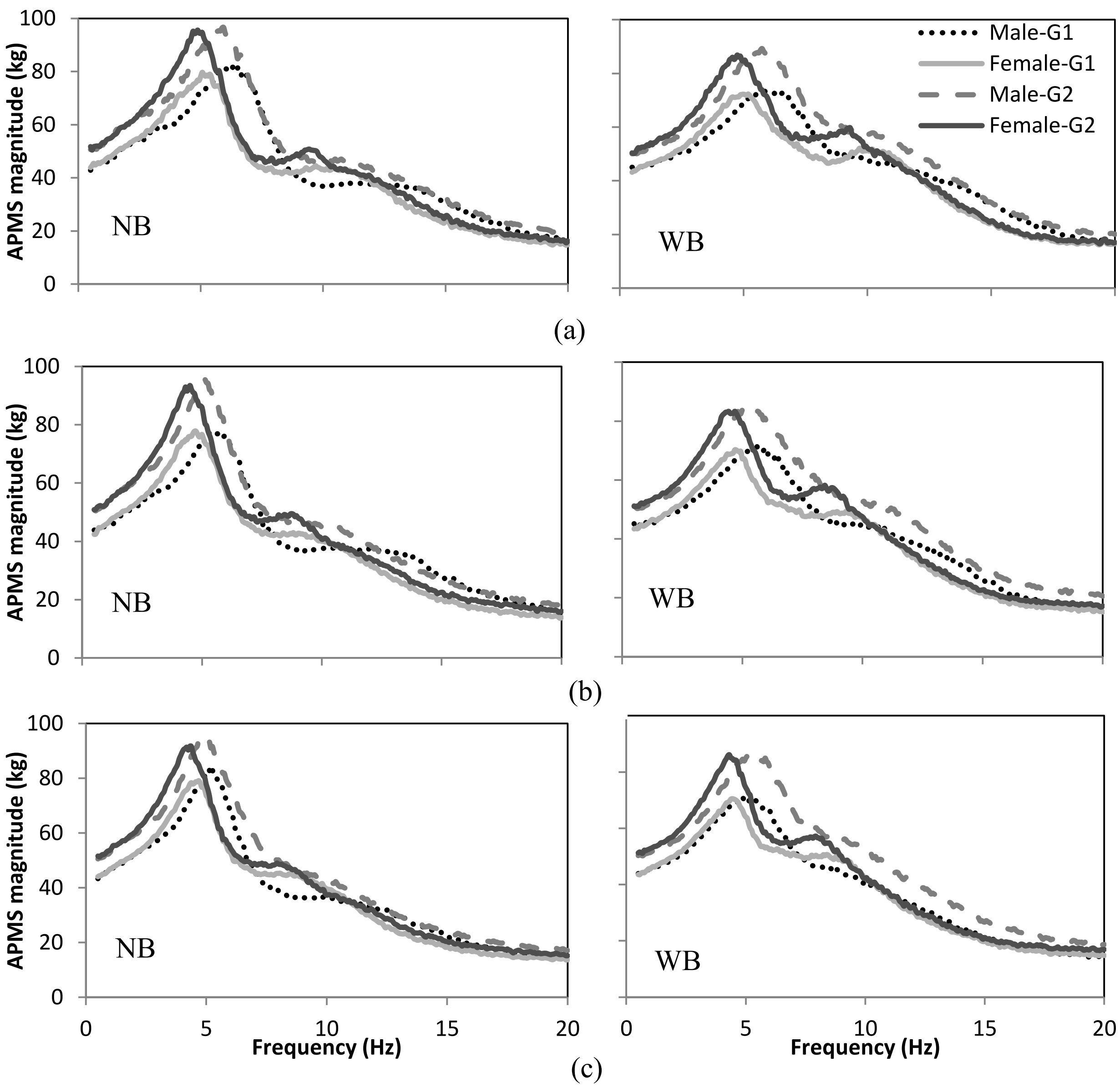


Figure 3.7: Mean APMS magnitude responses of male and female subjects in two different mass groups (60 and 70 kg) corresponding to different sitting postures and excitation levels: (a) 0.25 m/s^2; (b)0.50 m/s^2; and (c) 0.75 m/s^2.

3.4 Influence of Excitation Magnitude

Figure 3.8 illustrates the comparisons of APMS magnitude responses attained under the selected excitation magnitudes. The results are presented separately for the 31 male and 27 female subjects, and for the two postures. Softening tendency of the human body is evident from the results, which show decrease in the primary resonance frequency with increase in magnitude of excitation. This tendency is clearly evident irrespective of gender group and the back support condition. The peak APMS magnitude obtained under different excitations, however, are quite comparable. Such trends have also been reported in earlier studies [28,33,50,52,54,70]. The softening tendency with increasing vibration magnitude among the male and female subjects is further studied by considering the changes in the primary resonance frequency and the corresponding APMS magnitude, with increase in excitation magnitude from 0.25 to 0.75 m/s^2, the responses of the male subjects' exhibit greater softening tendency compared to the female subjects. The changes in the primary resonant frequency for the male subjects are near 0.86 and 0.72 Hz, respectively for the NB and WB posture. The corresponding changes for the female subjects are 0.43 and 0.53 Hz, respectively (Table 3.1). The measured data were further studied by considering the two gender groups of comparable body mass (Group G1 and G2). This facilitated the decoupling of the body mass effect. The comparisons, summarized in Table 3.2, suggest that the changes in primary frequency of female subjects' responses are in the order of 0.49 and 0.44 Hz for the NB and WB, postures, respectively for mass group G1 and 0.46 and 0.42 Hz for the NB and WB, postures, respectively for mass group G2. The comparisons reveal for greater softening tendency of the male subjects where the changes in primary frequency are 1.02 and 0.83 Hz for the NB and WB, postures, respectively for mass group G1, respectively and

0.70 and 0.0.59 Hz for the NB and WB, postures, respectively for mass group G2. The results also suggest greater softening tendency with the NB postures.

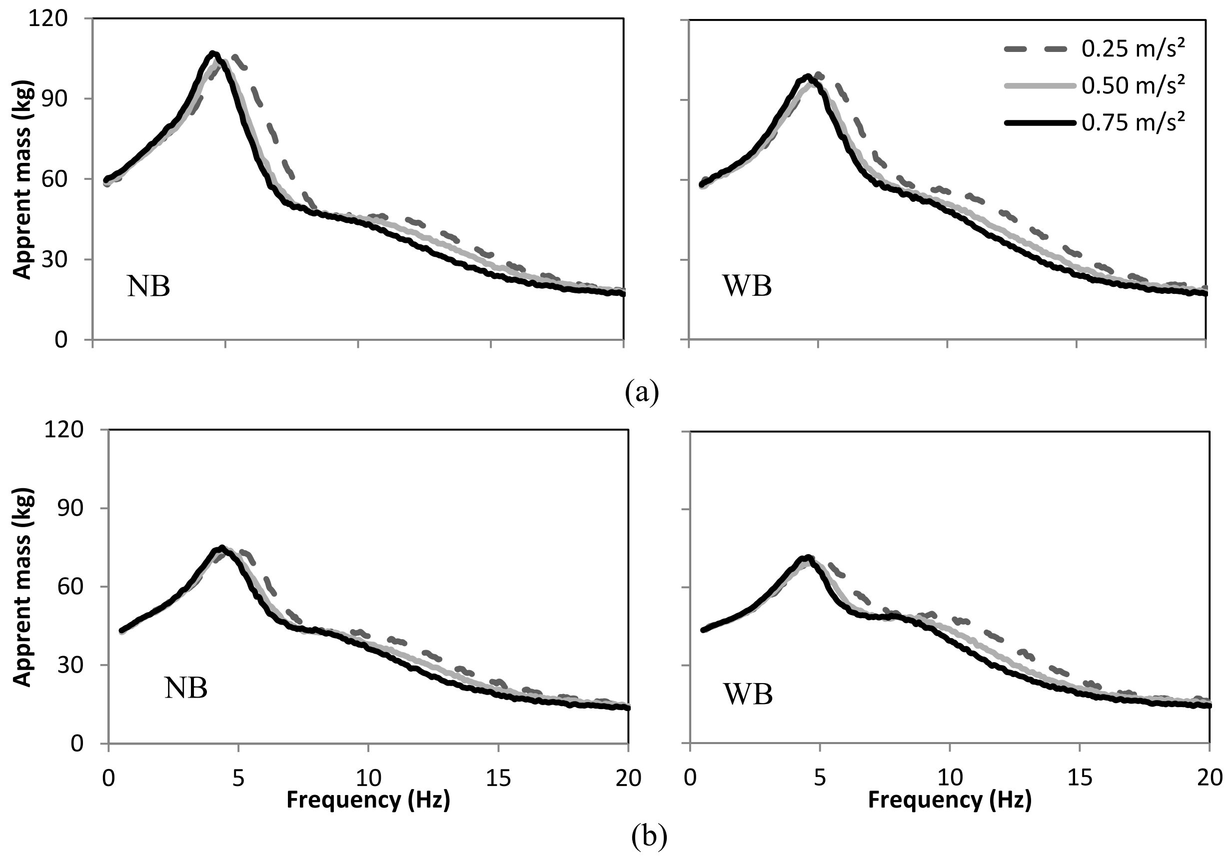


Figure 3.8: Influence of excitation magnitude on the mean APMS magnitude response: (a) male; and (b) female subjects.

3.5 Effect of Anthropometric Parameters on the APMS Responses

The variation in human anthropometry also affects the biodynamic responses, which may be attributed to variations in the bod mass, body fat, stature and build. The effects of such parameters on the measured APMS responses are thus investigated for both gender groups.

Table 3.1: Means (standard deviations) of the primary resonance frequencies and magnitude of APMS under different levels of excitation for 31 male and 27 female subjects

Gender	Male		Female	
Posture	NB	WB	NB	WB
Excitation magnitude	Primary resonance frequency			
0.25 m/s^2	5.86(0.55)	5.65(0.69)	5.18(0.59)	5.19(0.63)
0.50 m/s^2	5.29(0.61)	5.26(0.75)	4.90(0.49)	4.84(0.53)
0.75 m/s^2	5.00(0.52)	4.93(0.57)	4.75(0.48)	4.66(0.41)
	APMS magnitude			
0.25 m/s^2	121.89(29.02)	106.47(24.64)	82.50(15.05)	75.67(14.00)
0.50 m/s^2	116.72(30.23)	104.29(25.16)	81.66(15.35)	72.89(13.93)
0.75 m/s^2	119.34(29.88)	105.45(23.98)	82.13(15.40)	74.49(13.56)

Table 3.2:Means (standard deviations) of the primary resonance frequencies and magnitude of APMS under different levels of excitation for 7 male and 7 female subjects of two body mass groups

	Group – G1				Group – G2			
Gender	Male		Female		Male		Female	
Posture	NB	WB	NB	WB	NB	WB	NB	WB
Excitation magnitude	Primary resonance frequency							
0.25 m/s^2	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 m/s^2	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 m/s^2	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)
	APMS magnitude							
0.25 m/s^2	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 m/s^2	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 m/s^2	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)

3.5.1 Body mass

The effect of body mass variations on the PMS magnitude responses is investigated by comparing the mean responses of the male and female subjects within three mass groups (60 kg; 80 kg and 96 kg for male subjects; and 50 kg; 60 kg and 72 kg). Figure 3.9 compares the mean responses of the male and female subjects for the two postures and 0.50 m/s^2 excitation. For both genders, the peak APMS magnitude of lighter subjects was considerably smaller than that of heavy-weight subjects. The light-weighted subjects, however, showed considerably higher primary resonance frequency than the heavier subjects. The comparisons further show extreme differences in the APMS magnitudes at low frequencies up to nearly the primary resonant frequency. Subsequently, the means of the normalized responses are obtained and compared in Figure 3.10. While the normalization reduces the extreme differences at low frequencies, it emphasizes the mass effect at higher frequency, particularly in the 4 to 15 Hz range. The results, however, show normalized magnitude response for subject within the higher body mass group. These subjects also show lower normalized magnitude response at higher frequencies beyond the primary resonance frequency. The normalization thus yields opposite trends in APMS at higher frequencies.

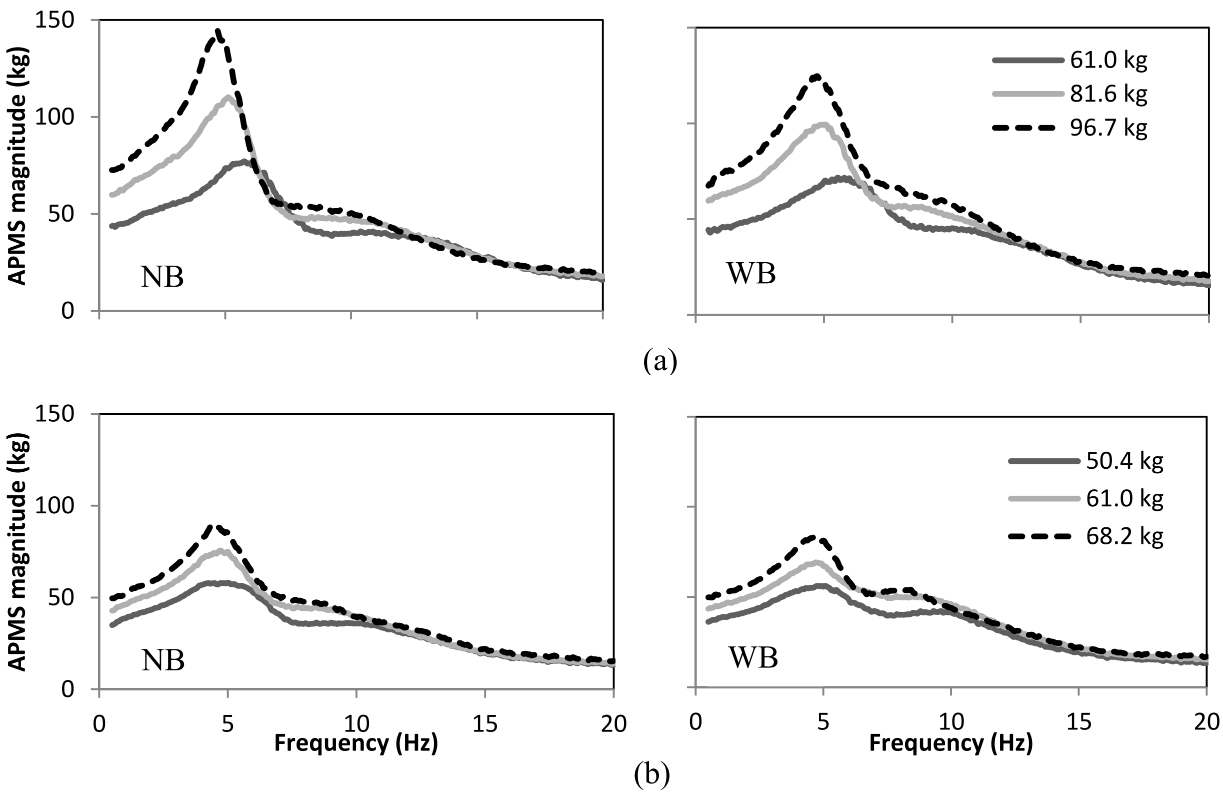
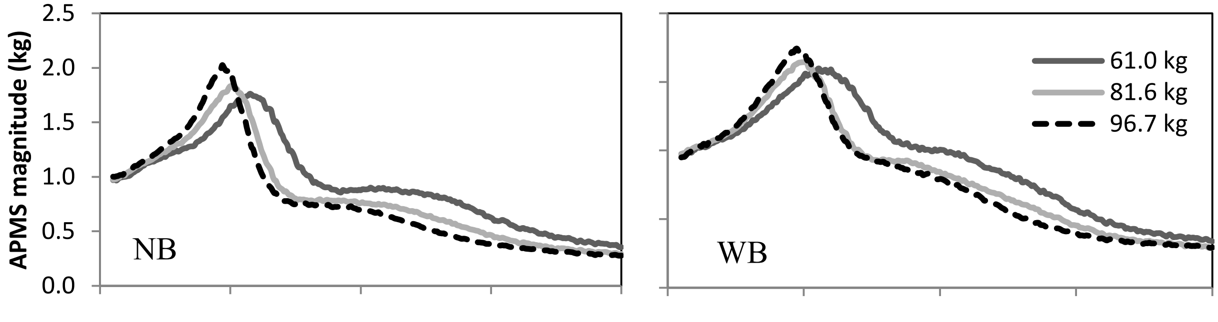
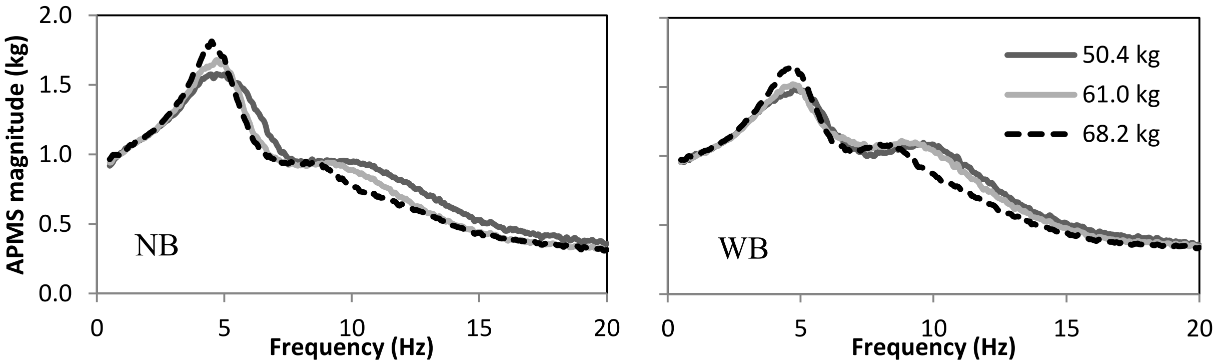


Figure 3.9: Comparisons of the mean APMS magnitude responses of male and female subjects in the three different mass groups corresponding to different sitting conditions and 0.50 m/s^2 excitation: (a) male; and (b) female subjects.



(a)



(b)

Figure 3.10: Comparisons of the mean normalized APMS magnitude responses of male and female subjects in the three different mass groups corresponding to different sitting conditions and 0.50 m/s² excitation: (a) male; and (b) female subjects.

3.5.2 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 the stature, BMI, body fat, body fat percent, lean body mass, hip circumference, sitting height and seventh cervical vertebrae (C7) height. For this purpose, the male and female subjects were grouped within narrow ranges of each parameter. The body-seat contact area and mean peak pressure, which invariably occurred around the tuberosities region, were also obtained for each subject from the body-seat interface pressure data. These relate to both the body mass and the build, primarily the hip circumference. The measured data are thus also grouped for different ranges of contact area and mean peak pressure. Table 3.3 summaries the ranges used for grouping of 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 Figures 3.11 to 3.13, which illustrate the effect of factors related to stature, body mass and the build, respectively. The results are presented for NB posture and 0.50 m/s^2 rms excitation. The similar trends, however, were observed under other excitation and the WB sitting posture.

Figure 3.11 presents the effects of standing height, sitting height and the C7-hieght on the mean magnitude responses of male and female subjects. The effects of BMI, body fat, percent body fat and lean body mass are illustrated in Figure 3.12. Figure 3.13 shows the influence of build related factors, namely the hip circumference, body-seat contact area and mean peak pressure. The effects of selected parameters on the primary resonant frequency and the mean peak APMS magnitude are also presented in Tables 3.4 and 3.5. The results clearly show large variations in the APMS magnitude with variations in the selected anthropometric factors of both male and female subjects. For both male and female subjects, large peak APMS magnitude was observed with higher dimensions of most of the anthropometric parameters, namely the BMI, body fat, lean body mass, hip circumference and contact area. However, with increase in anthropometric dimensions (BMI, body fat, lean body mass, hip circumference and contact area) a decrease in the primary resonance frequency was observed for the male subjects, while female subjects showed no clear trends.

Table 3.3: The ranges of selected anthropometric factors used to define subgroups of responses of male and female subjects.

Gender		male			Female		
Anthropometric parameters		Range	Mean	n	Range	Mean	n
stature-related	Stature (m)	1.60-1.72	1.66	10	1.48-1.60	1.56	9
		1.73-1.77	1.75	10	1.61-1.67	1.64	9
		1.78-1.92	1.84	8	1.69-1.73	1.71	9
	Sitting height (cm)	83.0-87.5	85.9	8	77.5-82.8	80.4	8
		88.0-92.9	91.2	10	83.0-85.5	84.4	8
		93.7-96.7	95.2	8	87.0-90.2	88.3	8
	C7 height (cm)	59.4-64.5	61.9	9	56.5-59.6	58.0	8
		65.8-68.7	67.4	10	60-62.5	61.4	8
		69.6-74.4	71.0	8	63-67.6	65.1	8
mass-related	BMI (kg/m^2)	20.0-23.1	21.6	12	15.8-20.9	19.4	9
		23.3-27.5	25.6	11	21.5-23.9	22.6	8
		28.4-35.0	31.0	8	24.4-26.3	25.3	10
	Body fat (kg)	8.6-12.9	11.0	11	12.3-15.6	13.5	8
		13.5-19.1	16.6	10	16.4-20.5	19.1	9
		20.5-29.3	26.2	7	21.5-25.3	23.7	9
	Body fat (%)	16.1-18.7	16.6	9	19.3-26.8	25.9	9
		20.4-23.8	21.9	10	27.9-33.8	30.8	9
		26.9-31.2	28.9	6	33.9-39.1	35.7	9
	Lean body mass (kg)	43.3-56.8	50.1	9	34.1-37.7	36.0	8
		58.1-64.5	61.5	10	38.9-44.6	41.4	11
		65.3-77.5	68.8	11	45.4-49.5	47.3	8
build-related	Hip circumference (cm)	91.8-97.5	95.5	9	89.5-95.0	92.6	8
		98.3-106.4	102.8	11	97.0-103.0	100.4	9
		107.0-116.0	110.7	9	104.0-109.0	105.2	10
	Contact area (cm^2)	265-443	370	10	250-425	350	9
		500-595	556	8	445-575	510	9
		615-695	666	8	600-760	682	6
	Mean peak pressure (N/cm^2)	8.1-10.4	9.1	11	5.8-8.4	7.6	9
		11.5-14.5	13.2	10	8.7-10.2	9.3	9
		15.2-20.7	17.1	8	10.6-14.0	12.3	8

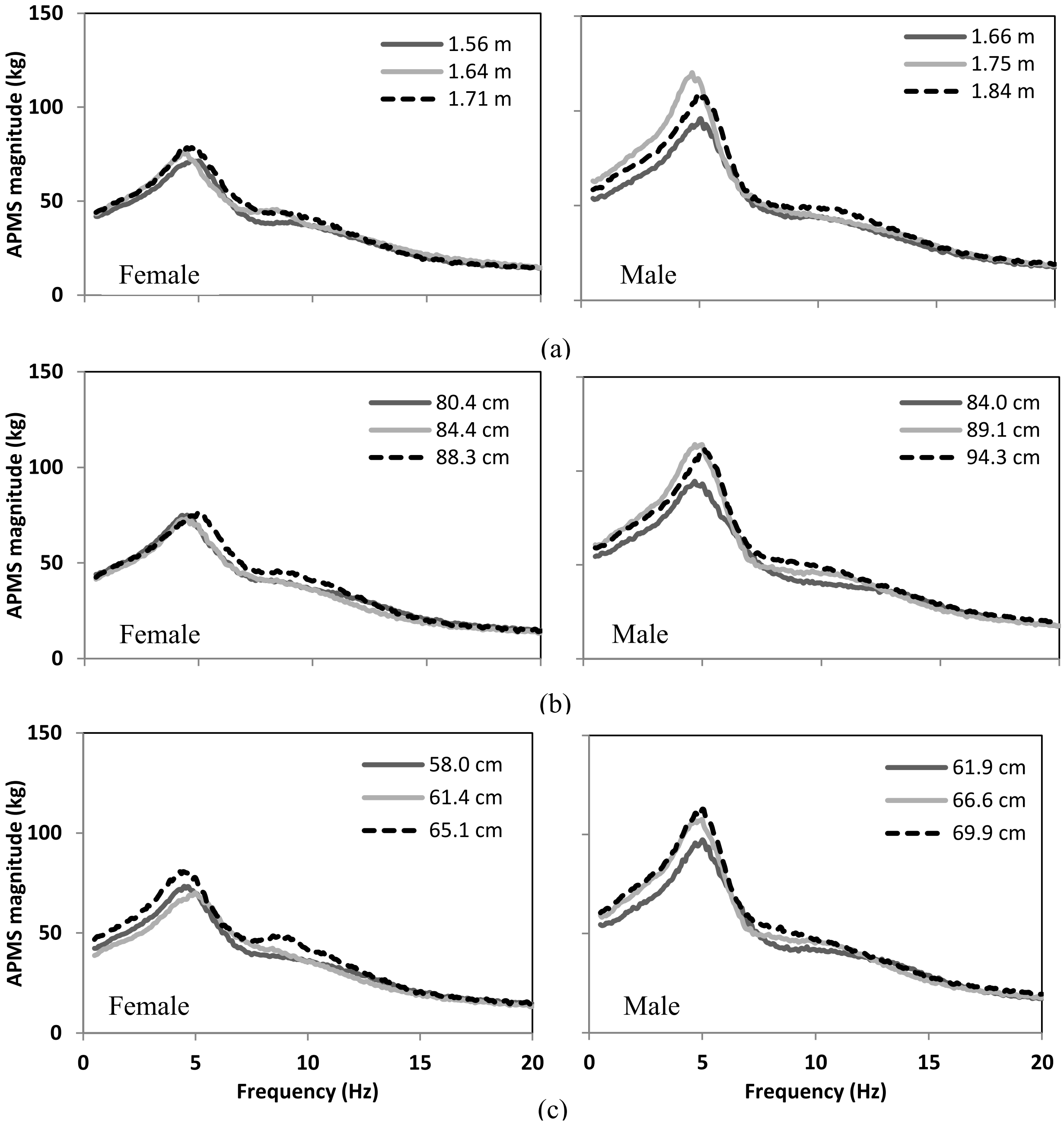


Figure 3.11: Effect of stature-related factors on the mean APMS magnitude responses of male and female subjects: (a) stature; (b) sitting height; and (c) C7 height.

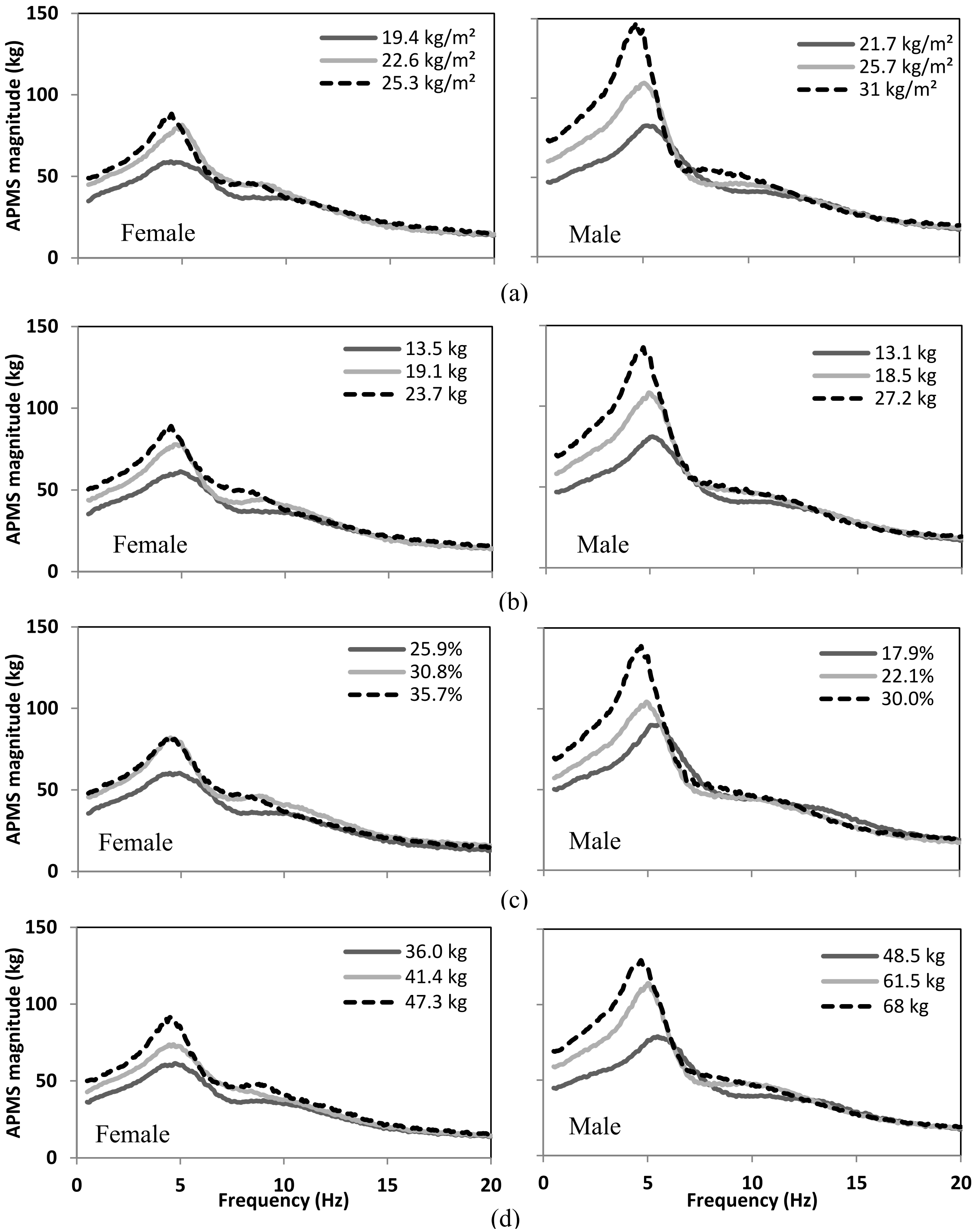


Figure 3.12: Effect of mass-related factors on the mean APMS magnitude responses of male and female subjects: (a) BMI; (b) body fat; (c) body fat percentage; and (d) lean body mass.

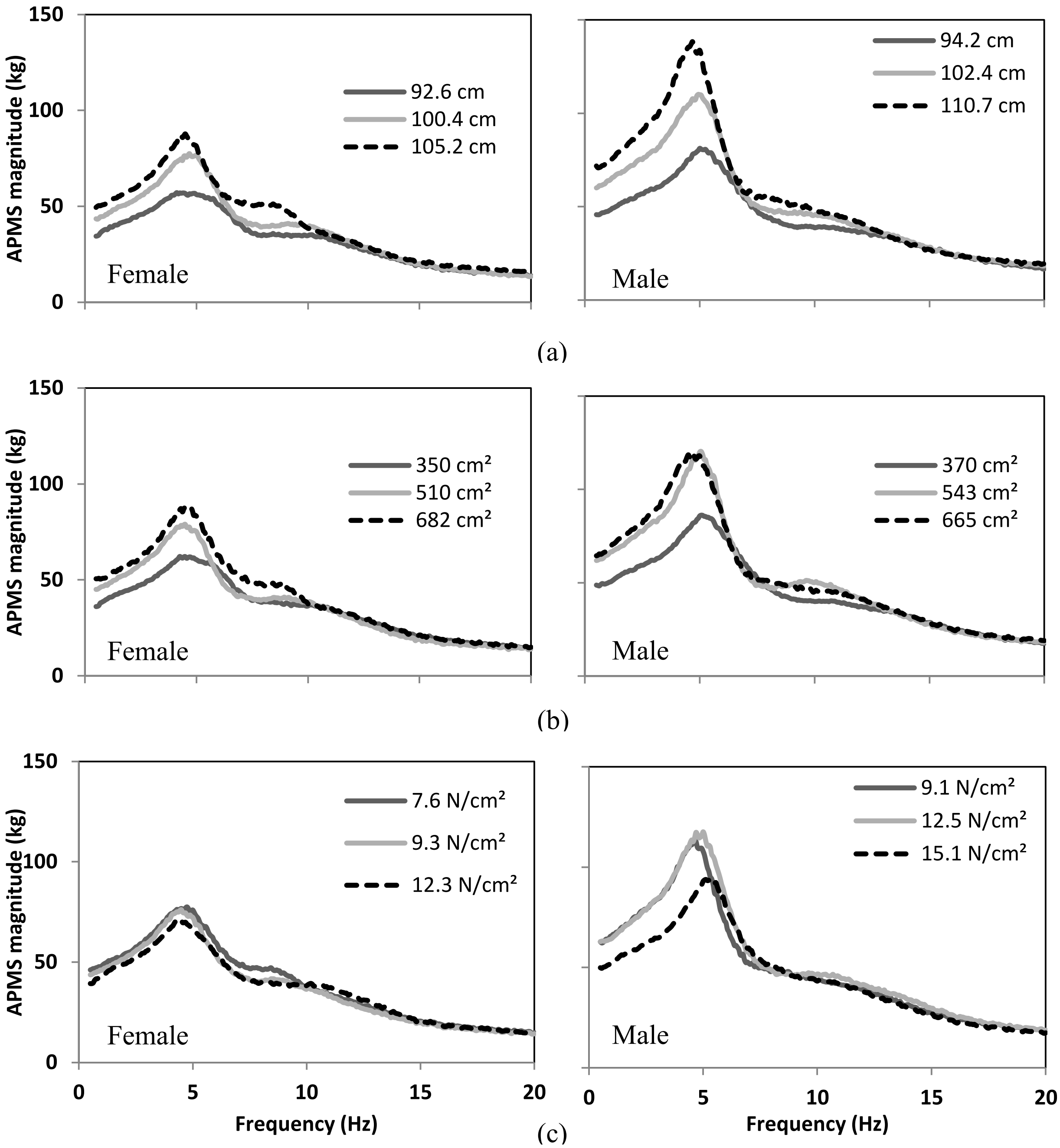


Figure 3.13: Effect of build-related factors on the mean APMS magnitude responses of male and female subjects: (a) hip circumference; (b) contact area; and (c) mean peak pressure.

Table 3.4: Influence of selected anthropometric factors on the mean (standard deviation) of peak APMS magnitudes of the male and female subjects.

Anthropometric parameters	Male						Female					
	No back support			Vertical back support			No back support			Vertical back support		
Excitation	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	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
Stature (m)												
M-1.66 F-1.56	97.8(14.6)	103.8(29.5)	110.2(32.9)	95.2(21.1)	92.9(24.4)	94.2(24.6)	77.4(8.4)	76.0(9.3)	77.6(10.6)	71.2(8.5)	68.4(8.3)	69.5(9.4)
M-1.75 F-1.64	139.5(28.0)	132.0(31.0)	131.6(30.6)	121.5(27.2)	113.9(26.4)	118.8(27.6)	85.2(19.7)	83.9(18.4)	85.7(18.7)	79.2(16.8)	76.5(17.2)	77.4(17.3)
M-1.84 F-1.71	127.5(22.9)	113.7(15.5)	116.6(17.2)	107.9(14.7)	103.0(17.7)	105.6(14.7)	86.9(14.3)	86.7(16.2)	84.1(16.4)	79.1(14.2)	73.4(14.3)	77.2(12.5)
Sitting height (cm)												
M-85.9 F-80.4	88.8(6.9)	106.4(35.6)	109.0(40.0)	98.5(25.3)	95.9(26.9)	97.4(29.3)	82.4(14.5)	81.8(16.3)	83.0(17.7)	74.8(13.7)	72.5(13.3)	73.3(13.6)
M-91.2 F-84.4	142.8(21.6)	127.5(28.5)	129.3(29.8)	113.1(23.0)	106.9(21.3)	107.3(24.3)	82.7(15.2)	80.8(16.0)	80.7(15.8)	73.5(14.3)	71.1(12.7)	73.4(13.6)
M-95.2 F-88.3	125.8(24.1)	115.5(20.4)	117.1(21.8)	110.2(18.1)	105.3(20.6)	107.5(20.0)	82.3(13.0)	82.0(14.3)	81.8(13.3)	77.4(12.9)	73.1(13.7)	74.4(12.8)
C7 height (cm)												
M-61.9 F-58.0	113.6(38.0)	107.7(40.2)	113.8(41.5)	98.1(26.9)	95.8(29.6)	98.9(29.1)	80.3(12.3)	79.1(13.3)	80.5(14.9)	74.0(12.5)	71.8(12.4)	73.0(13.2)
M-67.4 F-61.4	126.1(25.3)	120.9(26.0)	122.7(28.1)	107.7(21.3)	101.7(18.4)	101.5(21.7)	77.7(13.1)	75.8(12.6)	76.8(14.2)	68.3(12.8)	68.2(14.5)	68.8(12.8)
M-71.0 F-65.1	133.2(22.4)	121.3(22.1)	123.4(23.2)	115.5(17.5)	110.5(21.0)	114.5(20.7)	89.5(14.5)	88.3(14.5)	87.9(15.0)	84.2(12.0)	78.2(13.4)	79.2(11.4)
BMI (kg/m^2)												
M-21.6 F-19.4	95.0(12.0)	89.7(15.4)	91.7(14.6)	87.0(12.2)	81.9(10.2)	78.0(6.8)	68.4(5.5)	67.1(6.7)	66.5(7.8)	63.4(7.4)	60.0(5.9)	61.2(5.2)
M-25.6 F-22.6	124.4(14.3)	119.6(12.5)	118.6(11.8)	107.6(13.5)	106.4(14.5)	106.5(15.4)	84.5(10.6)	84.5(11.4)	84.3(11.1)	78.4(10.5)	75.5(11.0)	76.9(10.1)
M-31.0 F-25.3	159.8(9.9)	155.9(12.8)	160.7(15.8)	138.8(11.5)	132.7(13.2)	136.4(10.4)	95.4(12.7)	94.0(11.8)	95.4(9.7)	86.3(11.6)	83.8(10.0)	85.1(10.7)
Body fat (kg)												
M-11.0 F-13.5	97.9(13.9)	88.6(13.9)	92.7(14.8)	84.6(9.0)	81.5(8.9)	81.7(9.0)	68.6(5.8)	68.2(7.5)	68.5(7.6)	64.1(5.1)	61.5(5.4)	60.9(5.3)
M-16.6 F-19.1	132.3(11.5)	118.3(16.2)	118.4(15.1)	110.2(10.5)	103.8(15.6)	107.5(16.3)	81.8(9.1)	82.1(11.2)	82.6(10.6)	75.5(9.2)	72.1(8.9)	74.5(10.5)
M-26.2 F-23.7	154.1(15.5)	148.2(19.8)	150.7(21.7)	131.7(15.8)	125.6(13.7)	128.7(17.0)	99.3(9.9)	96.8(9.9)	97.8(7.6)	90.8(6.9)	87.8(7.0)	88.6(5.1)
Body fat (%)												
M-16.6 F-25.9	103.7(16.7)	95.3(15.6)	99.9(13.4)	90.9(11.3)	86.6(10.7)	90.6(9.0)	68.8(5.8)	68.7(6.7)	68.5(8.1)	63.7(7.5)	60.5(6.2)	61.0(5.0)
M-21.9 F-30.8	117.7(23.9)	113.3(25.5)	114.4(24.8)	107.8(19.2)	103.3(20.8)	104.2(23.3)	90.2(15.2)	88.0(17.1)	86.8(16.0)	81.5(13.5)	77.5(12.9)	80.1(12.2)
M-28.9 F-35.7	156.2(15.3)	151.5(19.4)	153.7(22.1)	132.4(17.2)	125.7(14.9)	130.2(18.1)	90.5(11.2)	89.9(10.3)	92.1(10.4)	83.7(10.5)	82.3(9.8)	83.0(9.7)
Lean body mass (kg)												
M-50.1 F-36.0	90.9(7.4)	83.2(10.1)	88.1(12.6)	84.1(9.9)	79.1(7.8)	78.6(7.9)	69.6(5.9)	68.3(8.1)	68.2(10.1)	62.2(6.6)	60.5(7.0)	62.1(6.4)
M-61.5 F-41.4	123.8(27.2)	120.7(25.2)	122.5(28.9)	108.4(18.6)	103.5(22.0)	106.2(20.9)	83.1(12.9)	81.1(11.7)	82.5(13.0)	77.4(10.2)	74.3(12.4)	75.4(12.2)
M-68.8 F-47.3	144.9(14.1)	141.5(17.4)	143.3(18.8)	128.8(15.7)	123.5(14.9)	126.4(15.3)	96.8(12.4)	97.7(10.2)	96.6(8.9)	88.9(10.4)	85.1(8.2)	86.3(9.4)
Hip circumference (cm)												
M-95.5 F-92.6	91.0(7.2)	88.1(13.2)	91.3(13.9)	85.6(10.3)	80.4(8.2)	79.1(7.4)	67.4(5.0)	65.9(5.3)	65.3(7.2)	62.0(6.5)	60.3(6.2)	60.3(4.9)
M-102.8 F-100.4	125.9(16.2)	120.1(15.1)	118.5(16.3)	109.6(13.4)	104.8(16.5)	109.0(14.6)	80.2(8.1)	80.6(8.8)	81.4(9.5)	75.0(9.0)	72.2(8.9)	73.6(10.7)
M-110.7 F-105.2	153.4(18.1)	150.5(19.1)	153.6(23.9)	133.1(18.4)	128.2(17.7)	130.1(19.0)	98.4(10.2)	96.6(10.5)	97.1(8.1)	89.0(9.1)	86.0(8.8)	87.2(6.6)
Contact area (cm^2)												
M-370 F-350	94.1(15.1)	93.7(15.3)	95.2(13.8)	88.1(11.2)	83.1(10.5)	84.8(10.0)	72.1(12.5)	70.0(12.8)	69.3(14.9)	65.8(12.3)	62.9(12.3)	64.6(12.6)
M-556 F-510	121.1(28.5)	125.3(29.6)	124.6(26.4)	115.6(24.9)	114.0(28.0)	111.1(25.2)	85.3(14.2)	86.0(15.3)	86.0(12.4)	80.4(11.2)	75.3(10.8)	78.7(12.3)
M-666 F-682	139.2(18.9)	135.7(19.6)	137.1(22.5)	121.5(16.4)	115.4(14.8)	120.0(17.1)	96.1(11.5)	94.9(8.5)	95.7(8.4)	87.6(11.9)	86.1(10.3)	83.6(10.2)
Mean peak pressure N/ (cm^2)												
M-9.1 F-7.6	129.0(27.8)	124.2(29.2)	124.9(31.2)	111.4(21.2)	110.7(22.2)	111.0(24.3)	84.5(15.1)	84.8(13.3)	87.1(12.6)	77.1(13.5)	76.2(12.8)	77.0(12.1)
M-13.2 F-9.3	141.1(26.3)	129.8(34.5)	137.0(32.7)	117.6(30.8)	116.8(27.1)	118.5(27.2)	85.7(17.5)	84.5(17.0)	84.1(14.3)	78.9(14.6)	74.0(14.3)	74.7(14.1)
M-17.1 F-12.3	121.0(31.8)	99.7(15.7)	100.7(14.9)	121.5(16.4)	87.9(11.4)	87.5(11.4)	78.7(14.5)	76.7(16.7)	75.6(19.5)	73.6(15.1)	69.9(15.3)	73.1(16.2)

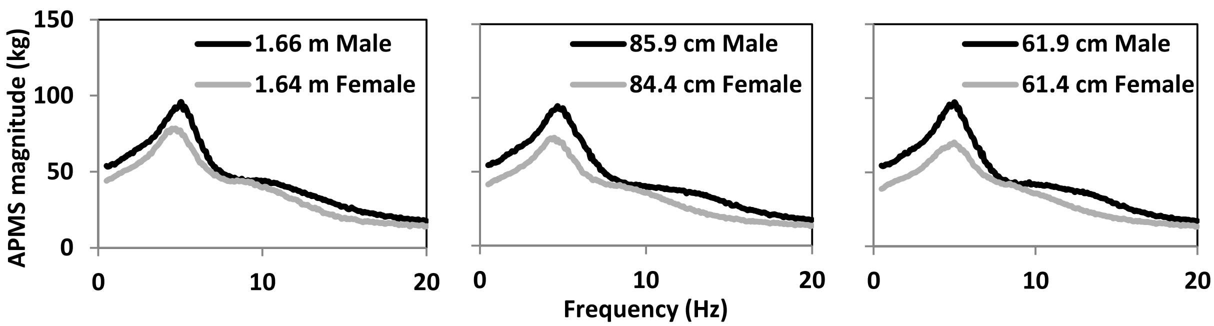
M-male subjects F-female subjects.

Table 3.5: Influence of selected anthropometric factors on the mean (standard deviation) primary resonance frequencies of the male and female subjects

Anthropometric parameters	Male						Female					
	No back support			Vertical back support			No back support			Vertical back support		
excitation	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	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
Stature (m)												
M-1.66 F-1.56	6.38(0.42)	5.41(0.61)	5.27(0.52)	5.88(0.74)	5.66(0.85)	5.18(0.55)	5.16(0.56)	4.86(0.44)	4.65(0.51)	6.05(2.43)	4.78(0.54)	4.72(0.57)
M-1.75 F-1.64	5.51(0.50)	5.03(0.55)	4.80(0.40)	5.53(0.48)	5.14(0.34)	4.80(0.45)	5.22(0.76)	4.91(0.67)	4.81(0.73)	5.01(0.68)	4.81(0.55)	4.59(0.46)
M-1.84 F-1.71	5.74(0.56)	5.22(0.38)	5.02(0.21)	5.48(0.49)	4.95(0.56)	4.99(0.67)	5.14(0.55)	4.88(0.31)	4.59(0.35)	5.30(0.61)	4.91(0.33)	4.62(0.27)
Sitting height (cm)												
M-85.9 F-80.4	6.37(0.43)	5.24(0.57)	5.05(0.51)	5.67(0.70)	5.46(0.84)	5.07(0.63)	4.93(0.59)	4.75(0.50)	4.52(0.60)	5.15(0.54)	4.68(0.41)	4.55(0.29)
M-91.2 F-84.4	5.56(0.62)	5.01(0.45)	4.88(0.39)	5.66(0.71)	5.04(0.36)	4.87(0.45)	5.32(0.41)	4.96(0.52)	4.82(0.53)	5.56(0.73)	5.07(0.49)	4.89(0.61)
M-95.2 F-88.3	5.76(0.47)	5.26(0.40)	5.04(0.21)	5.56(0.45)	5.14(0.61)	5.00(0.67)	5.20(0.65)	4.91(0.34)	4.67(0.48)	5.04(0.40)	4.72(0.36)	4.53(0.27)
C7 height (cm)												
M-61.9 F-58.0	5.88(0.58)	5.45(0.65)	5.13(0.58)	5.88(0.66)	5.63(0.88)	5.23(0.58)	5.01(0.60)	4.80(0.47)	4.58(0.57)	5.26(0.40)	4.73(0.37)	4.59(0.24)
M-67.4 F-61.4	5.79(0.57)	5.01(0.45)	4.89(0.38)	5.63(0.73)	5.13(0.44)	4.81(0.47)	5.44(0.43)	5.09(0.48)	5.07(0.48)	5.54(0.76)	5.05(0.50)	4.93(0.58)
M-71.0 F-65.1	5.57(0.49)	5.18(0.50)	5.00(0.30)	5.52(0.50)	4.99(0.56)	5.01(0.67)	4.99(0.59)	4.73(0.37)	4.38(0.23)	4.91(0.48)	4.61(0.39)	4.42(0.31)
BMI (kg)/m^2												
M-21.6 F-19.4	6.37(0.42)	5.60(0.53)	5.15(0.33)	6.11(0.65)	5.64(0.69)	5.25(0.64)	5.35(0.70)	5.03(0.62)	4.97(0.70)	5.52(0.70)	4.99(0.45)	4.70(0.33)
M-25.6 F-22.6	5.78(0.42)	5.06(0.32)	5.15(0.43)	5.52(0.44)	5.16(0.53)	4.93(0.46)	5.09(0.67)	4.91(0.35)	4.63(0.39)	5.23(0.58)	4.77(0.53)	4.77(0.58)
M-31.0 F-25.3	5.20(0.31)	4.73(0.34)	4.60(0.25)	5.37(0.48)	4.83(0.33)	4.70(0.38)	5.08(0.48)	4.73(0.41)	4.48(0.40)	4.93(0.46)	4.69(0.39)	4.49(0.38)
Body fat (kg)												
M-11.0 F-13.5	6.23(0.37)	5.51(0.58)	5.14(0.45)	5.91(0.72)	5.66(0.74)	5.11(0.59)	5.43(0.68)	5.16(0.58)	5.10(0.66)	5.52(0.68)	5.07(0.57)	4.86(0.58)
M-16.6 F-19.1	5.60(0.44)	5.19(0.43)	5.09(0.36)	5.73(0.47)	5.16(0.51)	5.10(0.60)	5.12(0.64)	4.82(0.35)	4.47(0.28)	4.99(0.43)	4.65(0.32)	4.53(0.24)
M-26.2 F-23.7	5.34(0.45)	4.78(0.40)	4.76(0.44)	5.38(0.52)	4.90(0.42)	4.70(0.38)	5.06(0.52)	4.78(0.43)	4.55(0.50)	5.01(0.43)	4.71(0.41)	4.51(0.40)
Body fat %												
M-16.6 F-25.9	6.20(0.40)	5.74(0.50)	5.25(0.50)	5.80(0.56)	5.47(0.52)	5.20(0.57)	5.45(0.65)	5.07(0.62)	5.01(0.67)	5.61(0.76)	5.14(0.50)	4.87(0.56)
M-21.9 F-30.8	5.88(0.62)	5.09(0.38)	5.09(0.33)	5.76(0.67)	5.27(0.88)	5.09(0.64)	5.10(0.50)	4.82(0.29)	4.51(0.23)	5.02(0.46)	4.79(0.50)	4.47(0.26)
M-28.9 F-35.7	5.33(0.42)	4.73(0.41)	4.66(0.37)	5.46(0.51)	4.97(0.42)	4.72(0.41)	4.97(0.62)	4.76(0.47)	4.53(0.52)	5.01(0.43)	4.66(0.40)	4.58(0.38)
Lean body mass (kg)												
M-50.1 F-36.0	6.32(0.45)	5.74(0.53)	5.30(0.48)	6.01(0.68)	5.70(0.81)	5.34(0.62)	5.18(0.63)	4.95(0.60)	4.91(0.69)	5.48(0.71)	4.85(0.41)	4.74(0.23)
M-61.5 F-41.4	5.73(0.53)	5.06(0.26)	4.96(0.33)	5.62(0.61)	5.19(0.55)	4.91(0.51)	5.34(0.71)	4.95(0.50)	4.69(0.55)	5.34(0.51)	4.94(0.54)	4.71(0.59)
M-68.8 F-47.3	5.57(0.51)	4.87(0.43)	4.81(0.37)	5.45(0.44)	4.99(0.40)	4.81(0.44)	4.94(0.40)	4.73(0.31)	4.45(0.25)	4.77(0.45)	4.59(0.32)	4.45(0.29)
Hip circumference (cm)												
M-95.5 F-92.6	6.36(0.43)	5.39(0.46)	5.22(0.49)	6.03(0.75)	5.63(0.72)	5.12(0.62)	5.38(0.72)	5.06(0.66)	5.07(0.68)	5.73(0.75)	5.08(0.53)	4.92(0.57)
M-102.8 F-100.4	5.68(0.41)	5.16(0.46)	5.03(0.31)	5.49(0.39)	5.06(0.51)	5.05(0.60)	5.02(0.61)	4.76(0.34)	4.44(0.28)	5.03(0.40)	4.67(0.27)	4.48(0.15)
M-110.7 F-105.2	5.42(0.55)	4.85(0.44)	4.73(0.36)	5.51(0.53)	5.01(0.42)	4.80(0.37)	5.14(0.52)	4.85(0.41)	4.59(0.47)	4.96(0.42)	4.71(0.42)	4.56(0.41)
Contact area (cm^2)												
M-370 F-350	6.24(0.40)	5.58(0.56)	5.10(0.38)	5.87(0.63)	5.67(0.68)	4.98(0.51)	5.35(0.74)	5.12(0.57)	5.01(0.68)	5.61(0.61)	5.05(0.35)	4.77(0.24)
M-556 F-510	6.06(0.51)	5.19(0.32)	5.16(0.49)	5.78(0.64)	5.16(0.41)	5.27(0.47)	5.03(0.60)	4.67(0.38)	4.41(0.29)	5.12(0.62)	4.80(0.53)	4.66(0.59)
M-666 F-682	5.46(0.43)	4.89(0.39)	4.88(0.30)	5.55(0.38)	5.01(0.53)	4.81(0.51)	4.97(0.43)	4.74(0.34)	4.51(0.45)	4.84(0.46)	4.45(0.16)	4.36(0.22)
Mean peak pressure (N/cm^2)												
M-9.1 F-7.6	5.47(0.50)	4.93(0.53)	4.88(0.49)	5.46(0.55)	5.02(0.58)	4.78(0.50)	4.95(0.61)	4.83(0.46)	4.67(0.56)	4.93(0.44)	4.60(0.40)	4.55(0.39)
M-13.2 F-9.3	5.57(0.48)	5.21(0.59)	4.97(0.39)	5.66(0.55)	5.18(0.63)	4.91(0.42)	5.35(0.47)	4.86(0.46)	4.64(0.52)	5.22(0.59)	4.88(0.56)	4.64(0.60)
M-17.1 F-12.3	6.12(0.48)	5.44(0.44)	5.21(0.35)	5.55(0.38)	5.52(0.72)	5.26(0.57)	5.07(0.77)	4.96(0.59)	4.75(0.64)	5.56(0.73)	4.98(0.38)	4.76(0.30)

M-male subjects F-female subjects.

The data were further analyzed to explore the gender effect on the mean measured responses. For this purpose, the data were grouped for male and female subjects with comparable anthropometric dimensions. Table 3.6 summarizes the data grouping and the ranges of parameters considered. While no trends could be observed with the stature related factors, the mass- and build-related factors showed notable gender effect on the mean APMS responses. As an example, Figures 3.14 to 3.16 show the gender effect on the mean APMS responses of subjects sitting with NB posture and exposed to 0.50 m/s^2 rms 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 are considerably higher than those of the female subjects, except in the case of the lean body mass. For comparable lean body mass, the peak APMS magnitude responses of female subjects are somewhat higher. However, with same body fat and mean peak pressures, the primary resonance frequency of male and female subject responses were comparable.



(a) (b) (c)

Figure 3.14: 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)

Table 3.6: Coefficient of determination (r^2) between the peak APMS magnitude with selected anthropometric parameters under different excitation magnitudes and two back support conditions

	Anthropometric parameters	Male						Female					
		No back support			Vertical back support			No back support			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	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
stature-related	Stature (m)	0.14	0.18	0.17	0.18	0.15	0.12	0.09	0.12	0.06	0.12	0.09	0.10
	Sitting height (cm)	0.08	0.13	0.11	0.14	0.15	0.07	0	0	0	0.02	0	0
	C7-height (cm)	0.08	0.11	0.09	0.12	0.11	0.08	0.09	0.07	0.04	0.08	0.03	0.03
mass-related	Body mass (kg)	0.92	0.93	0.90	0.93	0.89	0.88	0.81	0.82	0.84	0.89	0.80	0.83
	BMI (kg/m^2)	0.89	0.93	0.90	0.88	0.83	0.88	0.76	0.72	0.83	0.81	0.77	0.77
	Body fat mass (kg)	0.84	0.83	0.81	0.79	0.70	0.74	0.83	0.77	0.83	0.83	0.87	0.90
	Body fat %	0.66	0.64	0.62	0.57	0.49	0.54	0.70	0.56	0.65	0.64	0.74	0.75
	Lean body mass (kg)	0.77	0.68	0.66	0.73	0.73	0.68	0.54	0.57	0.54	0.61	0.44	0.46
build-related	Hip circumference (cm)	0.83	0.82	0.80	0.83	0.73	0.75	0.71	0.70	0.71	0.71	0.72	0.74
	Contact area (cm^2)	0.59	0.53	0.56	0.50	0.48	0.56	0.27	0.24	0.29	0.19	0.23	0.25
	Mean contact pressure (N/cm^2)	0.19	0.17	0.08	0.03	0.04	0.17	0.08	0.09	0.19	0.06	0.12	0.04

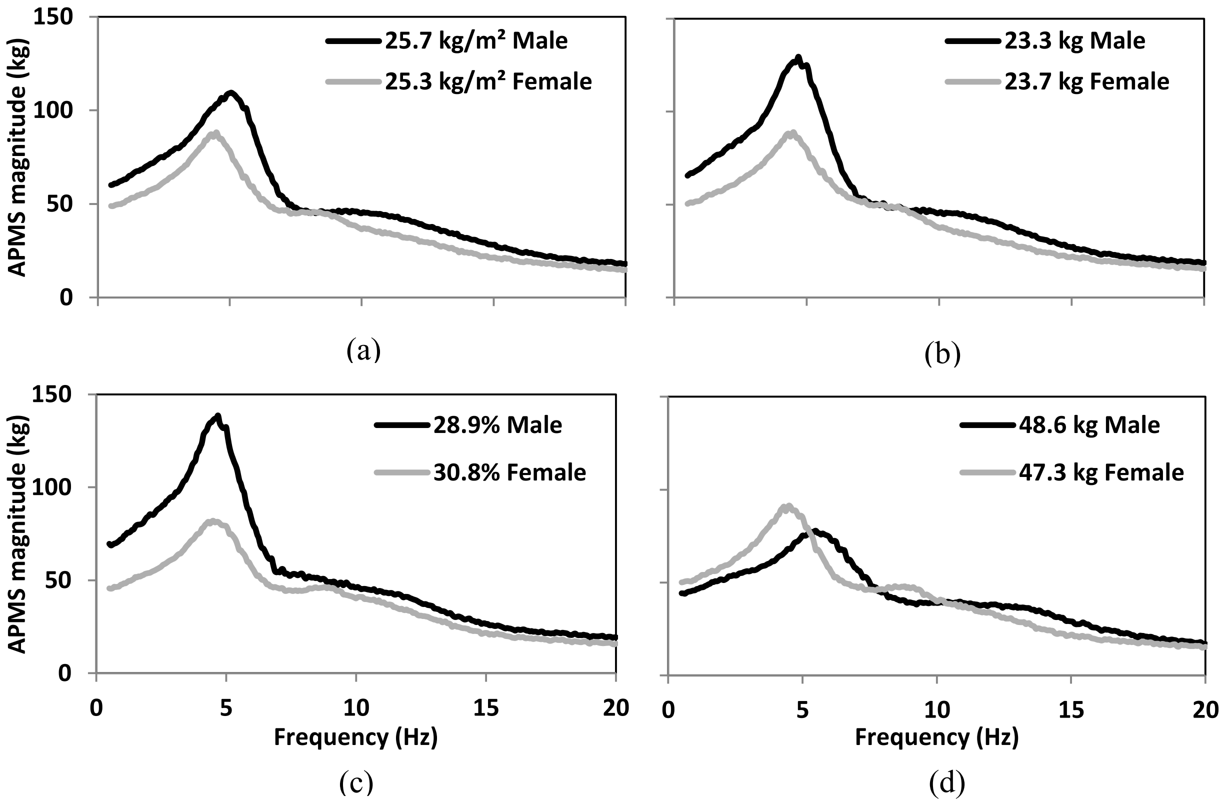


Figure 3.15: Effect of gender on the mean APMS magnitude responses considering comparable mass-related factors: (a) BMI; (b) fat body mass; (c) fat body percentage; and (d) lean body mass (NB posture, 0.50 m/s^2 excitation)

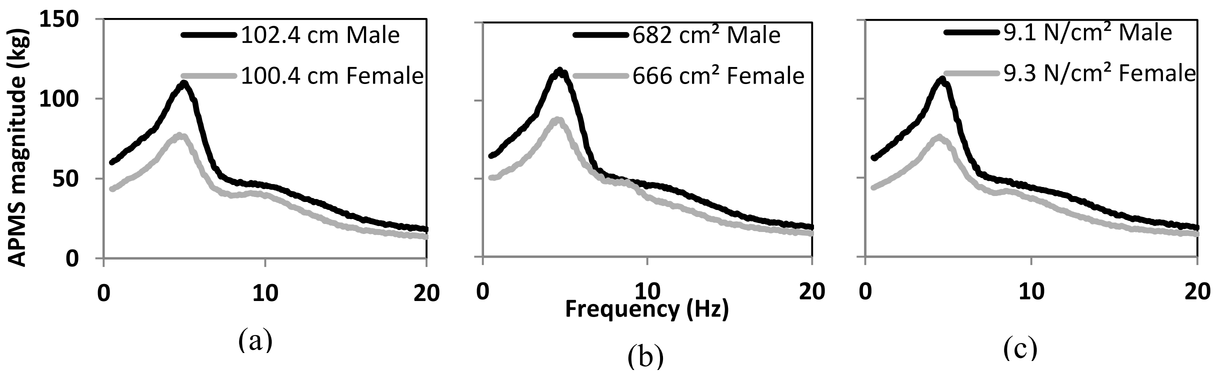


Figure 3.16: Effect of gender on the mean APMS magnitude responses considering comparable build-related factors: (a) hip circumference; (b) contact area; and (c) mean peak pressure; (NB posture, 0.50 m/s^2 excitation)

3.5.3 Peak response variations

The results in Figure 3.11 to 3.16 suggest highly complex and coupled effects of anthropometric dimensions, apart from the body mass and the gender. The data are further analyzed to study correlation of the mean peak APMS and the corresponding frequency with the selected anthropometric factors. Figures 3.17 and 3.18 illustrate the variations in peak APMS magnitudes of the male and female subjects over the ranges of mass-related variations of the subjects. The results are presented only for NB posture and 0.50 m/s^2 rms excitation. Similar correlations, however, were observed for the WB posture and higher excitation magnitudes. In a similar manner, Figures 3.18 and 3.19 illustrate variations in peak APMS magnitudes with variations in the selected body mass- and build-related factors, respectively.

The results in general show considerable dispersion in the peak response with all of anthropodynamic dimensions. Moreover, the female subjects responses were better correlated with the body fat compared to the male subjects responses, while the correlation with mass showed an opposite trend. Figures 3.20 to 3.22 illustrate the variations in primary resonant frequency (the frequency corresponds to Peak APMS magnitude) observed from the male and female subjects, data with variations in the bod mass, mass- and build-related factors. The results, in general, show that the primary peak resonance frequency of the male and female subjects is significantly and negatively correlated with most of the anthropometric dimensions. The responses of the male subjects generally exhibit better correlations than those of the female subjects. Moreover, the responses obtained with no back support were better correlated compared to those acquired with a back support. For both genders as well as sitting conditions, correlation coefficients decreased as the magnitude of excitations increased.

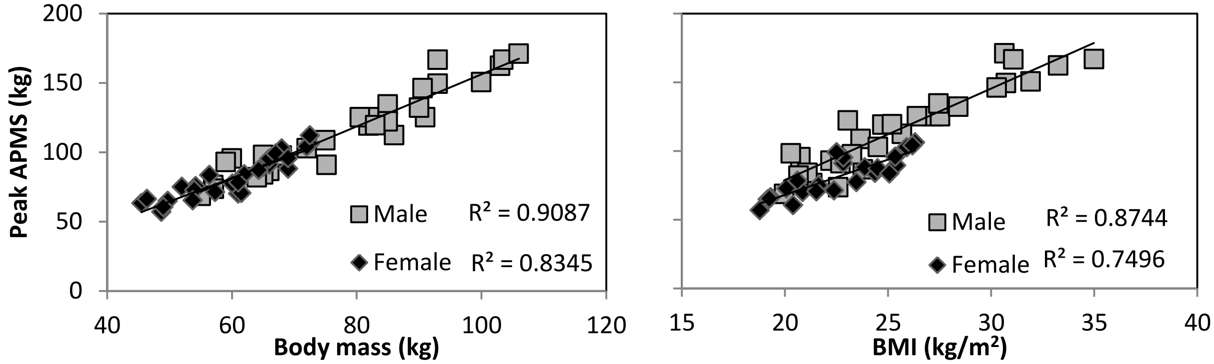


Figure 3.17: Correlation between the peak APMS magnitude responses of male and female subjects and the body mass and BMI (NB posture, 0.50 m/s² excitation)

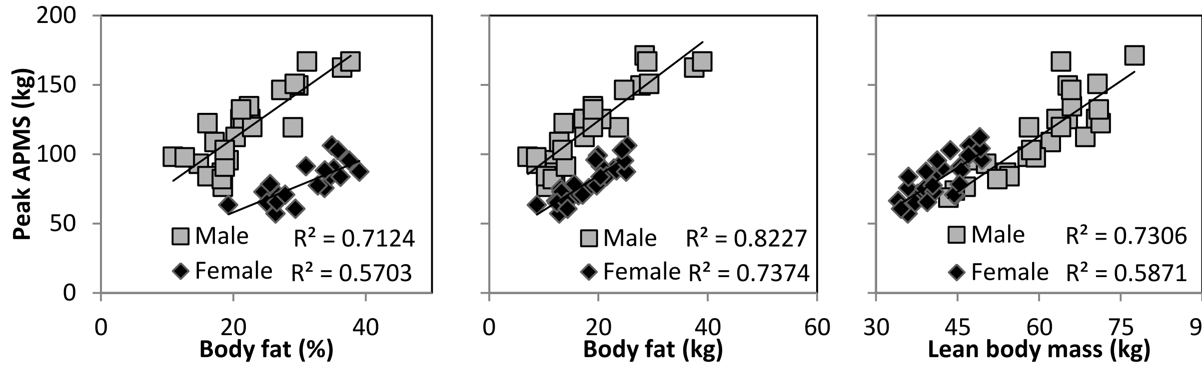


Figure 3.18: Correlation between the peak APMS magnitude responses of male and female subjects and the body fat percentage, body fat and lean body mass (NB posture, 0.50 m/s² excitation)

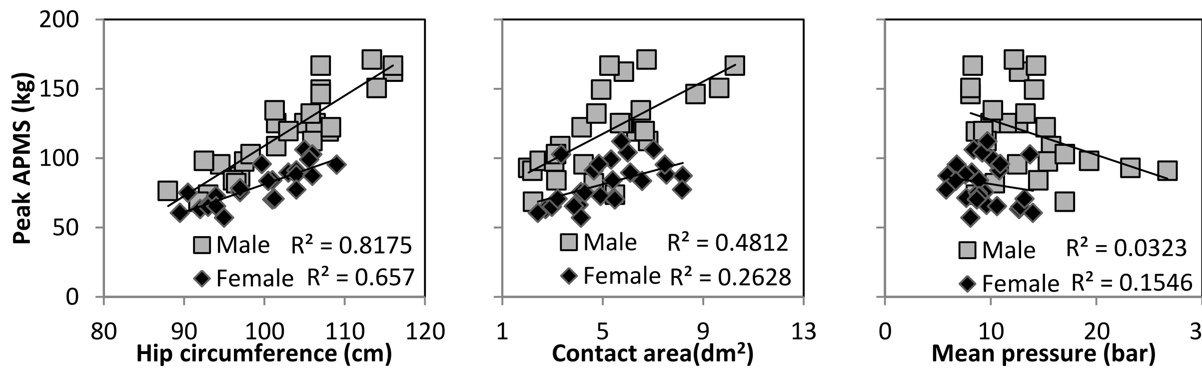


Figure 3.19: Correlation between the peak APMS magnitude responses of male and female subjects and the hip circumference, contact area and mean pressure (NB posture, 0.50 m/s² excitation)

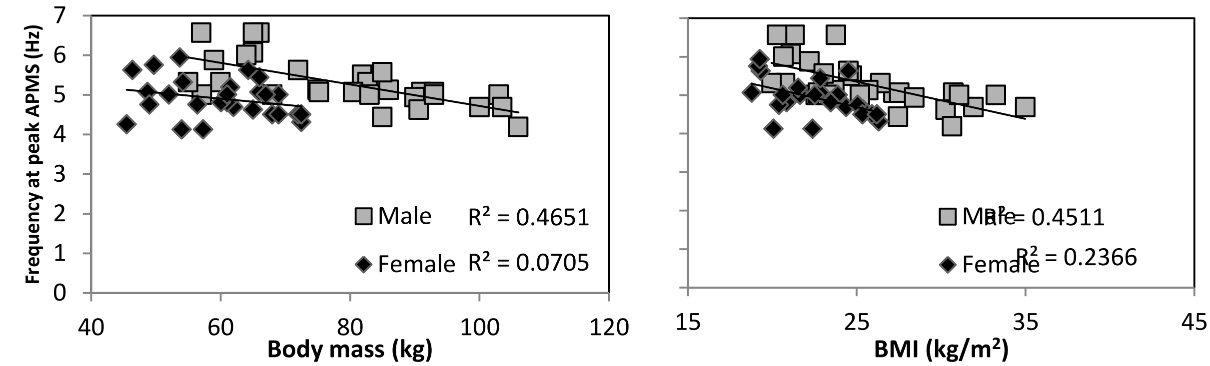


Figure 3.20: Correlation between the frequency at peak APMS magnitude responses of male and female subjects and the body mass and BMI (NB posture, 0.50 m/s^2 excitation)

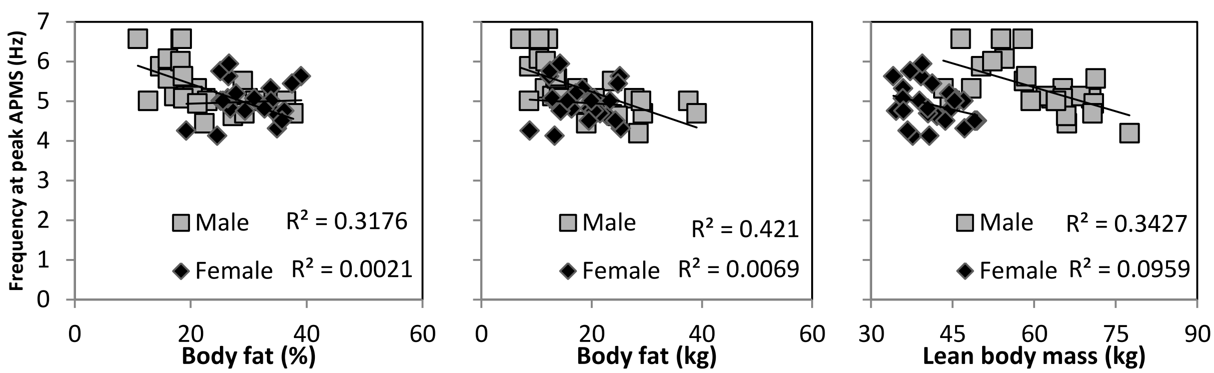


Figure 3.21: Correlation between the frequency at peak APMS magnitude responses of male and female subjects and the body fat percentage, body fat and lean body mass (NB posture, 0.50 m/s^2 excitation)

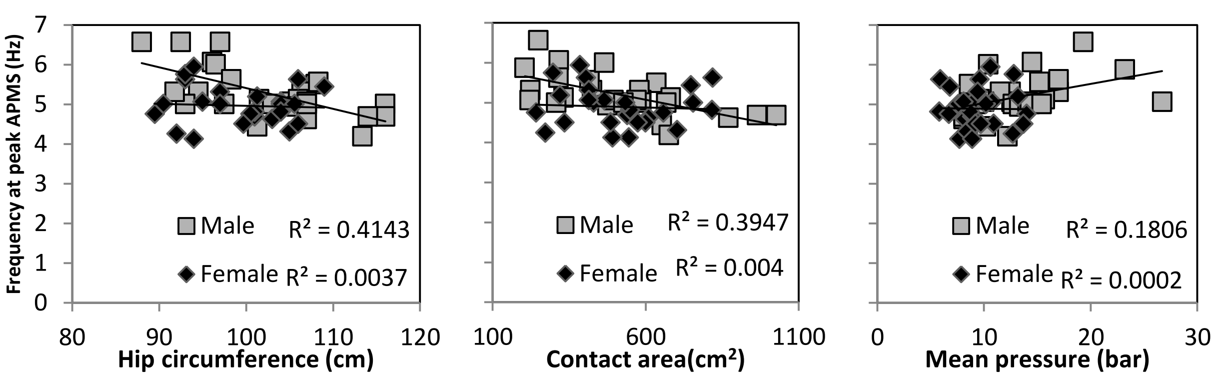


Figure 3.22: Correlation between the frequency at peak APMS magnitude responses of male and female subjects and the hip circumference, contact area and mean pressure (NB posture, 0.50 m/s^2 excitation)

3.6 Discussion of Results

3.6.1 APMS response characteristics

The general trend in the APMS responses were similar to those reported in early studies [33,52], and 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. Large variations in the body mass 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 in the reported studies [33,52,68,70]. Although the data scatter at lower frequencies reduced by normalization, however, 9.8 to 15.6 Hz for vertical back support posture and 6.3 to 17.2 Hz for the no back support posture were magnified. As reported by Toward and Griffin [52], the normalization significantly reduced standard deviation of the mean near resonance, while the scatter at higher frequencies could not be reduced. Wang et al. [33] also reported similar scattering of the normalized APMS responses.

Toward and Griffin [52] further suggested that the APMS response could be obtained by multiplying the appropriate normalized APMS response by the sitting weight target population. However, in 5.75 to 6.75 Hz frequency range, the estimated APMS response was higher. About 50% higher values was obtained for man subjects, while 40% of subjects showed lower value in this frequency range for the NB posture. Furthermore, for the male as well as female subjects the measured APMS responses and the estimated APMS response showed significant differences, particularly at 5 Hz and in the 8 to 10 Hz frequency range. Therefore, multiplying the normalized APMS response with the sitting body mass of the target population is not an appropriate option for computing the APMS magnitude response.

APMS response was also altered by normalization of the APMS magnitude. For example largest normalized magnitude occurred for the lower body mass (61.0 kg male subjects and 50.4 kg female subjects) at frequencies above 6 Hz, whereas the absolute APMS response peaks would be expected to be higher for higher body mass, as evident in Figure 3.10.The normalization may thus be considered desirable to reduce variability at lower frequencies but it cannot eradicate the strong effect of body mass and is not representative of APMS response characteristic of the group.

3.6.2 Effect of gender on APMS

Holmund et al. [54] reported lower mean resonance frequency the driving-point mechanical impedance (DPMI) of the female subjects as compared to the male subjects. Whereas according to Mansfield et al. [32], female subjects APMS responses revealed slightly higher mean resonance frequency than the male subjects. With the reclined rigid backrest significant effect of gender on the resonance frequency was observed by Toward and Griffin [52], while there was no effect of gender when sitting without a backrest, or against a vertical rigid backrest or a reclined elastic back rest. Furthermore, Manisfield et al. [32] reported lower normalized APMS magnitude of male subjects in 6 to 10 Hz range as compared to the female subjects. Similarly, Holmlund and Lundström [76] reported that the female subjects showed a more distinct second peak for DPMI at frequencies around 10 Hz, and in several cases this peak exceeded the primary peak in magnitude. The reported studies done evaluating the APMS and DPMI responses with respect to the gender effects considered male and female subjects of considerably different body masses. Wang et al. [33] suggested coupled effects of gender and the body mass on the APMS responses, which was evident from the data obtained in this study (Figure 3.7). In the present study higher value of the peak normalized APMS response of the male subjects is attributed to higher body mass of the subjects composed 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 as compared to the female subjects.

From the responses obtained with 5 subjects, of similar body mass (male: 71.4±7.4 kg; female: 71.4±3 kg) Wang et al. [33] observed the presence of more clear second resonance peak in the frequency range 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 the male subjects' responses revealed higher APMS magnitude at lower frequencies. According to few researchers, the secondary resonance peak may be attributed to pelvic and viscera mass of the human body. Kitazaki and Griffin [38] identified the pelvic pitch mode at 8.1 and 8.7 Hz, and the higher visceral mode at 9.3 Hz. These are also supported by the results reported by Coermann [47] which showed peak relative motions of the pelvis near 5 and 9 Hz. Matsumoto and Griffin [96] also observed peak seat-to-pelvis transmissibility in the 7 to 10 Hz range. The mode observed near 9.1, 8.7 and 9.3 have been suggested to correspond to secondary resonance 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 [75]. Females have most of the body fat (adipose tissue) deposited in the pelvis and thighs causing higher hip circumference and thus higher pelvic mass as compared to males. Therefore, higher APMS magnitude at secondary mode of vibration may be caused due to the higher pelvic mass. Moreover, the higher fat mass within the pelvic and thigh region may have resulted in relatively lower secondary resonance frequency of the female subjects.

In comparison to female subjects of same body mass, the male body is relatively stiffer as indicated by higher value of the primary resonance frequency in the present study. This difference in body stiffness may be due to anatomical differences between the genders. As compared to males, females possess higher fat mass and lower muscle mass. The stiffness-to-mass ratio is thus relatively lower due to higher ratio of body fat mass to lean body mass, which would result in lower resonance frequency [55].

Furthermore, muscles are visco-elastic material showing thixotropic behavior, i.e. viscosity decreases when stress is applied making it shear rate-dependent, whereas the body fat (adipose tissue) is anti-thixotropic material, i.e., an increase in shear rate would yield higher viscosity [97].

Furthermore, lower value of mean pressure is shown by female subjects at the seat-body interface and higher contact area as compared to the male subjects having same body mass. For female subjects, there was more uniform distribution of pressure at the body-seat pan interface, which could also contribute to lower primary resonance frequency.

Many studies have discussed the softening tendency of human body with increasing excitation magnitude [28,33,51,52,54,70]. For both body mass groups (60 and 70 kg), the male subjects responses in the present study showed relatively greater softening effect compared to the female subjects' responses. This increased softening tendency in the male subjects' responses may have been caused by lower body fat mass and higher muscle mass, i.e., the lean body mass, in comparison to the female subjects. The lean body of male and female subject within group I were 49.6 and 41.9 kg respectively, while those of group II were 58.8 and 47.6 kg. The reduction in the primary resonance frequency may have been caused by, although the muscle thixotropy body fat content also contributed to the resonance frequency. The primary resonance frequency of the male subjects might be more affected by the combined effects of muscle and fat mass.

In comparison to males seated with the reclined rigid backrest, study by Toward and Griffin [52] reported females to have significantly less softening tendency with increased vibration magnitude. Patra et al. [70] reported that at frequencies greater than the primary resonance frequency APMS response is influenced by variations in the excitation magnitude. The APMS responses in the 6 to 8 Hz showed far greater effect for no back support posture. For the no back support posture, the APMS response obtained in this study are comparable with those reported by Patra et al. [70] beyond primary resonance frequency. Unlike female subjects, male subjects' responses in the present study showed more variations in 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 [33,67,70]. The present study observed similar trends in APMS responses without and with a vertical back support for the 31 male and 27 female subjects under 0.25, 0.50 and 0.75 m/s^2 excitations (Figure 3.7).

ISO 5982 [77] defines the range of idealized value derived from the model, which were based on APMS response of the male subjects. Body mass effects on APMS responses recognized by this benchmark provide the reference values for three body masses of 55, 75 and 90 kg. However, with same body mass, the two gender exhibit different APMS response characteristics, where the differences are largely 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 [77] may not be applicable. Study of APMS responses for both genders having higher body mass may give little more insight as this study focuses on both genders of relatively lower body mass of 60 and 70 kg. Further, for revision of ISO-5982 [77] it would be desirable to study other biodynamic characteristics of male and female subjects of comparable body masses, as suggested by Rakheja et al. [86].

3.6.3 Effects of anthropometric parameters on APMS

According to reported studies [69,33,70], heavier subjects exhibit higher APMS magnitude and lower primary resonance frequency as compared to the lighter subjects. Identical trends are also evident in the results of the present study (Figure 3.9). Furthermore, the results in the study revealed that for subjects with considerably different masses, mean or median biodynamic responses do not clearly demonstrate the effect of body mass on the peak magnitude and the corresponding frequencies, nor are the properties of subjects of particular masses represented by them. Moreover, the mean and median responses tend to suppress the secondary peaks in the biodynamic responses. Furthermore, the mean responses that are widely reported do not strongly coupled with the body mass effect. It is true essential to consider subject population of particular body masses to establish the reference values for the purpose of standardization.

Similar to the body mass effect, the peak APMS magnitude increases with increase in dimensions of most of the anthropometric parameters considered in this study (Figures 3.11 to 3.13). 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 the trends with variation in the mean contact pressure were also not observed, which is also poorly correlated with the body mass(r^2<0.3). Toward and Griffin [52] reported that peak APMS magnitude increases with increase in stature and BMI, which are highly correlation. Holmlund et al. [54] 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 vertical APMS or DPMI magnitude at frequencies up to and slightly above the primary resonance, while there is negatively correlation of primary resonant frequency with the body mass [28,33,67,72]. With most of the anthropometric parameters considered in the study, the measured responses showed identical trends in peak APMS magnitude and the primary resonance frequency (Figures 3.17 to 3.22). There may be variety of reasons for poor correlation between primary resonance frequency and anthropometric parameters. Human body is a very intricate system and the recruited subjects vary largely in body dimensions, body type (endomorphic, ectomorphic and mesomorphic), type of muscles (fast twitched and slow twitched), ethnic group and pressure distribution over the seat pan due to different buttock profile. Furthermore, it was preferred to maintain normal posture, but some subjects failed to maintain the same 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.

3.7 Summary and Conclusions

Effect of gender and some anthropometric parameters on the apparent mass (APMS) responses of human occupants seated on a rigid seat and exposed to whole body vertical vibration was investigated through measurements performed on 31 male and 27 female subjects. Comparison of responses characteristics of male and female subjects' of comparable body masses revealed that peak APMS magnitude responses of both genders were comparable, while the male subjects responses revealed considerably higher primary resonance frequency as compared to the female subjects. The secondary mode of vibration was more prominent for the female subjects, relatively higher APMS magnitude near the secondary mode of vibration was observed for the female subjects compared to the male subjects. In both sitting conditions, with increase in excitation magnitude, male subjects showed greater softening effect of body as compared to the female subjects. Irrespective of the excitation magnitude, sitting with a vertical back support resulted in nearly 10% lower peak, APMS magnitude compared to no back support for both genders. The magnitude of excitation significantly affected the primary resonance frequency, while peak APMS magnitudes were comparable under the chosen excitation levels. However, the sitting conditions showed an opposite trend, i.e., with no back support there was significantly higher peak APMS magnitude compared to that obtained with sitting against a vertical back support. The effect of postural variations on the primary resonance frequency was relatively negligible.

With exception of the lean body mass, for the same anthropometric dimension, the male subjects demonstrate considerably higher peak APMS magnitude response compared to female subjects. There were complex effects of anthropometric parameters on the primary resonance frequency. Irrespective of the back support condition and excitation magnitude, a very high linear positive correlation (r^2>0.7) was observed between peak APMS magnitude and body mass, body mass index, body fat and hip circumference for both the genders. However, the peak APMS magnitude was moderately (lean body mass and body fat percentage) to poorly (stature, age, contact area) correlated with other anthropometric variables.

Normalization, obtained by dividing the APMS magnitude by seated mass of the subject altered the APMS response considerably but it could not eradicate strong effect of the body mass. At some frequencies, normalized APMS response magnitudes were significantly greater than measured magnitudes. From the study, it can be concluded that APMS response characteristics are significant affected by the gender. Irrespective of the gender, the peak APMS magnitude further depends on the body mass, whereas, the primary resonance frequency depends on the body fat and few other anthropometric parameters in addition to the body mass.

CHAPTER 4
APPARENT MASS RESPONSES MEASURED USING SEAT PRESSURE MAT

4.1 Introduction

The biodynamic responses of seated occupants on the rigid seat subjected to vertical whole-body vibration have been extensively characterized under broad ranges of experimental conditions. On the basis of a synthesis of the reported data [10], International standards organization has defined idealized ranges of biodynamic response characteristics of the seated subjects exposed to vertical vibration in the 0.25 – 20 Hz range [77]. The defined ranges are applicable for adult human subjects sitting erect without a back support but feet supported and exposed to vertical vibration with magnitude equal to or less than 5 m/s^2, and body mass in the 49 to93 kg range. Passive and active anthropodynamic manikins have been developed using the apparent mass (APMS) responses defined in the standard [77]. Furthermore, a number of biodynamic models have been developed for applications in seating design and dynamics [18-22]. However, the applications of both the anthropodynamic manikins and biodynamic models have met limited success thus far [17,98], which is partly due to lack of considerations of the body coupling with elastic seats.

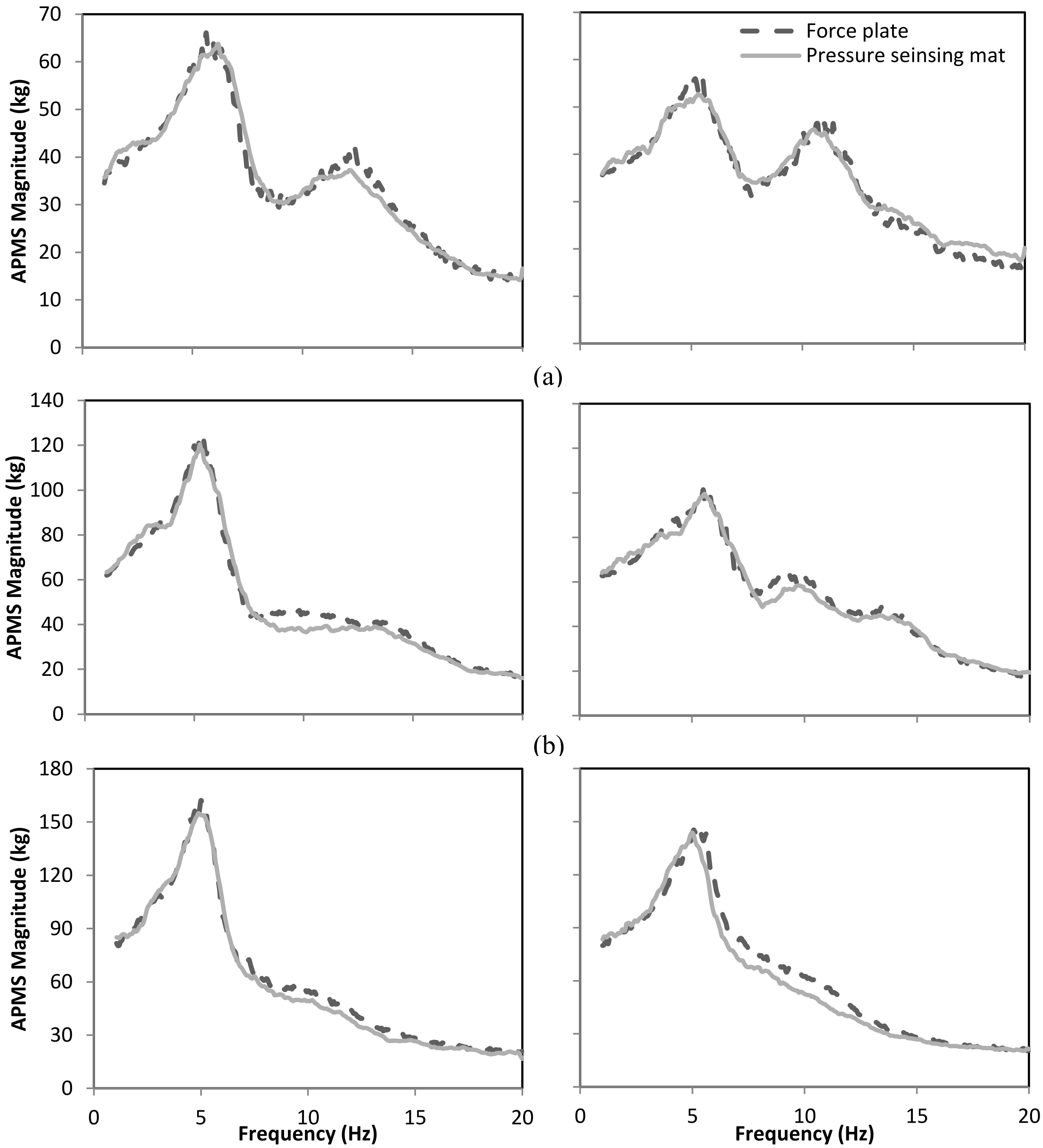
In order to attain uncoupled body responses to vibration, the human body biodynamic responses are invariably characterized with body seated on a rigid seat. This condition cannot be considered representative of vehicle seats since an elastic seat cushion substantially alters the body-seat contact, sitting posture and the seated body weight distribution on the seat [56,57]. Wu et al. [57] measured distribution of contact pressure and forces of the human subjects seated on a rigid and a visco-elastic seat while exposed to vertical vibration. They observed that interface pressure on the cushion seat is more evenly distributed on a larger effective contact area than on rigid seats. The peak contact pressure on an elastic cushion seat is significantly lower compared with that on a rigid seat, while the effective contact area on the elastic seat is significantly larger, which suggested more uniform distribution of body weight on elastic seats. Furthermore the magnitude of dynamic pressure was considerably larger than the static pressure, irrespective of excitation frequency and magnitude, posture and seat height. Heavy subjects generally revealed lower ischium pressure as a result of increased effective contact area compared to light-weight subjects [11,81]. Furthermore, sitting on a soft flexible seat causes relative motions across the legs, which is absent with a rigid seat [82]. The pelvis rotates about the ischial tuberosities in the sitting position, which causes dominant pelvic motion.

The biodynamic properties of the seated body on an elastic seat under whole body vibration are thus expected to differ from those acquired while sitting on a rigid seat. Characterization of biodynamic response of human subjects seated on more realistic elastic seats is thus vital for developing effective seating design tools and anthropodynamic manikins. The measurement of biodynamic forces at the elastic body-seat interface, however, involves numerous difficult challenges, particularly for contoured seat cushions. Thus far, only a single study has attempted to measure biodynamic responses of subjects seated on elastic seats and exposed to vertical WBV [26]. Though this pioneering study on the soft seat has provided important guidance studies, the study revealed many limitations. A tri-axial accelerometer embedded in a rubber pad was fixed at the seat cushion near one of the ischial tuberositisty to capture the interface acceleration, which might have altered the contact pressure and thus the biodynamic force. Most of all, the study employed controlled vibration at the seat base only, which resulted in considerably different vibration levels at the human-seat interface depending upon visco-elastic properties of the cushion. Owing to considerably different vibration levels encountered on rigid and elastic seats, the differences in the measured APMS could not be entirely attributed to cushion elasticity

It is thus important to measure APMS responses of the human body sitting on the cushion seats and under levels of vibration comparable to those employed for the rigid seat. In this chapter the seated body APMS for a cushion and a rigid seat are presented under comparable levels of broad-band random vibration. The data acquired on a flat cushion are analysed to derive APMS responses for the three excitation levels (0.25, 0.50 and 0.75 m/s^2). The mean responses are compared with those obtained for the rigid seat and the contributions due to the seat cushion are discussed.

4.2 APMS Responses of Seated Subjects-Rigid Seat

The force data acquired from the seat pressure measurement system placed on the rigid seat are initially analysed together with the measured acceleration data. To obtain APMS of subjects seated on the rigid seat. The correction function derived in section 2.4.2 was applied to derive the APMS responses of the subjects. The resulting APMS responses, when compared with those reported in chapter 3, permitted the verification of the proposed correction function. The comparisons were performed for the data obtained under selected vibration excitations for (i) each individual subject; (ii) mean responses of each mass group; and (iii) 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, Figure 4.1 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) exposed to 0.5 m/s^2 rms excitation. The results are presented for both sitting conditions (NB and WB), which show reasonably good agreements in 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 frequency was greater for the light-weight subject (46.4 kg). The APMS magnitude derived from the force plate revealed peak magnitude of 66.10 kg at 6.25 Hz, while in case of the pressure sensing mat it was 63.69 at 6.19 Hz. For the WB condition, the error was also greatest for the light subject with peak magnitude derived from force plate being 56.24 kg at 5.5 Hz compared to 52.67 kg at 5.31 Hz from the pressure sensing mat. The comparisons for the light-weight subject resulted in errors in peak magnitude and corresponding frequency of 3.6% and 10%, respectively, for the NB condition, and 6.3% and 3.4% for the WB condition. The difference magnitudes were relatively lower for the medium- and high-weight subjects. The observed error is partly caused by lower pressure of the light-weight subject and poor resolution of the pressure sensing mat. The smoothing of the measured data could also cause a shift in frequency.



(c)

Figure 4.1: Comparisons of APMS magnitude responses of three subjects sitting without (NB) and with a back (WB) support, obtained from two measurement systems. Subject mass: (a) 46.4 kg; (b) 83.7 kg; and (c) 103 kg (0.50 m/s² excitation)

Figure 4.3 compares the APMS responses of the subjects of male and female subjects within specific body mass groups for the NB sitting condition. The mean responses of the male and female subjects were obtained for three different mass ranges (60, 80 and 92 kg for male subjects; 50, 60 ad 72 kg for female subjects), while each group consisted of 9 subjects. The results obtained from two measurement methods are presented for the selected three excitation magnitudes. The results again show greater differences in the APMS acquired from two methods under lower excitation magnitude of 0.25 m/s^2, which is mostly attributed to poor resolution of the pressure sensing mat. The results, obtained from two methods exhibit very good agreements for higher excitation magnitudes, particularly at frequency up to 10 Hz. Comparisons of the responses obtained from pressure sensing system and conventionally used force plate, presented in Figures 4.1 to 4.3, show that the APMS responses of subjects seated on a rigid seat could be accurately characterized by the pressure sensing system when the proposed correction function is applied to account for poor acquisition rate and resolution of the measurement system. Figure 4.2 illustrates comparisons of mean APMS responses of all the subjects under the three excitation magnitudes and two sitting conditions considered in the study. The responses obtained from the two methods compared reasonably well in the entire frequency range for both sitting conditions and different vibration levels. Relatively larger differences, however, are evident from the responses under the lower excitation (0.25 m/s^2), which is again attributed to poor resolution of the seat pressure measurement system. The comparisons showed differences of 3.0% and 3.2% in the peak APMS magnitude for the NB and WB conditions, respectively. However, in the vicinity of the secondary resonance frequency the peak differences in the order of 6.0% and 2.9% were obtained for the NB and WB sitting conditions, respectively, under 0.75 m/s^2 excitation.

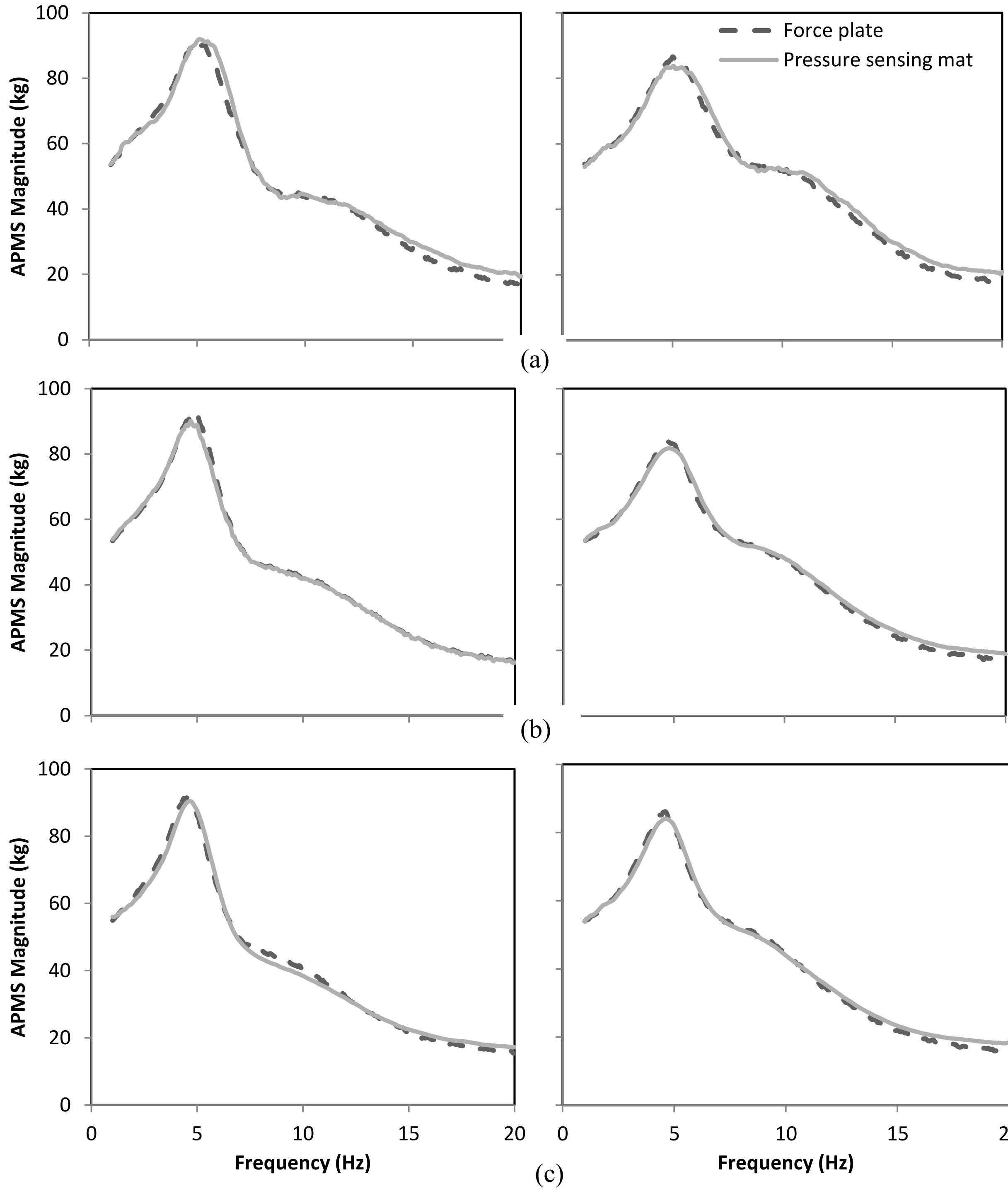


Figure 4.2: Comparisons of mean APMS magnitude responses of 31 male and 27 female subjects seated with different postural condition exposed to : (a) 0.25 m/s^2; (b)0.50 m/s^2; and (c) 0.75 m/s^2 excitation

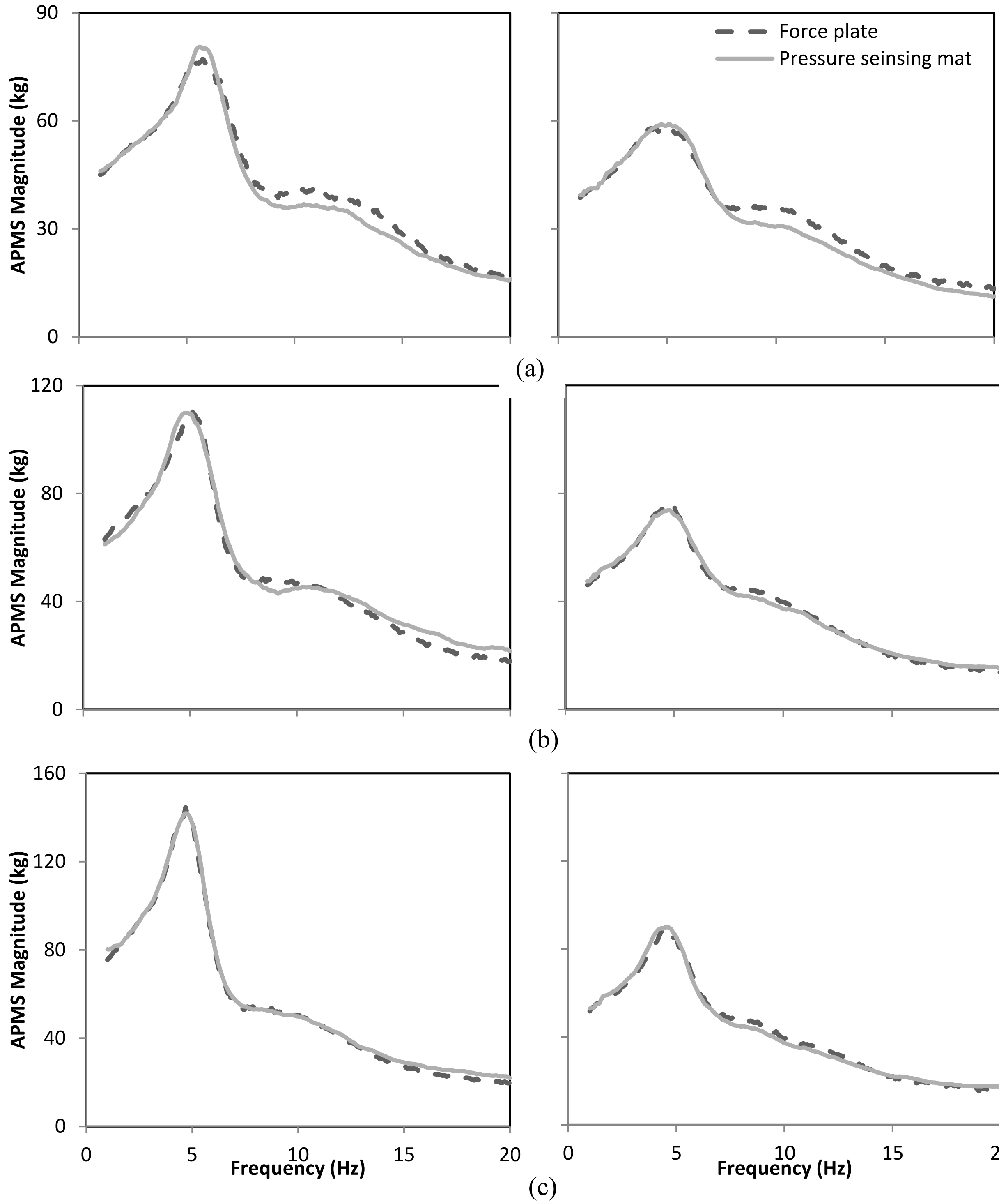
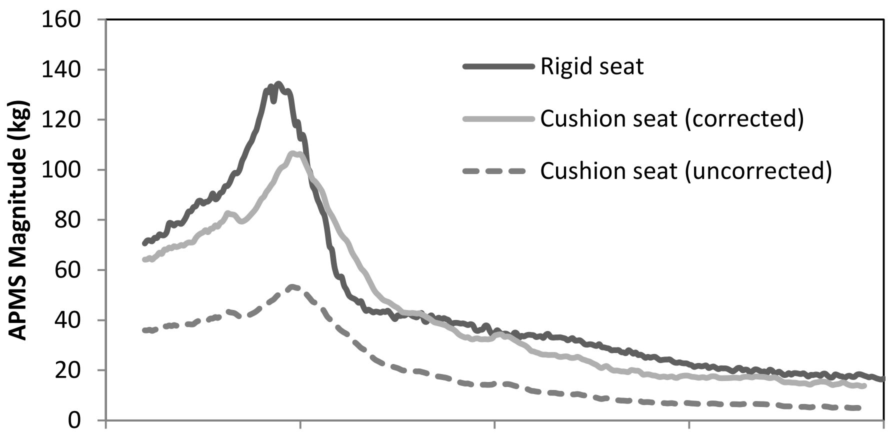


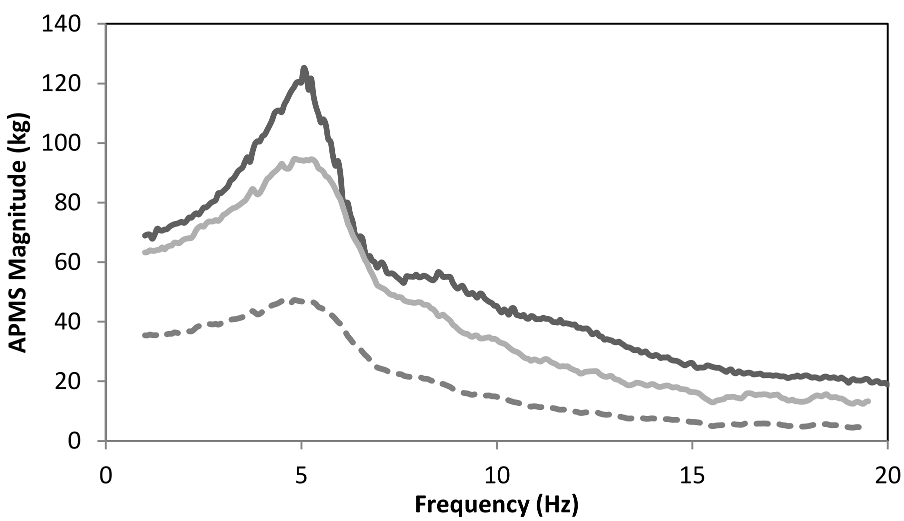
Figure 4.3: Comparisons of mean APMS magnitude responses of subjects seated in different mass groups (male 60kg, 80kg, 92kg; and female 50kg, 60kg and 72 kg) with no back support condition exposed to: (a) 0.25 m/s^2; (b)0.50 m/s^2; and (c) 0.75 m/s^2 excitation

4.3 Application of Correction Function on Cushion Seat

The applicability if the seat pressure measurement system was further examined through analyses of APMS responses of the human subjects seated on a cushion seat and exposed to three selected magnitudes of vibration. For this purpose, the correction functions derived from the rigid seat data were applied. The APMS responses were derived for both sitting conditions, NB and WB. The applicability of the measurement system was initially examined by comparing individual responses acquired for the cushion seat with those derived for the rigid seat. The measured responses, invariably, showed large differences between the APMS of the subjects seated on rigid and cushioned seats. As an example, Figure 4.4 illustrates comparisons of the measured APMS responses of an 81 kg subject seated on rigid and cushion seats with back unsupported and supported conditions and exposed to 0.5 m/s^2 excitation. The figure also illustrates APMS responses of the subject sitting on the cushion with both sitting conditions when the correction functions are applied. The results clearly show large differences between the rigid seat APMS and the uncorrected APMS for the cushion seat in the entire frequency range. Similar large differences are also evident at the low frequency of 1 Hz, which is expected to be close to static seated mass of the subject. Upon application of the correction functions, the low frequency APMS magnitudes of the subject seated on the cushion approach those obtained for the rigid seat. The comparisons, however, show considerable differences between the corrected APMS magnitudes of the subject seated on the cushion seat and those obtained for the rigid seat, particularly around the primary resonance. These differences are attributed to the elastic properties of the cushion and changes in the contact area. The results in general show lower APMS magnitude for the cushion seat compared to the rigid seat. It should be also noted that the responses do not show presence of a peak corresponding to resonance frequency of the seat cushion (around 4.3 Hz). This is due to equalization of the vibration level at the occupant-cushion interface by the vibration controller. The controller suppresses the control signal around the resonance to achieve nearly flat PSD of the excitation at the subject-cushion interface.



(a)



(b)

Figure 4.4: Comparisons of corrected and uncorrected APMS responses of an 81 kg subject seated on the cushion with those obtained for the rigid seat under 0.5 m/s² excitation: (a) no back support; and (b) with a vertical back support.

Similar trends were also observed in the data acquired for all the subjects. From the comparisons, it was concluded that the seat pressure measurement system could be applied to estimate APMS responses of human subjects seated on the cushion seats, and exposed to vertical vibration. The corrected APMS responses, however, show 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 resolution and acquisition rate would be desirable.

The biodynamic force developed at occupant-cushion interface is expected to depend strongly on many factors. These include the visco-elastic properties of the cushion, contouring of the cushion surface, sitting condition that can alter the pressure distribution on the seat cushion, thigh contact with the seat cushion, and anthropometry-related factors. Owing to relatively poor resolution of the measurement system, the contributions of the peripheral low pressure contact zones may not be adequately accounted for, which may further depend upon the build of the individual subjects. The corrected data obtained for all of the 58 subjects were thoroughly examined in view of the low frequency APMS magnitude, which was expected to be in the order 78 to 80% of the standing boy mass. Some of the data revealed deviations in excess of 15% when compared to the low frequency APMS magnitude obtained with the rigid seat, particularly under lower excitation of 0.25 m/s^2. This large deviation was believed to be caused by poor resolution 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 the subsequent analyses. The selected datasets, grouped under different mass groups of the two genders, are summarized in Table 4.1.

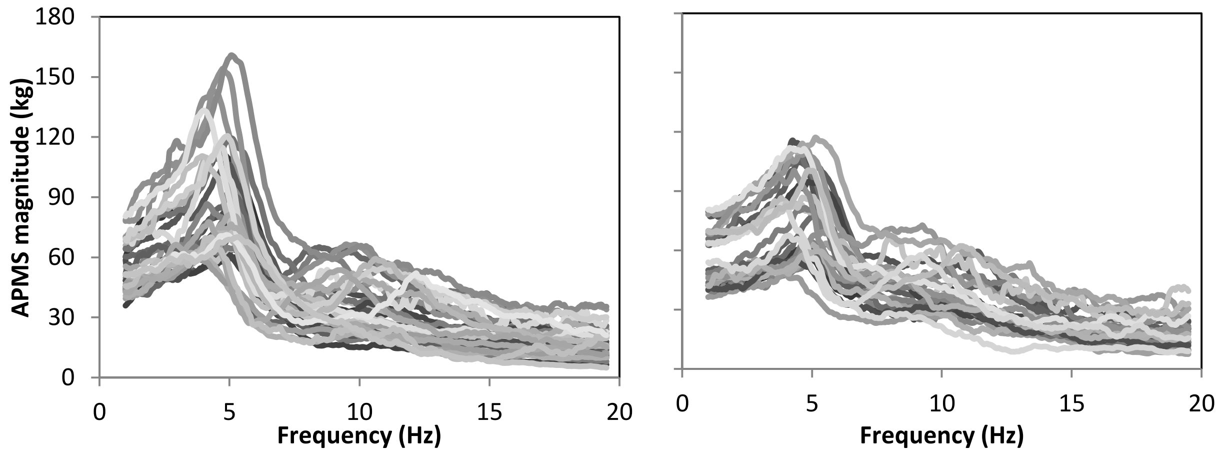
This grouping of selected datasets was undertaken so as to study the effect of excitation magnitude, body mass and the posture. Relatively fewer dataset, however, could be selected for the WB posture, particularly under 0.25 m/s^2 excitation.

Table 4.1: Selected datasets for analysis of APMS responses of subjects seated on the cushion seat

Sitting Condition	Excitation magnitude (m/s^2)	Datasets n	Body mass (kg)		Datasets within mass groups						
					Male ≈				Female ≈		
			Mean	SD	60kg	70kg	80kg	92kg	50kg	60kg	72kg
NB	0.25	30	72	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	24	74.8	18.3	5	1	6	7	4	0	1
	0.50	28	74.1	18.1	4	1	5	7	3	4	4
	0.75	31	71.9	16.8	4	2	5	6	4	5	5

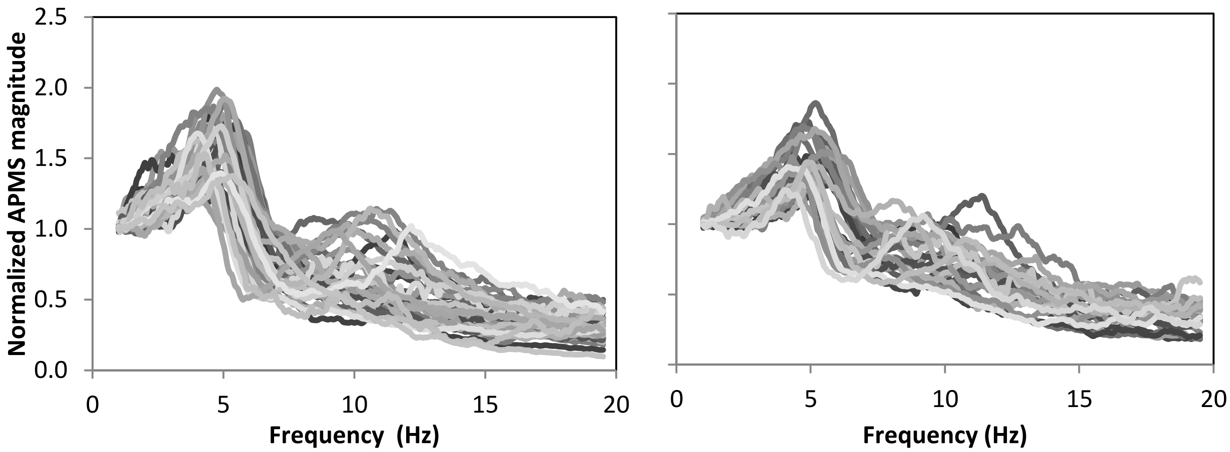
4.4 Characteristic of APMS Responses of Subjects Seated on the Cushion

The measured APMS responses of the subjects are initially compared to examine inter-subject variability in a qualitative sense. As an example, Figure 4.5 illustrates variations in the APMS magnitude responses of selected subjects exposed to 0.5 m/s^2 rms acceleration excitation. The results show large differences in both the magnitude and phase responses, while the predominant magnitude peaks occur within narrow frequency bands. The responses obtained for no back support posture exhibit peak APMS magnitude in 3.52 to 5.38 Hz range, while the peak APMS for the back supported posture occur in the 3.56 to 5.38 Hz range, The observed ranges of primary resonance frequency, are lower than those observed for the rigid seat (NB: from 4.1 to 6.1 Hz; and WB: 4.06 to 6.94). Distinct secondary peaks are also evident in responses of many subjects in the 7 to 13 Hz range. The measured data show considerable scatter, which at lower frequencies, is mostly caused by the body mass variations. For no back support posture, the coefficient of variation (CoV) ranged from 22% to 34% in the 1 to 6 Hz frequency range. Within same range of frequencies, the results for the vertical back support posture revealed slightly lower CoV, in the 23% to 30% range. Irrespective of the sitting posture, unlike the rigid seat data the coefficient of variation did not decrease with increase in the frequency for the no back support posture. The coefficient of variation (CoV) ranged from 27% to 48% at frequencies above 7 Hz the data obtained for the back support posture also revealed relatively lower CoV as in case of lower frequency range, form 23% to 42%. These again suggest poor acquisition rate and resolution of system in the high frequency range the scatter in the lower frequency range may be reduced through normalization of the APMS magnitude with respect to the static sitting mass. Figure 4.6 illustrates the normalized APMS magnitude responses of the selected subjects for the two sitting conditions exposed to 0.5 m/s^2 excitation. The normalized responses exhibit slightly lower scatter in the entire frequency range. The peak values of CoV of the normalized data were obtained near 40% for the no back support posture and 35% for the back supported posture. Similar to the results obtained for the rigid seat, the results for the cushion seat suggest that the scatter in the data cannot be eliminated through normalization with respect to the body mass alone.



(a) (b)

Figure 4.5: Apparent mass magnitude responses of subjects seated on the elastic cushion with (a) no back support and; (b) a vertical back support (excitation: 0.50 m/s^2)



(a) (b)

Figure 4.6: Normalized apparent mass magnitude responses of subjects on the elastic cushion with (a) no back support and; (b) a vertical back support (excitation: 0.50 m/s^2)

4.4.1 Comparisons of mean APMS responses on the cushion seat with rigid seat

Figure 4.7 illustrates comparisons of mean APMS response of the subjects seated on the cushion and rigid seat with and without a back support under 0.50 m/s^2 rms excitation. The figures show mean responses of 31 subjects seated on the cushion without a back support (mean body mass= 73.2) with mean APMS of same subjects seated on the rigid seat. For the back support sitting condition, the mean response for the cushion seat is evaluated from 28 subjects datasets (mean mass=74.1 kg). The two APMS responses exhibit nearly identical magnitudes at low frequency, which is attributed to comparable body masses of the subjects used in the two studies. The comparisons further show that the APMS magnitude, obtained with the rigid seat are considerably higher compared to those for cushion seat in the nearly 3 to 15 Hz range. The differences appear to be greater in the vicinity of the primary and secondary resonance frequencies. For NB sitting condition, the peak mean APMS magnitude for the cushion seat is 84.4 kg, occurring at 4.625 Hz, compared to 99.3 kg for the rigid seat occurring at 5 Hz. Similarly for the WB condition, the cushion seat resulted in peak APMS of 77 kg at 4.625 Hz compared to 91.1 kg a 5.625 z for the rigid seat. The results thus show that irrespective of sitting posture, a cushion seat yields lower peak APMS and lower corresponding frequency. Similar trend were also observed under other vibration magnitudes. This is attributed to distribution of body weight over a larger contact area and elasticity of the seating surface.

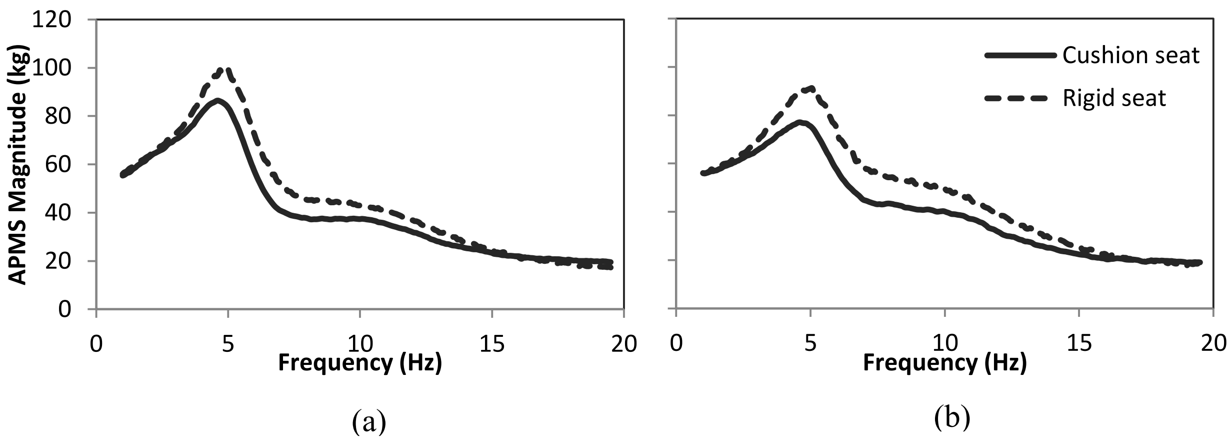
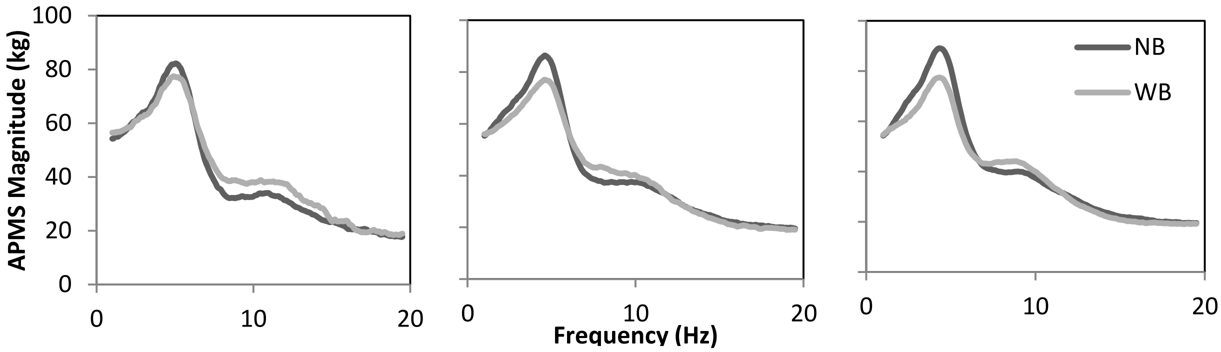


Figure 4.7:Comparison of mean APMS responses of subjects seated on a rigid seat and cushion seats and exposed to 0.5m/s^2 excitation :(a) no back support ; and (b) with back support.

The results, further show that the secondary peak APMS magnitude corresponding to NB posture is in the order of 37.6 kg for the cushion seat occurring at 8.44 Hz. For the rigid seat this peak value tends to be higher (45.5 kg) and occurs at a slightly higher frequency of 8.5 Hz. Similar trend is also evident in the responses obtained with WB sitting condition. In this support condition, the peak APMS for the cushion seat is 43.42 kg occurring at 7.88 Hz compared to 5.68 kg for the rigid seat at 8.63 Hz. The results suggest that an elastic seat tends to shift the primary resonance in APMS towards a lower frequency, while the cushion seat yields lower peak response that may be attributed to its damping.

4.4.2 Effect of back support

The results in Figure 4.7 also illustrate the important effects of back support on the APMS magnitude responses, which have been reported for rigid seats only [12,33].The data are further analyzed to study the effect of back support on the APMS responses of subjects seated on the cushion seat alone under different excitations. The mean responses are presented considering the data for 24 (mean mass =74.8 kg), 28 (mean body mass =74.1 kg) and 31 subjects (mean mass= 71.9 kg), respectively, under 0.25, 0.50 and 0.75 m/s^2 excitations. The result presented in Figure 4.8, show that the APMS response magnitudes of subjects sitting with no back support are higher than those obtained with a back support around the primary resonance frequency. Sitting with a back support yields peak APMS magnitudes of 82.3, 86.4 and 89.0 kg, respectively, under 0.25, 0.50 and 0.75 m/s^2 excitations. The corresponding peak magnitudes for the WB posture were obtained as 7.5, 77.8 and 77.4 kg. Opposite trends, however, are evident with regard to the back support effect around the secondary resonance. These suggest that a back support serves to constrain the body motion and yields more damping response. Such trends have also been reported in the responses obtained with rigid seats [12,33]. Although the second peak in the mean responses is less clear due to data averaging, the results further show the primary frequencies corresponding to mean peak response with no back support (5.06, 4.64 and 4.31 Hz under 0.25, 0.50 and 0.75 m/s^2 excitations, respectively) are quite close to those observed from responses with the vertical back support (4.94, 4.64 and 4.31 Hz, respectively). This may in-part be attributed to contributions of elastic properties of the cushion. These frequencies may relate to resonance frequencies of the coupled seat-occupant system unlike those obtained with a rigid seat.



(a) (b) (c)

Figure 4.8: Comparisons of mean APMS magnitude of selected subjects siting with different postures exposed to (a) 0.25 m/s2; (b) 0.50 m/s^2; and (c) 0.75 m/s^2

4.4.3 Effect of vibration magnitude

Figure 4.9 illustrates comparisons of APMS magnitude responses attained under selected excitation magnitudes. The results are presented for the two sitting conditions, NB and WB. Softening tendency of the human body is evident from the results for both sitting conditions, which show decrease in primary resonance frequency with increase in magnitude of excitation. Such a softening tendency has been widely reported in many studies on characterization of biodynamic responses of human subjects seated on rigid seat and exposed to WBV [24,29,33,36,58,59]. But unlike the APMS responses measured on a rigid seat, the peak APMS for the cushion seat increases with increase in excitation magnitude corresponding to NB sitting condition, as seen in Figure 4.9(a). The peak APMS magnitudes with WB sitting condition, however, remain quite comparable irrespective of excitation magnitude. The softening tendency with increasing vibration magnitude for the two postures was further studied by considering changes in the primary resonance frequency and the corresponding APMS magnitude, with increase in excitation magnitude from 0.25 to 0.75 m/s^2. The analyses revealed comparable softening effect of vibration magnitude for both sitting conditions. The primary frequency of the mean responses shifted from 5.06 to 4.31 Hz for NB condition and from 4.93 to 4.31 Hz for WB condition, when the excitation magnitude was varied from 0.25 to 0.75 m/s^2.

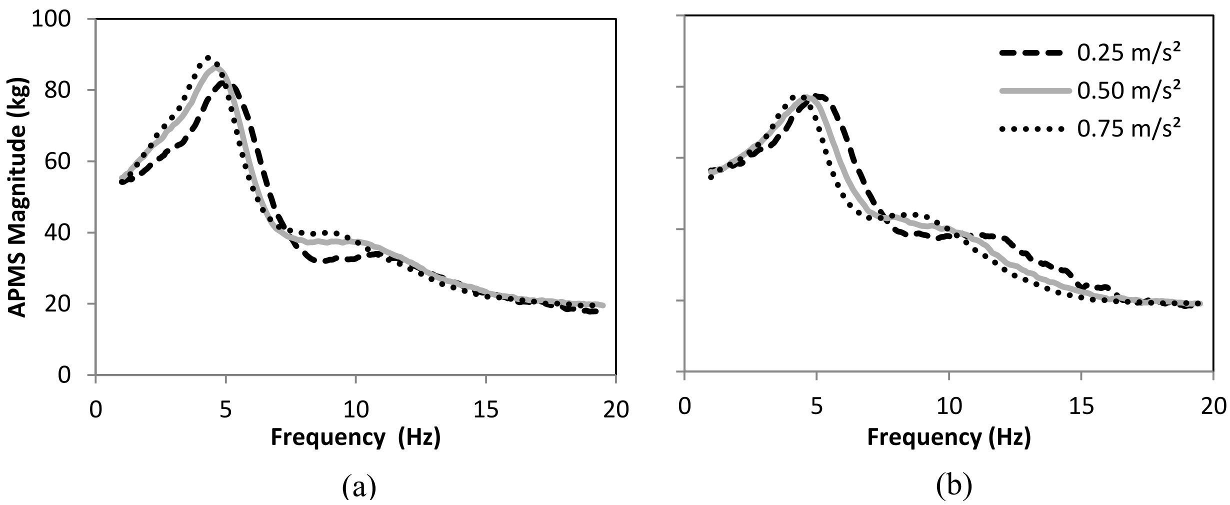


Figure 4.9: Comparisons of mean APMS magnitude responses of subjects exposed to different vibration magnitude while sitting on a cushion seat with: (a) no back support; and (b) with a vertical back support.

4.5 Discussions

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 [26]. The study investigated APMS responses of 12 subjects (79.3±24.3 kg) seated on a cushion seat with back support against a inclined backrest, (inclined angle = 17 to28 degrees with respect to vertical axis). The study employed three different vibration magnitudes at the seat base, while amplification/attenuation of vibration to the cushion was not considered. The white-noise random vibrations with nearly flat acceleration PSD were synthesized at the seat base to realize rms acceleration of 0.25, 0.80 and 1.6 m/s^2, the rms acceleration and spectra of vibration encountered at occupant-seat interface thus differed considerably.

In the present study, the experiment was designed so as to realize nearly constant acceleration PSD spectra at the seat cushion with overall rms acceleration of 0.25, 0.50 and 0.75 m/s^2. The resulting acceleration at the seat base also measured and analyzed. The Transmissibility of base to cushion surface has been analysed and revealed peaks around 4.19, 9 and 14.6 Hz, attributed to resonance frequency of cushion (Figure 4.10), while the overall rms accelerations were obtained as 0.35, 0.68 and 0.98 m/s^2 corresponds to 0.25, 0.50 and 0.75 m/s^2 rms accelerations at the seat cushion. These clearly show that a seat cushion would impose significantly different levels of vibration upon the occupant, when the control is limited to seat base alone.

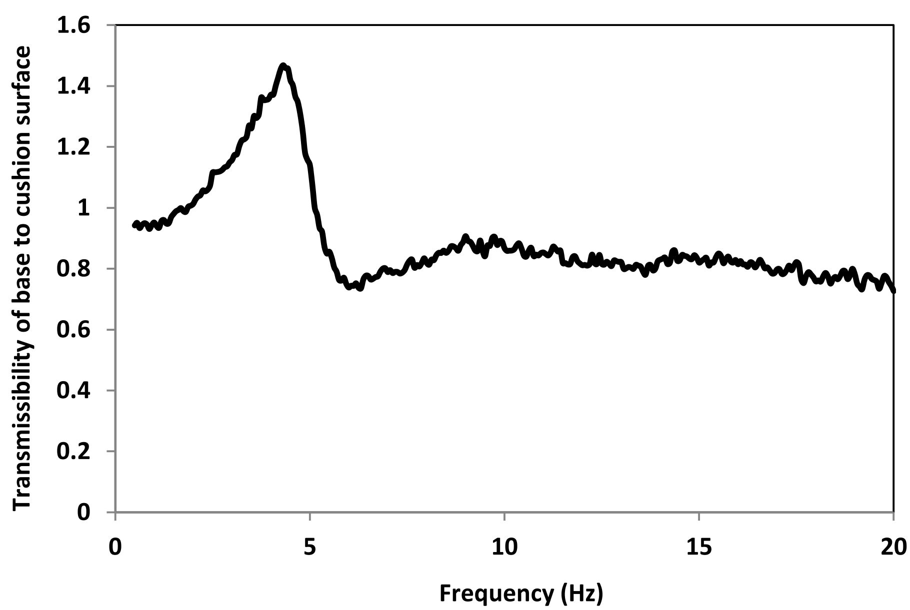


Figure 4.10: Transmissibility of the base to cushion surface while 81 kg subjected seated on the cushion seat under 0.5m/s^2 excitation.

The mean APMS magnitude response of subject reported under 0.8 m/s^2 [26] is compared with that obtained in this study under 0.75 m/s^2 excitation (Figure 4.11). Although the mean body mass of subjects considered in the reported study (79.3 kg) was higher than that of subjects in the present study (71.9 kg), the low frequency APMS magnitude in the reported study is significantly lower compared to corrected and uncorrected result of current study. This may in-part be caused by low resolution of the capacitive pressure sensing mat used in the study. Furthermore, the peak APMS in the reported study is slightly below 50 kg, which is believed to be quite low. This peak magnitude is even lower than the mean body mass supported by the 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.

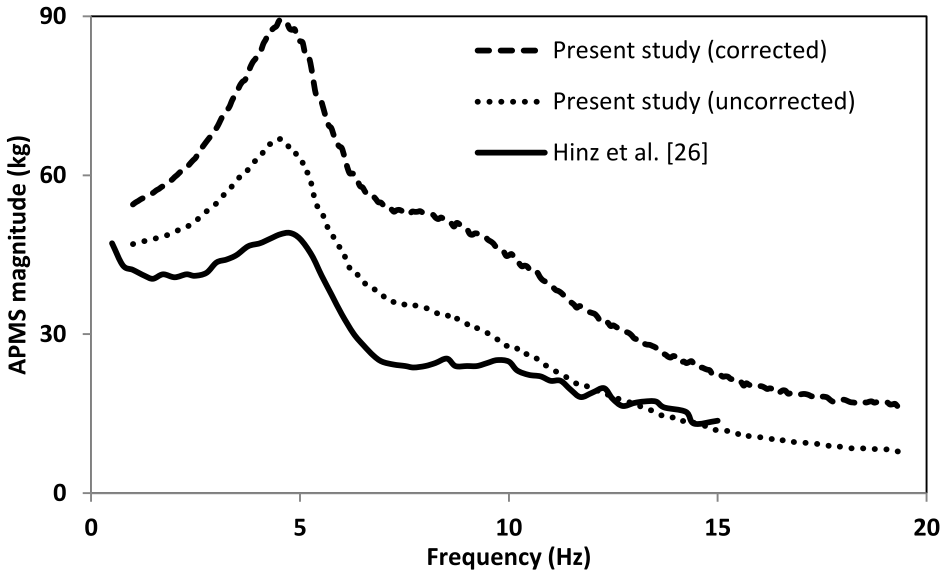


Figure 4.11: Comparison of mean APMS magnitude obtained in the current study (31 subjects mean mass= 71.9 kg; and a vertical back support) corrected and uncorrected, with that reported by Hinz et al. [26] (13 subjects mean mass=79.3 kg; and an inclined back support).

Table 4.2 compare the primary and secondary peak magnitudes and the corresponding frequencies with those reported [26]. The comparison again shows that the peak values obtained in this study are considerably larger than the reported values. Furthermore, the frequencies corresponds to the primary and secondary peaks are also generally lower that those reported, except in the case of primary frequency under 0.75 m/s^2 excitation. This may be partly caused by differences in the stiffness of two cushions used in the study and the backrest inclination.

Figure 4.12 further compares the normalized APMS magnitude with the reported normalized response under the same excitation. In the present study, the data were normalized by seated mass of respective subjects (75% of the standing body mass), while the normalizing in the reported study was performed using the measured seated mass which ranged from 46% to 61% of the total body mass if the subjects. The comparison also reveals identical trends in the measured and reported responses. The reported APMS magnitude is considerably smaller than that obtained in this study in the entire frequency range. Comparable values are observed only at low frequency of 1 Hz, which is due to different normalization factors considered in the two studies.

Table 4.2: Comparisons of the reported primary and secondary peak APMS magnitudes and the corresponding frequencies with those obtained in the current study

	Hinz et al. [26]		Present study	
Excitation (rms acceleration m/s^2)	0.25	0.80	0.25	0.75
Primary peak magnitude (kg)	48	53.3	77.5	77.4
Primary peak frequency (Hz)	5.25	4.08	5.06	4.31
Secondary peak magnitude (kg)	29.0	29.8	55.8	53.1
Secondary peak frequency (Hz)	10.48	8.32	9.63	7.69

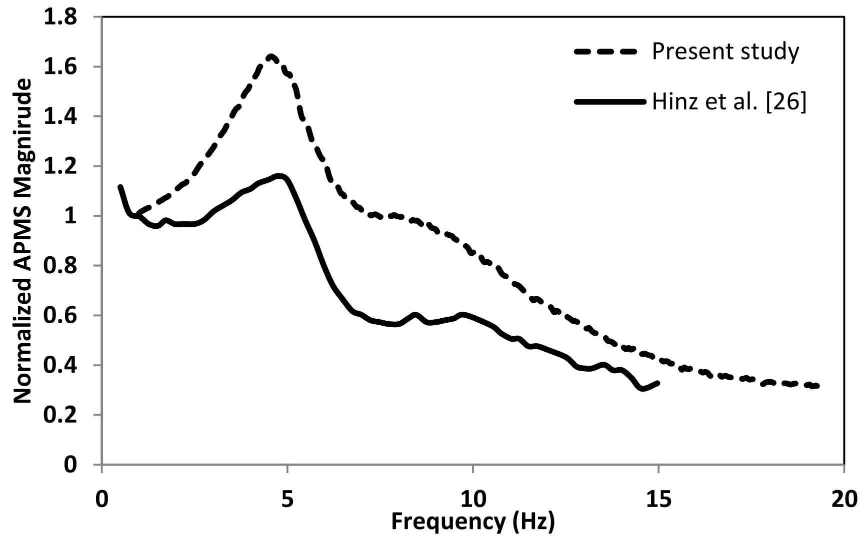


Figure 4.12: Comparison of mean normalized APMS magnitude obtained in the current study (31 subjects mean mass= 71.9 kg; and a vertical back support), with that reported by Hinz et al. [26] (13 subjects mean mass=79.3 kg; and an inclined back support).

4.6 Summary

The applicability of the pressure sensing system for APMS responses of human subjects seated on a cushion seat is explored. It is shown that the measurement system could provide good estimates of the biodynamic responses of subjects seated on elastic seats when the proposed correction function is applied. It is further noted that the biodynamic force measured at the occupant-seat interface is strongly related to cushion properties, the pressure distribution and build of the subject. A pressure distribution over a broad contact area would yield lower pressure of the sensels near the periphery of the contact zone, which may be below the resolution of the sensels. A greater error may thus be encountered for subjects with wider contact area. The results show that the primary peak APMS magnitude of the subjects seated on a cushion seat is lower than that measured for the rigid seat. The primary resonance frequency is also lower for the cushion seat composed to the rigid seat, which is attributed to elastic seat cushion. An opposite trend, however, was observed around the secondary resonance, which is believed to be caused by damping properties of the cushion.

CHAPTER 5
CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

5.1 Major Contributions of the Study

The primary goals of this dissertation research included investigation of a methodology for characterizing apparent mass responses of human subjects seated on an elastic seat and exposed to whole-body vertical vibration, and the effects of anthropometric factors on the APMS responses. The major contributions of the study are summarized below:

a. A flexible and thin-film pressure mapping system is explored for measurement of biodynamic force developed at the human-seat interface, and its limitations in terms of resolution and limited acquisition rate are thoroughly illustrated through repeated measurements of responses with known rigid masses placed on rigid and elastic seats.
b. Owing to observed errors in the measured responses of known masses, a correction function is proposed in order to account for limited resolution and acquisition rate of the measurement system.
c. The vertical apparent mass (APMS) responses of male and female subjects of varying body mass and anthropometric dimensions are measured using the conventional force plate and the pressure sensing systems. The data obtained are thoroughly analyzed to illustrate the effects of gender, and mass-, stature- and build-related anthropometric factors, where the current knowledge is limited. These analyses however were limited to data acquired with the rigid seat.

d. The validity of proposed correction function is demonstrated by comparing the responses obtained from the two measurement systems for the rigid seat.

e. Proposed correction function is applied for characterizing the responses of body seated on cushion seats, and the results are discussed in view of effects of the cushion and other selected contributory factors such as back support condition and magnitude of vibration.

5.2 Major Conclusions

The major findings of the study are summarized below:

a. The APMS responses of subject seated on the rigid seat derived from pressure measurement system was considerably lower than that derived from a force plate. The difference in magnitude increased nearly linearly with frequency suggesting limited acquisition rate of the hardware. The ratio of the APMS magnitudes derived from pressure sensing mat and the force plate is thus proposed to serve as an appropriate correction function.

b. The application of the correction function to the responses derived from pressure sensing system resulted in APMS magnitudes comparable with those obtained from the force plate for all excitation and back support conditions considered.

c. From comparisons of APMS responses of subjects seated on rigid and elastic seats, it is concluded that the APMS response with a cushion seat is considerably lower in the 3 to 15 Hz range, irrespective of the back support and excitation conditions. This is attributable to more uniform distribution of the body weight on an elastic seat and partly due to pelvic rotation. Furthermore, the seat cushion owing to its visco-elastic properties results in relatively lower primary resonance frequency of the APMS responses.

d. The peak APMS response of subjects seated on elastic seat without a back support increased by nearly 7.5% with increase in vibration magnitude, while the change in peak magnitude was negligible when sitting with a vertical back support. That may be attributed to elastic properties of the cushion; the effect tends to diminish with friction arising from the vertical back support.

e. Normalization of the measured responses cannot eliminate the effect of body mass, although it helps reduce data scatter at low frequencies but significantly alters the APMS responses at higher frequencies.

f. The effect of gender on the biodynamic response is strongly coupled with body mass and gender effect could be observed only when decoupled from the body mass effect. Comparisons of responses of male and female subjects of similar body mass revealed higher APMS magnitudes of female subjects near secondary resonance but lower magnitude near the primary resonance compared to the male subjects, irrespective to back support condition and excitation magnitude. Irrespective of the back support condition, male subjects revealed greater softening effect with increasing vibration magnitude compared to female subjects, while the gender effect on peak APMS magnitude was relatively small.

g. The APMS responses of the body are strongly affected by the back support; the peak magnitude without a back support is nearly 10% that than with a vertical back support.

h. Irrespective to vibration magnitude and back support condition, the peak APMS magnitude of subjects revealed a linear positive correlation ($r^2>0.7$) with the body mass, body mass index, body fat and hip circumference for both the genders. However, the peak APMS magnitude was moderately correlated with lean body mass and body fat and poorly correlated with stature and contact area. Furthermore, the peak APMS magnitude of male subjects is higher compared to the female subjects of comparable anthropometric dimensions.

5.3 Recommendations for Future Work

Owing to considerable complexities associated with measurements of biodynamic forces developed at an elastic human-seat interface under vibration, the present study is considered as an important attempt towards characterization of biodynamic responses of human body seated on typical elastic seats and exposed to whole body vertical vibration. Far greater efforts would be desirable in developing a more effective measurement system, which would facilitate more thorough studies on biodynamic responses to whole-body vibration and the contributions of visco-elastic properties of the seats. Some of these desirable further studies are briefly described below:

a. It is important to explore alternate measurement systems with relatively smaller number of sensels so as to improve the acquisition rate and resolution. The signal conditioning hardware that permits simultaneous acquisitions of force and acceleration would also be desirable to capture the phase responses more accurately.
b. The visco-elastic properties of the seat are expected to influence the body mass distribution, contact pressure and contact area in a significant manner. The biodynamic responses are thus expected to depend upon the seat properties. It would be desirable to characterize APMS responses of seated body coupled with seats of different visco-elastic

properties. The results would permit an analysis of dependence of APMS on seat cushion stiffness and damping properties and would thus allow for development of coupled seat-occupant models.

c. It would be possible to design seats that help reduce the power absorption by the body. Characterization of power absorption properties of the human body coupled with different seats would thus be desirable.

d. Considering the significant effects of back support condition, it is suggested that response characterizations be undertaken with inclined elastic back supports, as in typical vehicle seats. Measurements of through-the-body biodynamic responses of subjects seated with elastic cushion and backrest would be most desirable since this represents the true vehicle seating.

e. Developments in biodynamic models of the body seated on elastic seats are vital for developing effective seating design tool. The measured data should be analyzed to derive guidance towards modeling of the seated occupant.

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