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Transmissibility Response Analysis of a Human Body in Semi-Supine Posture Exposed to Low-Frequency Vibrations

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Abstract

The study presents transmissibility responses of 14 male subjects exposed to vertical sinusoidal vibration (2.0-16.0 Hz) at five vibration magnitudes (0.5-1.5 m s^{-2} r.m.s.). The vibration magnitudes are measured at five body locations: head, sternum, abdomen, thigh, and leg, for which the transmissibility at each body location is statistically analyzed. The nonlinearity in the transmissibility response, i.e., decrease in resonance frequency with an increase in vibration magnitude, is evident for the sternum, abdomen, thigh, and leg. The higher vibration magnitude causes greater segmental transmissibility at excitation frequency lower than the resonance frequency. The highest vibration transmissibility has been observed for the abdomen, followed by thigh, sternum, and head. The findings indicate that the higher energy content associated with the sinusoidal waveform further softens the tissues in contact with the vibrating surface.

Keywords: Semi-supine; Sinusoidal vibration; Transmissibility; Wilcoxon signed-rank test; Friedman two way analysis

Introduction

In the last few decades, many private enterprises such as SpaceX, Blue Origin, and Virgin Galactic have entered into space exploration with the motivation to make space accessible to people who are not astronauts, i.e., human spaceflight. During the dynamic phases of spaceflight, i.e., launch and re-entry, humans in semi-supine posture would be exposed to elevated vibration levels [1]. It would undoubtedly have a detrimental effect on health and could lead to deterioration of physical and psychological performance. To protect and prevent humans from the harmful impact of vibration, the dynamical response of the human body under such conditions must be known. Most of the existing studies on the human body address the effects of vibration along with eyeballs up/down (head-to-foot) condition, whereas, in spaceflight, the crew would experience the vibration along with eyeballs in/out (chest-to-back) condition [2]. Only a handful of studies deal with the influence of whole-body vibration on humans in semi-supine (eyeballs in/out) posture. A study on the supine subject under random excitation in a vertical direction obtained resonance frequency of head and sternum at 17.0 Hz and 10.0 Hz, respectively. In another study with semi-supine subjects, transmissibility responses showed a decrease in primary peak frequency from 10.94 to 9.38 Hz in the sternum, from 7.03 to 6.25 Hz in the upper abdomen, and from 9.38 to 7.81 Hz in the lower abdomen with the increase in vibration magnitude from 0.0625 to 1.0 ms^{-2} r.m.s. These studies show the presence of softening characteristics in the head, sternum, and abdomen, which lead to the resonance frequency shift with the increase in vibration magnitude [3-8].

Previous studies on the semi-supine subjects were designed to establish the mechanism of nonlinearity in the human body under varying vibration magnitude. The studies were mainly focused on the torso region without considering the responses of other body parts such as the head and lower limbs [9]. During spaceflight, the head would be critical for human- machine interaction, and vibration on lower limbs causes numbness, muscle tone, and formication. Therefore, the responses of these body parts would be required to completely map the dynamics of the semi-supine subject in a vibration environment. Secondly, for semi-supine posture under random vibrations, the nonlinearity in transmissibility responses was less consistent than in apparent mass response [10]. Although, the equal magnitude of random and sinusoidal vibration resulted in a similar apparent mass for the seated posture. Since semi-supine posture involves less soft tissues in contact with the vibrating surface, and the sinusoidal waveform has higher energy content. Therefore, the effect of sinusoidal vibration on the transmissibility response of the semi-supine subject might be different and hence needs further investigation, which was the motivation of this paper [11-16].

In light of the above facts, the present study is designed to investigate the significance of sinusoidal vibration on the vertical transmissibility of human subjects in semi-supine posture. In this experimental study, the transmissibility responses of 14 male subjects exposed to vertical sinusoidal vibrations (2.0-16.0 Hz) are measured at five body locations viz, head, sternum, abdomen, thigh, and a leg for five vibration magnitudes (0.5, 0.75, 1.0, 1.25 and 1.5 m s^{-2} r.m.s.). The statistical analysis is performed to evaluate the significance of variation in vibration magnitudes on the transmissibility at each body segment. The effect of inter-subject variability and demographic characteristics of subjects on the vertical transmissibility are also investigated [17].

Methods and Procedures

Subjects

In this experimental study, a group of fourteen healthy male subjects, involving faculty and students at the IIT Roorkee, voluntarily participated. The subjects are prior verified to not having any critical medical history, especially musculoskeletal disorders. The median (range) age of the subjects is 28, with weight and stature as 76.5 kg (58-98 kg) and 1.72 m (1.64-1.78 m), respectively. The Institute Human Ethical Committee approved the experimental study on human subjects, and consent was taken from each subject before beginning the experiment [18].

Apparatus

The experiment was conducted on the vibration simulator available in the Vehicle Dynamics Laboratory, IIT Roorkee, as detailed in Narayanamoorthy et al.. The vibration simulator consists of a rigid platform (2 m × 2 m) fabricated from a lightweight aluminum frame and a thick stainless steel corrugated plate supported by four helical coil springs. The platform was vertically excited by a 50 mm stroke and a 5.0 kN capacity hydraulic actuator (Bangalore Integrated System Solutions) [19]. The sinusoidal vibration of the platform was generated via actuator and controller through onboard software Test Builder. The actuator has a feedback loop that facilitates onboard monitoring and through which the controller fine-tunes the input signal to match the desired output excitation (Figure 1).

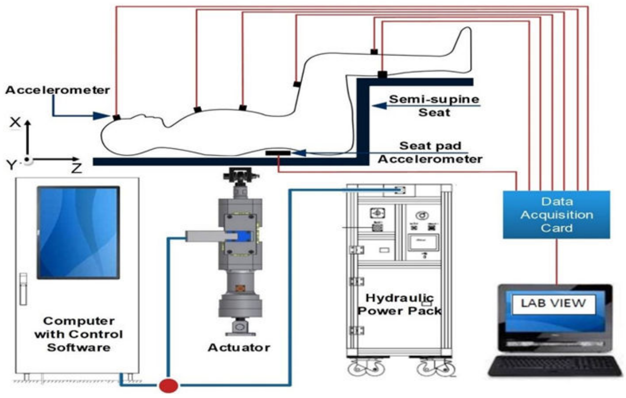

Figure 1: Schematic representation of vibration simulator.

The subject secures a comfortable posture by lying in a face-up position on the semi-supine seat. The leg rest of the seat was adjustable to accommodate subjects of different stature. The seat was firmly bolted to the simulator platform. Before beginning the experiments with subjects, a test was conducted to ensure that the natural frequency of neither seat nor platform falls within the current studied range (2.0-16.0 Hz). The transmission of vertical acceleration through the body was measured at five locations: head, sternum, abdomen, thigh, and leg [20]. Four lightweight low-frequency accelerometers (KISTLER 8305B10) were placed at the forehead, middle of the sternum, on the abdomen above the navel, and on the left lower leg anterior to the calves, respectively. One accelerometer (PCB 356A32) was mounted in the middle of the left thigh. The accelerometers were securely tied normal to the body surface with the help of the elastic strap. The vertical acceleration on the seat surface was measured at the backrest with a seat pad accelerometer (PCB 356B51) and leg rest with an accelerometer (PCB 356A02). The locations of all the accelerometers attached to the body and the seat pad are shown in Figure 2.

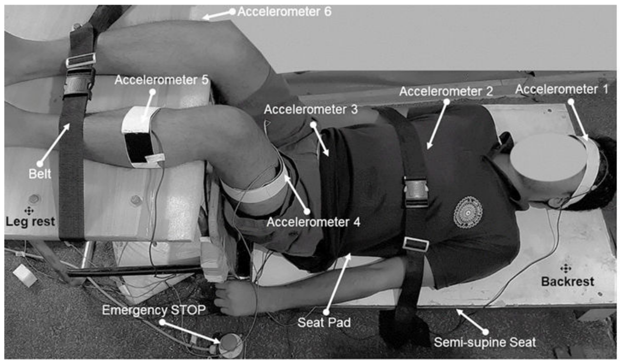

Figure 2: Subject lying on a semi-supine seat. The vibration signals were acquired using five accelerometers attached to the body at the head (1), sternum (2), abdomen (3), thigh (4), and leg (5). The semi-supine seat vibration was measured at the backrest by the seat pad accelerometer (beneath the subject) and the leg rest by an accelerometer (6).

The mounting of accelerometers on the body surface can cause local skin-accelerometer motion, which induces errors in the measured biodynamic responses. Different procedures have been devised to either minimize or correct their effect in the surface measurement [21]. Some investigators have applied preload to the mounted accelerometer in the form of mass preload, spring preload, and strap preload to increase the tissue stiffness and thus minimized the error. Mathematical techniques have also been proposed both in the time and frequency domain to estimate and correct the errors due to local skin movement. Pranesh reported that the correction to the measured fore-aft transmissibility of a seated subject exposed to vertical vibrations was insignificant, attributed to higher skin stiffness along the fore-aft direction [22]. Mansfield and Griffin stated that the corrected measurement brings only slight changes in the transmissibility response above 10 Hz. Huang and Griffin (2009) obtained the natural frequencies of local systems at the upper and lower abdomen (25-32 Hz) well above the frequency of interest (0.25-20 Hz); therefore, the local skin- accelerometer motion was not compensated. In the present study, owing to higher skin stiffness in the vertical (x-) direction and the frequency range (2-16 Hz) of interest was much lower than the natural frequency of the skin-accelerometer system, no correction was applied to the measurement. However, accelerometers were mounted on the body surface using an elastic strap to eliminate any local skin-accelerometer motion [23].

A pilot experiment was performed to estimate the inclination of the accelerometer at each body location relative to the direction of excitation (Figure 3). The accelerometer inclination (δ) was calculated from the measured vertical and horizontal transmissibilities at a very low excitation frequency (0.5 Hz) (27). The inclinations were estimated between 2°-4° at the head, 2°-5° at the sternum, 2°-7° at the abdomen, 4°-7° at the thigh, and 4°-6° at the leg. Since the accelerometer inclination relative to the direction of excitation was less than 10°, its effect would be insignificant and therefore was ignored. However, during experimentation, the position and direction of accelerometers attached to the body surface were verified before each vibration stimulus to avoid any misalignment [24].

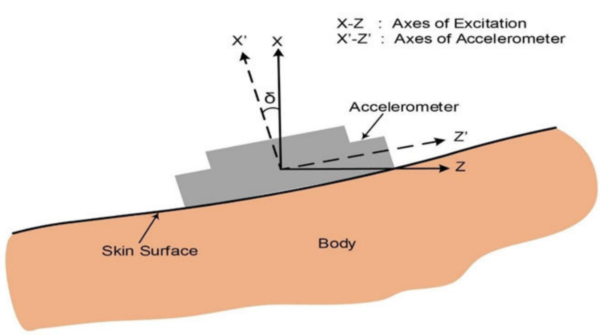

Figure 3: Illustration of accelerometer axes attached to the body relative to the excitation/platform axes.

The acceleration signals of five accelerometers and seat pads were captured at a sampling frequency of 1024 Hz and 40 Hz anti-aliasing filters using a data acquisition card (NI 6218) and LabVIEW Signal Express software.

Vibration stimuli

The experiment was performed in a single session where each subject was exposed to a series of sinusoidal excitations in a vertical direction. The subjects were randomly exposed to 50 stimuli consisting of ten frequencies in the range 2.0-16.0 Hz in ⅓ octave band at five vibration magnitude (0.5, 0.75, 1.0, 1.25 and 1.5 m s^{-2} r.m.s.). Each stimulus was of 20-sec duration with a 0.5-sec cosine taper at the beginning and end [25].

Posture

The subject acquired a relaxed semi-supine posture with arms on the side, resting on the seat's backrest. The lower legs raised and rested horizontally on the leg rest, thus ensured maximum contact between back and platform. The leg rest height was altered as per the comfort of the subject. The subject was instructed to make maximum contact of their thighs with the support and keep their eyes closed while exposed to the stimulus. Safety belts made of nylon fabric were wrapped around the abdomen and arms, and legs [26].

Analysis

Dynamic response analysis

The acceleration signals acquired from the subject's forehead, sternum, abdomen, thigh, and leg were used to determine the vertical transmissibility (TRxx) of each body segment of the semi-supine subject exposed to the vertical excitation. The transmissibility is expressed as the ratio of output acceleration measured at the body location to the input acceleration at the seat surface:

$$TR_{xx}(f) = \frac{\ddot{x}_{rms}(f)}{\ddot{x}_{0,rms}(f)} \quad (1)$$

The input acceleration measured at the backrest was employed to determine transmissibility at the head, sternum, abdomen, and thigh. The leg rest acceleration was used to determine the leg transmissibility. The phase of the transmissibility was calculated from the maximum value of the cross- correlation function between the accelerations measured at the body location and the seat surface [27].

Statistical analysis

The effect of vibration magnitude on the vertical transmissibility was statistically estimated using Wilcoxon matched-pair signed-rank test. The test was performed among five vibration magnitudes at each of the ten excitation frequencies, which leads to 100 significant comparisons for each body segment. Out of which, 40 comparisons are between adjacent vibration magnitudes. The number of pairs of significant differences obtained for each body segment specifies their degree of nonlinearity. The correlation between the peak transmissibility of body segments and demographics of subjects was calculated using Kendall's τb correlation coefficient test. The effect of inter-subject variability on the vertical transmissibility was quantify using the Interquartile Range (IQR). It indicates the spread of modulus and phase of vertical transmissibility of each body segment at different vibration magnitudes and frequencies. All the statistical analyses were performed in SPSS 16.0 [28].

Results

Response of head

Transmissibility: The individual and median responses with interquartile ranges of modulus and phase of vertical transmissibility of the head at five vibration magnitudes are shown in Figure 4. The responses showed a small spike between 5.0-6.0 Hz, followed by a steady rise in the transmissibility with the excitation frequency increase. The inter-subject variability at frequencies lower than 5.0 Hz was relatively low for both modulus and phase [29]. The considerable variability was observed at 6.3 and 16.0 Hz; however, no significant variation was seen due to the change in vibration magnitude. The correlation between the demography of subjects (age, weight, and stature) and the peak transmissibilities at different vibration magnitudes was insignificant (p>0.05, Kendall) and hence not presented.

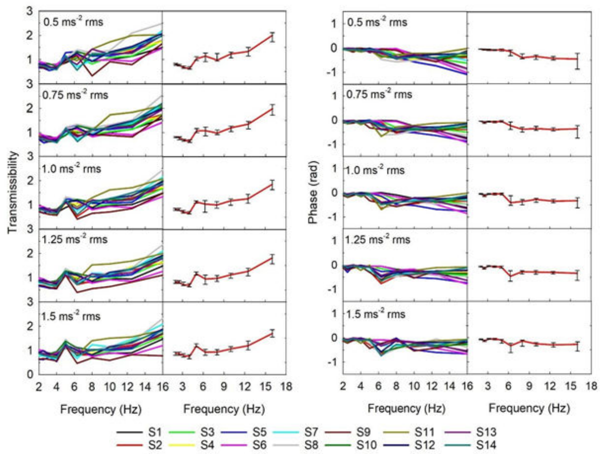

Figure 4: Individual and median with inter-quartile range of modulus and phases of vertical transmissibility responses of the head of fourteen subjects (S1-S14) exposed to vertical excitation at five vibration magnitude

Effect of vibration magnitude: The statistical significance of the effect of vibration magnitudes on the head transmissibility was evaluated, employing a non-parametric Wilcoxon matched-paired signed- rank test at all the examined frequencies. The procedure of the statistical test as an example for head transmissibility. The head response showed higher transmissibility with greater vibration magnitude for the frequencies up to 5.0 Hz ($p<0.05$, Wilcoxon). In contrast, at excitation frequency above 5.0 Hz, higher transmissibility was recorded with lower vibration magnitudes ($p<0.05$, Wilcoxon).

The number of significant pairs between the vibration magnitudes obtained for each body segment is illustrated in Figure 5. The effect of variation of vibration magnitude was significant at higher frequencies. For example, the comparison of head transmissibility between adjacent vibration magnitudes leads to 24 significant pairs, out of which 14 significant pairs occurred at frequencies between 6.3-16.0 Hz. Moreover, the variation of vibration magnitudes higher than 1.0 m s^{-2} r.m.s showed greater pairs of significant differences.

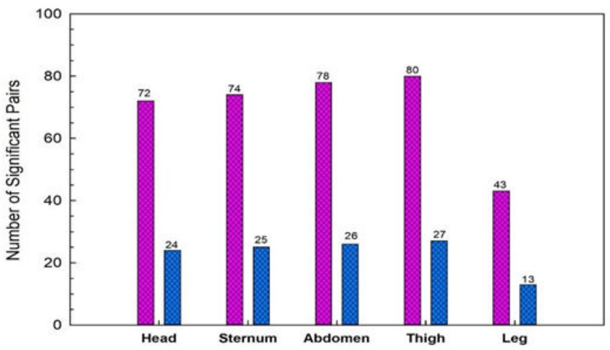

Figure 5: Pairs of significant difference in vertical transmissibility estimates of each body segment at ten frequencies: Among each vibration magnitudes (100 Comparison for each body segment); Among adjacent vibration magnitudes (40 Comparison for each body segment).

The median vertical transmissibility response (Figure 6) indicated that the head resonance would occur at a frequency somewhat higher than 16.0 Hz. The median phase response showed almost zero phase difference up to 5.0 Hz. Then a decrease in phase angle was registered up to 10.0 Hz, and after that, it became almost constant [30].

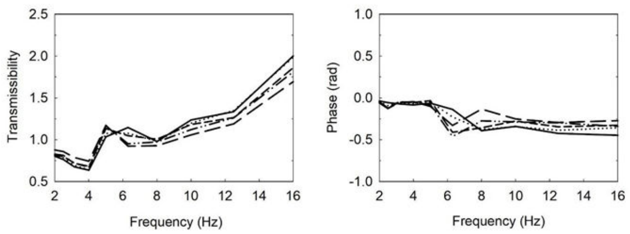

Figure 6: Median transmissibility responses of the head of fourteen subjects under vertical excitation at five vibration magnitude.

Response of sternum

Transmissibility: The sternum transmissibility response under vertical excitation at five vibration magnitudes is shown in Figure 7. For most subjects, an almost flattened response appeared in the frequency range 6.0-12.5 Hz without any defined peak. Similar to the head response, the inter subject variability of the sternum was relatively low in the frequency range 2.0-5.0 Hz. The modulus responses shown greater scatter between 6.3-12.5 Hz, while in the phase responses, it increased with the increase in frequency. The inter-subject variability in sternum transmissibility responses at different vibration magnitudes was almost similar. The variation of peak transmissibility modulus of the sternum at resonance among the subjects was significant ($p<0.001$, Friedman). Similar to the head, no significant correlation was obtained between demographic characteristics and primary peak transmissibility of the sternum.

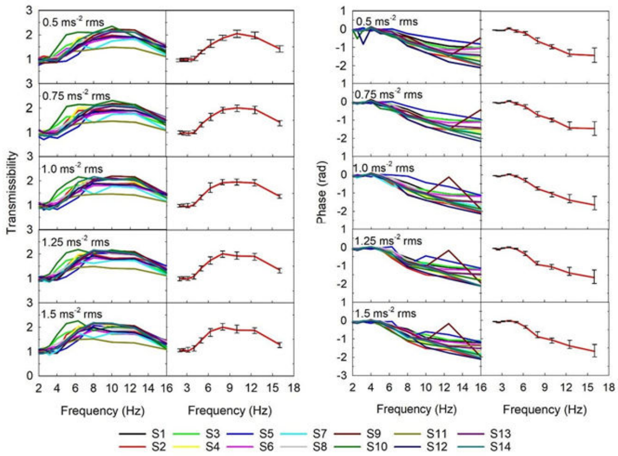

Figure 7: Individual and median with inter-quartile range of modulus and phases of vertical transmissibility responses of the sternum of fourteen subjects (S1-S14) exposed to vertical excitation at five vibration magnitude.

Effect of vibration magnitude: The influence of vibration magnitudes on the transmissibility of the sternum was analyzed utilizing the same statistical test used for the head transmissibility response. The statistical test showed a rise in transmissibility for the sternum as the vibration magnitude increased ($p<0.05$, Wilcoxon), particularly at 2.5, 4.0, 5.0, 6.3, and 8.0 Hz. At higher frequencies (≥ 10.0 Hz), lower vibration magnitude resulted in higher transmissibility ($p<0.05$, Wilcoxon). A greater number of significant pairs (15 significant pairs out of a total of 25) were obtained for the sternum as compared to the head at frequencies higher than 6.3 Hz (Figure 5). The comparison of transmissibilities between vibration magnitudes in the range of 1.0-1.5 m s^{-2} r.m.s showed a greater number of significant pairs. The nonlinearity was consistent in the median transmissibility response of the sternum (Figure 8) as the primary resonance frequency decreased from 10.0 to 8.0 Hz with the rise in the magnitude of vibration over the range 0.5-1.5 m s^{-2} r.m.s. The phase angle tended to increase with the increase in the vibration magnitude. The median phase responses were consistent with the median modulus responses of the vertical transmissibility of the sternum.

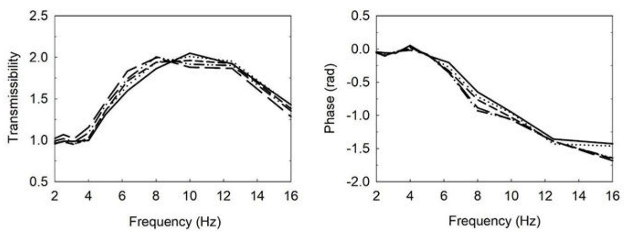

Figure 8: Median transmissibility responses of the sternum of fourteen subjects under vertical excitation at five vibration magnitude.

Response of abdomen

Transmissibility: The abdomen transmissibility response of individual subjects and their median with the inter-quartile range at five vibration magnitudes are shown in Fig. 9. The inter-subject variability in the modulus and phase of abdomen transmissibility responses were extremely low at 2.0 and 2.5 Hz. The dispersion of transmissibility modulus was significant within the frequency range 6.3-12.5 Hz, whereas, in the phase responses, the dispersion was concentrated in the frequencies above 10.0 Hz. The primary peak transmissibility of the abdomen at resonance had a significant difference ($p<0.001$, Friedman) between the subjects. It varied from 1.631 (S11) to 2.682 (S10) at vibration magnitude 1.5 m s^{-2} r.m.s. The peak transmissibility and demographic characteristics (age and stature) showed a negative but non- significant correlation ($p>0.05$, Kendall).

Effect of vibration magnitude: The statistical test performed to evaluate the effect of vibration magnitude on abdomen transmissibility showed greater pairs of significant differences (Figur 5). It indicates that nonlinearity is more consistent in the abdomen relative to the sternum and head. At frequencies lower than 6.3 Hz, the variation among adjacent vibration magnitudes leads to a greater number of significant pairs (18 significant pairs out of the total of 26) as compared to frequencies above 6.3 Hz (8 significant pairs). At lower frequencies (<6.3 Hz), transmissibility increased significantly with the increase in the vibration magnitude ($p<0.05$, Wilcoxon). In contrast, lower vibration magnitudes at frequencies above 6.3 Hz resulted in a significant rise in abdomen transmissibility ($p<0.05$, Wilcoxon).

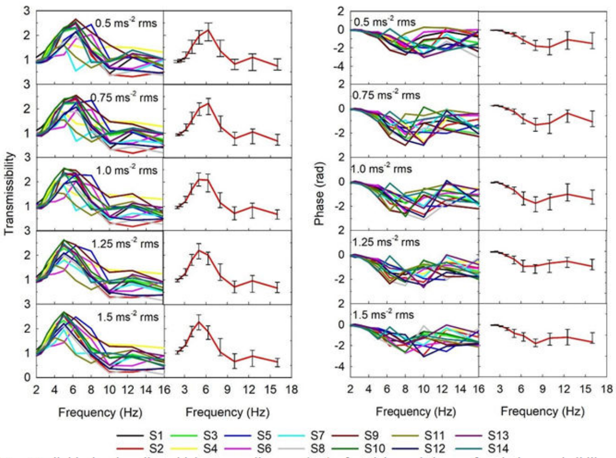

Figure 9: Individual and median with inter-quartile range of modulus and phases of vertical transmissibility responses of the abdomen of fourteen subjects (S1-S14) exposed to vertical excitation at five vibration magnitude.

The median transmissibility response (Figure 10) displayed a decrease in primary resonance frequency from 6.3 to 5.0 Hz with the increase in vibration magnitude across the range 0.5-1.5 m s^{-2} r.m.s. A secondary resonance peak at 12.5 Hz was also observed in the sternum response. The transition in the median phase responses was consistent with the median modulus responses of the vertical abdomen transmissibility.

Response of thigh

Transmissibility: The thigh transmissibility responses of individual subjects and their median with the inter-quartile range at five vibration magnitudes are shown in Fig. 11. The inter-subject variability in the transmissibility modulus was relatively low at frequencies of less than 3.15 Hz. In contrast, in the phase responses, extremely low variability was seen at frequencies less than 5.0 Hz. The spread of the transmissibility modulus and phase was witnessed high at frequencies greater than 10.0 Hz. The peak transmissibility at resonance varied between 1.81 (S7) and 2.13 (S11) at 1.5 m s^{-2} r.m.s., indicated a significant difference ($p<0.001$, Friedman) amongst the subjects. The peak transmissibility and weight showed a negative but non-significant correlation ($p>0.05$, Kendall).

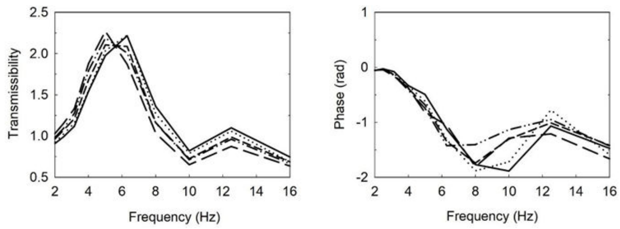

Figure 10: Median transmissibility responses of the abdomen of fourteen subjects under vertical excitation at five vibration magnitude.

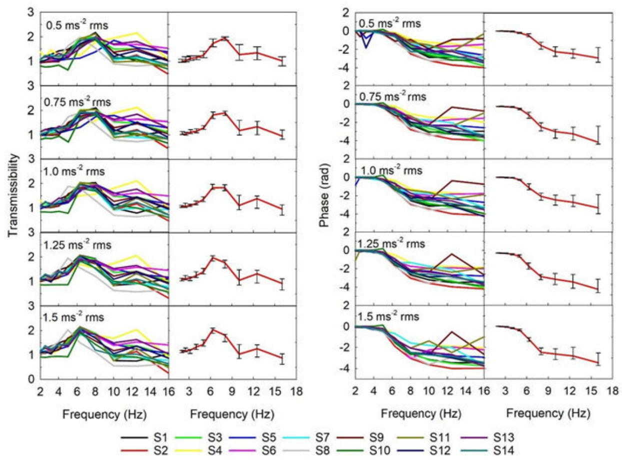

Figure 11: Individual and median with inter-quartile range of modulus and phases of vertical transmissibility responses of the thigh of fourteen subjects (S1-S14) exposed to vertical excitation at five vibration magnitude.

Effect of vibration magnitude: The effect of vibration magnitude on transmissibility responses was estimated utilizing the statistical procedure as described earlier. At lower excitation frequency (≤ 6.3 Hz) except at 3.15 Hz, thigh transmissibility significantly increased with the increase in vibration magnitude ($p<0.05$, Wilcoxon). At 8.0 Hz and above, lower vibration magnitude resulted in higher transmissibility ($p<0.05$, Wilcoxon). The effect of vibration magnitudes on the vertical transmissibility as observed most prominent at the thigh (27/40 significant pairs, Figure 5) among all the body segments. A lesser significant pair were obtained at frequencies of less than 6.3 Hz (11 significant pairs out of 27). The median response (Figure 12) indicated a drop in the primary resonance frequency from 8.0 to 6.3 Hz as the vibration magnitude increased in the range 0.5-1.5 m s^{-2} r.m.s. Further, at 12.5 Hz, a secondary transmissibility peak was observed, having higher transmissibility at a lower vibration magnitude. The variation in the phase responses was consistent with the modulus responses of the vertical thigh transmissibility.

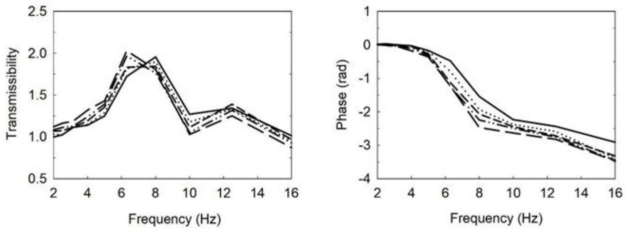

Figure 12: Median transmissibility responses of the thigh of fourteen subjects under vertical excitation at five vibration magnitude.

Response of leg

Transmissibility: The leg transmissibility responses of individual subjects and their median with the inter- quartile range at five vibration magnitudes over the range 0.5-1.5 m s^{-2} r.m.s. are shown in Figure 13. The inter-subject variability in the transmissibility modulus and phase was relatively low at frequencies of less than 5.0 Hz. The transmissibility modulus showed significant variability in the frequency range 10.0-16.0 Hz, while the variability in the phase responses was significant between 12.5-16.0 Hz. A significant difference in the primary peak transmissibility at resonance was obtained among the subjects ($p<0.001$, Friedman) with modulus varying between 1.267 (S6)-2.0 (S1) at vibration magnitude 1.5 m s^{-2} r.m.s. The correlation between the peak transmissibility and physical stature was obtained positive but non-significant ($p>0.05$, Kendall). A positive correlation implies that a taller person, which in turn has long leg length and that too mostly skeletal, would result in high vibration transmissibility during vertical excitation.

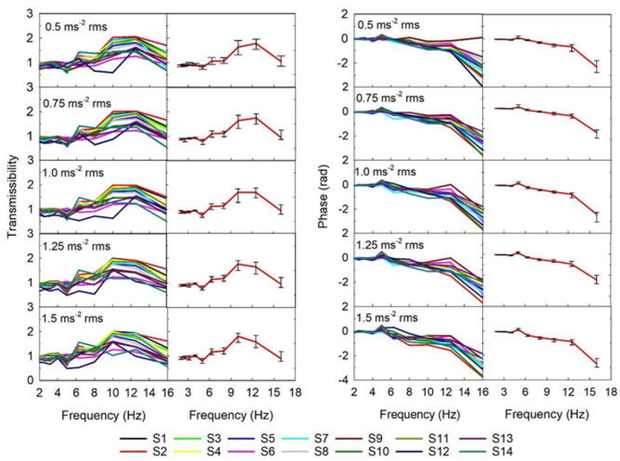

Figure 13: Individual and median with inter-quartile range of modulus and phases of vertical transmissibility responses of the leg of fourteen subjects (S1-S14) exposed to vertical excitation at five vibration magnitude.

Effect of vibration magnitude: Following the same statistical procedure described earlier, the effect of vibration magnitude on the leg transmissibility responses was estimated. At excitation frequency up to 10.0 Hz, higher transmissibility was recorded at higher vibration magnitudes ($p<0.05$, Wilcoxon). At a frequency greater and equal to 12.5 Hz, the higher vibration magnitude resulted in lower vibration transmissibility through the leg ($p<0.05$, Wilcoxon). The statistical analysis indicated that the leg had the least pairs of significant differences (Figure 5). The effect of variation in vibration magnitudes was dominant only at frequencies 4.0, 8.0, 10.0, and 12.5 Hz ($p<0.05$, Wilcoxon). It indicated that the nonlinearity was less consistent in the leg than other body segments, and the effect of vibration magnitude on leg transmissibility was marginal. The median modulus of leg transmissibility responses (Figure 14) showed that primary resonance frequency decreased from 12.5-10.0 Hz as the vibration magnitude increased from 0.5 to 1.5 m s^{-2} r.m.s. The effect of vibration magnitude on the median phase response was insignificant for frequencies of less than 5.0 Hz. However, with frequencies above 5.0 Hz, the phase angle increased with the increase in vibration magnitude. The variation in the median phase responses was consistent with the median modulus responses [31].

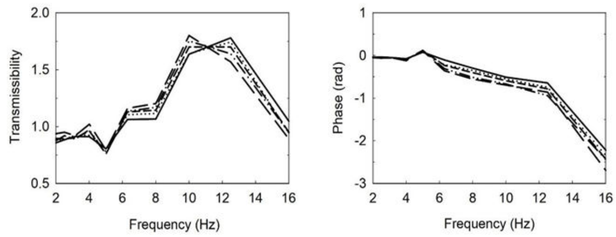

Figure 14: Median transmissibility responses of the leg of fourteen subjects under vertical excitation at five vibration magnitude.

Discussion

The nonlinearity in the vertical transmissibility response of semi-supine subjects was consistent, and the change in vibration magnitude significantly affected the vertical transmissibility of all the body segments. The consistent and significant effect of vibration magnitude on transmissibility response may be due to the use of a sinusoidal waveform, which has higher energy content compared to the random waveform for the same r.m.s. magnitude. In general, the variation in vibration magnitudes across the range of 1.0-1.5 m s^{-2} r.m.s. produced a more significant difference in the vibration transmissibilities. Although, the transmissibility and demographic characteristics of the subject had shown a significant correlation for seated subjects, no statistically significant correlation was found in the present study for semi-supine subjects. The inter-subject variability had a reasonable impact on the transmissibility response of each body segment, with a prominent effect at frequencies above 6.3 Hz [32].

With vertical excitation, the head resonance frequency was reported at 17.0 Hz and between 50.0-80.0 Hz for the supine posture and between 5.0 - 6.3 Hz for both seated and standing posture. In the present study, the head transmissibility response showed no well-defined peak except a minor peak at 5.0 Hz. Since, the transmissibility rises steadily after 6.3 Hz, the head resonance was expected to occur above 16.0 Hz, as reported. The change in head transmissibility due to increased vibration magnitude was significantly greater at a higher vibration magnitude. The crewmembers of the vertical launch vehicle are exposed to vibration greater than those experienced by the shuttle crew (0.1 g). The transmission of elevated vibration to the head would critically affect the vision and fine motor control and deteriorate the crew performance during the dynamic phases of flight. Therefore, higher vibration levels on the crew seat, especially near resonance frequency, must be eliminated through effective attenuation systems [33].

The resonance frequency of the sternum has been reported to be reduced from 10.94 to

9.38 Hz and 10.16 to 7.03 Hz for semi-supine and supine posture, respectively, as the magnitude of vertical excitation increased from 0.0625 to 1.0 m s^{-2} r.m.s. The median transmissibility response for the sternum in the present study had shown a decrease in resonance frequency from 10.0 to 8.0 Hz as the vibration magnitude increases from 0.5 to 1.5 m s^{-2} r.m.s. Though, the decrease in resonance frequency with the vibration magnitude increase was significant, the change in transmissibility at resonance frequency was insignificant. It may be due to the reduction in stiffness of tissues at the body-seat interface at higher excitation. But the reduction may not be appreciable to cause a substantial change in transmissibility magnitude. Further, the coarse frequency resolution of sinusoidal excitation considered in the study might be the reason for it.

For semi-supine posture, the transmissibility response of the abdomen revealed the primary resonance frequency to vary between 7.03 to 6.25 Hz across the vibration magnitude 0.0625 to 1.0 m s^{-2} r.m.s. The impedance response of the abdomen reported peak frequencies at near 7 and 140 Hz. The present study obtained abdomen resonance frequency between 6.3 to 5.0 Hz across the vibration range 0.5 to 1.5 m s^{-2} r.m.s. The resonance frequency of the abdomen obtained with sinusoidal excitation exhibited a slight deviation as compared to Huang and Griffin with random excitation. It may be attributed as energy content in sinusoidal excitation is higher relative to random excitation for the same r.m.s acceleration; this resulted in more softening of abdomen tissues. Moreover, the abdomen responses yielded a greater number of significant pairs at frequencies lower than 6.3 Hz. In comparison, the other body segments had a greater number of significant pairs at frequencies higher than 6.3 Hz. The above results indicate that each body segment has a distinct frequency spectrum. In general, around the segment's resonance frequency, the influence of variation in vibration magnitude would be substantial and instigate nonlinearity in the responses [34].

In a semi-supine posture, vibration to the thigh is transmitted via the lower back and pelvis or the vertical seat surface. The peak resonance frequency for the pelvis and thigh has been reported at 6.6 Hz and between 13.0-15.0 Hz respectively, for the semi-supine subject. The fore-aft cross-axis apparent mass of thigh for a seated subject had depicted the resonance frequency around 6.0-8.0 Hz. The primary (8.0-6.3 Hz) and secondary (12.5 Hz) resonance frequencies for the thigh obtained in the present study were consistent with the previously reported studies. Moreover, peak transmissibility around 6.0 Hz indicated that the vibration to the thigh was predominantly transmitted through the pelvis. Since the subjects were instructed to maintain maximum thigh contact with the seat during the experiment, the effect of cross-axis vibration transmission from the vertical seat surface was also apparent in the vertical thigh transmissibility response.

The vertical transmissibility response of the leg showed the resonance frequency around 10.0-12.5 Hz, which is consistent with the model test (6.1 and 11.4 Hz) and experimental (20.0 Hz) frequencies reported in. Compared to other body segments, the degree of nonlinearity was least for legs (43 significant pairs out of 100 comparisons). It may be caused by the harness provided at the legs that have reduced the local movement of the soft tissues of the calves.

Conclusion

The present study investigated the effect of sinusoidal excitations on the transmissibility response at the head, sternum, abdomen, thigh, and leg of semi-supine subjects. The transmissibility response of each body segment was analyzed to evaluate the degree of nonlinearity. Also, the significance of inter-subject variability and demographic characteristics of subjects on the transmissibility response were examined. Based on the study, the following conclusions are drawn:

- When semi-supine subjects are exposed to sinusoidal excitation, the vibration magnitude has a noticeable influence on the transmissibility. The variation in vibration magnitudes across the higher range (1.0-1.5 m s r.m.s.) is produced a more significant difference in the vibration transmissibilities.
- The transmissibility response exhibits consistent nonlinearity at the head, sternum, abdomen, thigh, and leg, which indicates higher energy content associated with the sinusoidal waveform further softens the tissues in contact with the vibrating surface.
- The peak frequencies are obtained between 10.0 to 8.0 Hz for the sternum, 6.3 to 5.0 Hz for the abdomen, 8.0 to 6.3 Hz for the thigh, 12.5 to 10.0 Hz for the leg across the vibration magnitude range 0.5 to 1.5 m s r.m.s. The peak frequency for the head is expected above 16.0 Hz.
- Higher vibration magnitudes before the peak frequency are resulted in greater transmissibility, while after the peak frequency, higher transmissibility is observed with lower vibration magnitudes.
- The pronounced transmissibility is noted for the abdomen among the examined body segments, followed by the thigh, as both consists of a majority of soft tissues.
- Although, the demographic characteristic shows no significant influence on transmissibility, inter-subject variability has a considerable impact.

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