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Supine human response and vibration-suppression during whole-body vibration

John Carl Meusch
University of Iowa

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SUPINE HUMAN RESPONSE AND VIBRATION-SUPPRESSION DURING WHOLE-BODY VIBRATION

by

John Carl Meusch

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of the requirements for the Master of
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Thesis Supervisor: Assistant Professor Salam Rahmatalla

Graduate College
The University of Iowa
Iowa City, Iowa

CERTIFICATE OF APPROVAL

MASTER'S THESIS

This is to certify that the Master's thesis of

John Carl Meusch

has been approved by the Examining Committee
for the thesis requirement for the Master of Science
degree in Biomedical Engineering at the May 2012 graduation.

Thesis Committee: ___________________________
Salam Rahmatalla, Thesis Supervisor

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Nathan Fethke

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Fred Gerr

____
Nicole Grosland

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David Wilder

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ABSTRACT

Whole-body vibration (WBV) has been identified as a stressor to supine patients with head and spinal injuries during medical transportation. Limited information is available on the dynamic effects of the long spinal board and stretcher in vibrating environments. This is the first study to investigate the transmission of vibration through the long spinal board, military stretcher, and supine human in relation to a control case with full-rigid support. A sample of eight healthy male participants was used in this study. Each was placed on a vibration platform using spinal immobilization. Random vibration was applied in the fore-aft, lateral, and vertical directions, and the transmission of vibration was computed for the head, sternum, and pelvis. In addition, a novel approach to assess relative motion between segments, called relative transmissibility, was introduced. Compared to full-rigid support, the long spinal board strapped to a standard military litter system showed a 50% increase in transmission of anterior-posterior vibration to the head and a 100% increase to the sternum at its resonance frequency of 5 Hz ($p < 0.05$, Wilcoxon) for vertical vibration. Use of the cervical collar during immobilization increased the head nodding and the relative head-sternum flexion-extension as a result of the input fore-aft (axial) whole-body vibration. Yet, head nodding was reduced from vertical (anterior-posterior) input vibration. Relative transmissibility has revealed that at 5 Hz, the acceleration difference between the head and sternum was 1.5 times the vertical (anterior-posterior) input acceleration using the spinal board upon the military litter. During air, ground, and hand transportation, WBV may occur around 5 Hz. Patients with head and spinal cord injuries may benefit from vibration-suppression designs that minimize (1) the overall transmission of vibration in each axis and (2) the relative accelerations between segments for the most common vibration frequencies that occur during transportation. Furthermore, vibration applied in each axis independently showed transmissibility results comparable to that of simultaneous stimuli in three axes. Although the effects of vibration are quantified in this study, transient shock type vibration should be investigated and future research should be done to fully understand the clinical significance and application of these results.

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CHAPTER I

INTRODUCTION

Motivation

In the U.S., there are an estimated 12,000 – 20,000 new spinal cord injuries each year [1-2], with approximately 20% of deaths and 25% of cases exacerbated prior to arrival at the hospital [1-3]. The estimated direct cost of spinal cord injuries exceeds $7 billion in one year [4]. Patients may also be affected by other factors during pre-hospital transportation such as a lack of oxygen at high altitude, temperature shifts, vibration, noise, and g-forces [5]. It is apparent that pre-hospital transportation is a critical period for patients for both civilian and military medical teams, yet healthcare on the battlefield presents some of the most dangerous and controversial methods in providing aid for combat casualties. Advancements in armor and current war tactics have changed the pattern of injury; current research has revealed that a larger proportion of head and neck injuries are emerging with most due to an explosive mechanism [6]. Within this harsh environment, the effects of whole-body vibration on patient transportation remains relatively understudied. Subjective reports have indicated a variety of complications from vibration such as bleeding [7] and difficulty monitoring patients [7, 8].

Background

Stretchers and Litters

During conflict and warfare, injured soldiers must be transported to a location where they can receive medical care. The military litter or stretcher may be used to help carry a casualty using two or four soldiers. This device mainly consists of two parallel poles with a fabric connecting them. As early as the Roman Empire, the litter concept was implemented to transport injured soldiers [9]. Figure 1-1 displays use of the litter during the Civil War and Figure 1-2 depicts a modern military litter that can be folded into a much smaller size for easy storage. Interestingly, basic litter design concepts have not changed much since the Civil War [10].

Spinal Immobilization

Prior to evacuation, at the discretion of the medical team, spinal immobilization may be used. The goal of spinal immobilization is to constrain the injured person such that no further harm may be done while transporting the individual to more definitive care. First, the patient is placed onto a long spinal board and constrained. The spinal board is a device to provide rigid support and reduce movement of the patient. A cervical collar may also be recommended and fitted before securing the head. Following that, the patient constrained to the spinal board is transferred to the litter for ease in transportation. Two additional straps attach the patient and spinal board to the litter. Figure 1-3 illustrates the basic steps in mobilizing the casualty. For more details refer to the spinal immobilization section in Appendix A.

Vibration in Transportation

The phases of medical evacuation can be characterized by ground, vehicle, and aerial transport [11], and whole-body vibration exists in all of these modes. A study [12] on off-road ambulance and hand transportation showed the largest un-weighted average accelerations—1.87 and 1.46 m/s^2, respectively. In addition, helicopter and ambulance accelerations have been recorded in medical transportation [13]. Due to the lack of safety standards pertaining to supine vibration, whole-body vibration exposure has been studied using ISO standards for hand transport, ground vehicle transport, and aerial methods relating to a mountain rescue operation, even though these standards apply mainly to seated vibration.

Supine Human Vibration

Huang and Griffin [14] observed the apparent mass for the semi-supine human body during vertical and longitudinal dual-axis vibration, the apparent mass during longitudinal and horizontal vibration [15], and the apparent mass and transmissibility during vertical vibration for the semi-supine, full supine, and constrained supine postures [16]. Specific to spinal immobilization, Perry et al. [17] reported relative neck motions associated with horizontal vibration; the neck motion was deemed clinically significant by a neuroscientist for a potential contribution to spinal cord injury. In civilian applications, the use of a cervical collar is recommended during spinal immobilization [18-19].

Multi-Axis Vibration

In designing vibration-suppression systems, many seated studies have used single-axis input vibration during analysis. Mansfield and Maeda [20] observed a cross-axis effect in apparent mass similar to the nonlinear softening characteristics presented by increasing the magnitude of vibration. They demonstrated that the resonance frequency of a particular direction is affected by the addition of vibration in orthogonal directions.

Hypotheses

This study demonstrates the effect of WBV between supporting conditions in the supine position, investigates the relative motion between segments, and discusses the application of 1 dimensional analysis to more real-life 3 dimensional situations.

1. *Support conditions*: Investigating the transmission of vibration through the spinal board, military litter, and cervical collar will provide a means to understand the coupled system and gain insight into possible solutions. It is hypothesized that body-support and constraint conditions will affect the transmitted motion to the head, sternum, pelvis, cervical spine, and lower back during whole-body vibration.

2. *Relative motion of segments*: While the transmissibility for seated and standing positions can give valuable information to vibration-suppression designers about the relationship between the input ground motion and the output motion at different points on the body, it has difficulties providing them with the same level of information for supine positions. In the supine position the input energy enters the body from different locations (head, torso, pelvis, and legs), and while it looks like each segment is vibrating independently due to the input motion, it is also clear that the motion of each segment is affected by the motion of the neighboring segments. A novel approach termed relative transmissibility is introduced in this study and is hypothesized to capture the effect of the input ground motion on the motion of the cervical spine (relative motion between the head and sternum) and on the motion of the lower back (relative motion between the sternum and pelvis).
3. *Axis of Vibration*: The experimental cost of vibration studies would be more feasible if designer were not require to use expensive 6 DOF (degrees of freedom) vibration platform to produce vibration in each axis simultaneously. Although the addition of vibration in one direction may affect the resonance frequency of orthogonal directions, using the RMS (root mean square) equivalent in tri-axis vibration may produce similar results as single-axis vibration. The final hypothesis is that the study of supporting conditions and the transmission of energy to the immobilized supine human using 1 dimension vibration stimuli will apply to real-life situations that most commonly are comprised of at least 3 dimension inputs.

By understanding the supine human response for these conditions, future developments and designs may be incorporated to reduce the transmitted vibration to the supine patients during transportation.

Figure 1-1. Illustration of military litter use during the U.S. Civil War.
Source: National Museum of Civil War Medicine [21].

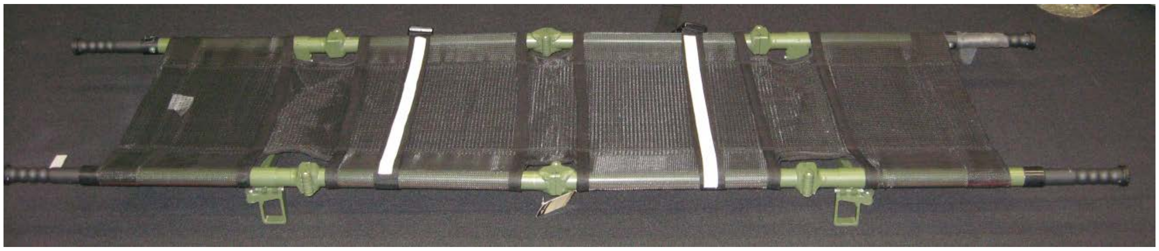

Figure 1-2. Modern foldable military litter.

Step 1: Place patient on spinal board.

Step 2: Strap down torso and legs, place cervical collar, and immobilize head.

Step 3: Place patient and spinal board on the litter and fix straps (white lines represent litter straps).

Figure 1-3. Illustration of mobilizing the patient using the military litter, spinal board, and cervical collar.

CHAPTER II

METHODOLOGY

Subjects and Setup

Eight healthy male participants with mean age of 23 years (SD 3.16), mean weight of 81 kg (SD 14.98), and mean height of 182 cm (SD 8.36) voluntarily took part in this study. The participants had no history of musculoskeletal disorders or injury. The study was approved by the University of Iowa Institutional Review Board (ID # 200811705) for human subject studies, and informed consent was obtained for each participant prior to the study. An unsigned informed consent document is presented in Appendix C.

Each participant was placed upon a 6-DOF vibration platform (Moog-FCS E-CUE 624-1800 electrical system, Ann Arbor, MI) able to replicate up to 20 Hz vibration accurately, more details are noted in Appendix B. Four back-support conditions were used to attach the spinal- immobilized, supine subjects. These include: (a) the baseline rigid platform covered by a thin rubber sheet (rigid platform, Figure 2-1a); (b) a long spinal board (Spine Board 50-013, North American Rescue, Greer, SC) secured to the rigid platform (board, Figure 2-1b); (c) a long spinal board strapped to a standard military litter (Talon II Model 90C Litter, North American Rescue, Greer, SC), secured to the rigid platform (board-litter, Figure 2-1c); and (d) board-litter with the addition of a cervical collar (Cervical Collar 50-0010, North American Rescue, Greer, SC) (board-litter-collar, Figure 2-1d).

For each supporting condition, the input vibration will travel through a different set of structures. Figure 2-2 displays the rigid-platform, board, board-litter, and board-litter-collar conditions and the associated layers of support.

In all cases, a 10-point harness was used to constrain the subjects to the long spinal board or rigid platform. For the board-litter-collar condition, a cervical collar was fitted properly for each participant such that a neutral head position was maintained. Methods used during spinal immobilization were taken into consideration from pre-hospital emergency references [18-19] as well as the local emergency medical services provider.

Inertial sensors (MTx inertial tracker, Xsens Technologies, Enschede, Netherlands) were placed at four locations on the supine human: head (forehead), sternum (xiphoid process), right pelvis (right anterior superior iliac spine), and left pelvis (left anterior superior iliac spine). For the sternum and pelvis, a thin layer of medical tape was placed on the location where the inertial sensor was fixed using double-sided tape. Then, an adjustable strap was fitted to the participant in the supine position and fixed securely while considering each participant's comfort. Bearing in mind the local tissue-accelerometer motion, the strapping method used was similar to that used by Huang and Griffin [16], and no correction was applied. One sensor was placed upon the participant's forehead and was fastened with foam wrap. During head immobilization, Figure 2-1d, the head strap was placed over the head sensor. For the sternum and pelvis, the 10-point harness was not placed directly over the sensor locations as there were already fastened with an adjustable strap, Figure 2-1a. Inertial sensors were also secured to the back of the long spinal board approximately below the head, sternum, and pelvis, as well as on the rigid platform.

Data Collection

Accelerometers are traditionally considered the main measuring tool in whole-body vibration experimentation. However, several new technologies have emerged during the last decade, and one of them will be used in this study. An inertial-based system [22] was used in this work. The system is comprised of - 18 g to + 18 g accelerometers, - 1200 deg/s to 1200 deg/s gyroscopes, and magnetometers. Each sensor has a 3D orientation accuracy of < 0.5 degrees, a dynamic accuracy of 2 degrees, a resolution of 0.05 degrees, a weight of 30 grams, and a sampling rate up to 120 frames per second. The operation bandwidth for the inertial sensor acceleration was 1-30 Hz. Each sensor is provided by the manufacture calibrated and acceleration is converted from the electrical signal by the software. The lab test showed that the sensor has a resonance frequency around 25 Hz, and therefore, it is expected to cause minimal problems for the frequency range under consideration. The inertial system recorded linear acceleration and calculated orientation represented in quaternion form. Acceleration was filtered with a low pass Butterworth filter where the cut-off frequency was 20 Hz.

Vibration Stimuli

Continuous random vibration files consisting of white noise were used in the fore-aft, lateral, and vertical directions for (a) single-axis input and (b) tri-axis input vibration. Each direction, dimension of input vibration, and supporting condition was presented in a randomized order. Figure 2-3 displays the axis in which vibration was applied relative to the supine human.

The power spectral density across the bandwidth of 0.5 -20 Hz was approximately flat for each file. During single-axis vibration a magnitude of 1.0 m/s^2 RMS random vibration was used for each input file in the fore-aft, lateral, and vertical directions. In the vertical direction, two additional cases were performed: 1.0 m/s^2 swept sinusoidal vibration and 0.5 m/s^2 random. For tri-axis stimuli, each direction was given a different random signal with a total RMS magnitude of 1.0 m/s^2. All files represented a time history of 60 sec in length. In comparison, [16] used Gaussian random vibration from 0.0313 m/s^2 – 1.0 m/s^2 for 90s. Due to the discomfort associated with longer spinal immobilization, the file length in the current study was reduced to 60 sec. Such file length has been commonly used in transmissibility, apparent mass, and absorbed power studies for seated applications [23-26]. Subjects were safely exposed to a total of 28 minutes of vibration consistent with the limits and guidance established in ISO 2361-1, 2631-5, and 13090-1 [27-30].

Analysis

Data Interpretation

Both linear acceleration and sensor orientation data were recorded by the inertial system. Raw data from accelerometers contained the constant acceleration of gravity. By transforming the acceleration data to the global reference frame, the gravity component was subtracted. For application in the study, the local linear acceleration was transformed into the global reference system using a rotation matrix. The rotation matrix is found from the quaternion output for each sensor as seen in the following equation [22].

$$R = \begin{bmatrix} q1^2 + q2^2 - q3^2 - q4^2 & 2(q2 * q4 \mp q1 * q4) & 2(q2 * q4 + q1 * q3) \\ 2(q2 * q3 + q1 * q4) & q1^2 - q2^2 + q3^2 - q4^2 & 2(q3 * q4 - q1 * q2) \\ 2(q2 * q4 - q1 * q3) & 2(q3 * q4 + q1 * q2) & q1^2 - q2^2 - q3^2 + q4^2 \end{bmatrix}$$

For calculation of transmissibility, local linear acceleration from each sensor was transformed to the global system as follows.

$$\begin{bmatrix} G_{a-x} \\ G_{a-y} \\ G_{a-z} \end{bmatrix} = \begin{bmatrix} R_{11} & R_{12} & R_{13} \\ R_{21} & R_{22} & R_{23} \\ R_{31} & R_{32} & R_{33} \end{bmatrix} * \begin{bmatrix} L_{a-x} \\ L_{a-y} \\ L_{a-z} \end{bmatrix}$$

Transmissibility

Transmissibility is defined as the ratio between the input and output acceleration of a system. In this case, the input motion is the platform and the output motion is measured on the human body. For the rigid-platform condition, the system can be seen as the human response. With the addition of the spinal board and litter, the system then comprises of the board-litter and human response. If the transmissibility is greater than 1, then the input acceleration is amplified, and for transmissibility less than 1, input acceleration is attenuated.

For single-input and single-output motions, the transmissibility can be represented as the ratio between the cross-spectral density (S_{Xx}) of the input acceleration at the rigid platform and the output acceleration at a point on the human body divided by the auto-spectral density (S_{XX}) of the input acceleration.

$$H_{Xx}(\omega) = S_{XX}{}^{-1}(\omega) S_{Xx}(\omega)$$

where the uppercase letter (X) represents the input direction and the lower case letter (x) represents the output direction.

Relative Transmissibility

The relative transmissibility is defined in this study as the ratio between the cross-spectral density of the input acceleration at the rigid platform and the output acceleration represented by the difference between the acceleration of two adjacent segments (SXxy) of the human body divided by the auto-spectral density of the input acceleration (SXX),

$$H_{Xxy}(\omega) = S_{XX}{}^{-1}(\omega) S_{Xxy}(\omega)$$

While the platform-to-head and platform-to-sternum transmissibilities are good measures of how the segments are moving relative to the platform, the relative transmissibility checks the severity of the motion between adjacent segments as a result of the input motion. For example (Figure 2-4), in the vertical direction the sternum and head may be undergoing the same motion and acceleration. In this case, the acceleration difference would be zero; therefore the ratio of this difference with the input acceleration (relative transmissibility) would be zero as well. Relative transmissibility is larger when there is an acceleration difference and zero when the acceleration of the two segments are equal in a particular direction. In other words, the higher the relative transmissibility, the worse the motion is in the cervical area. While it is based on acceleration, the relative transmissibility also gives an indication of the severity of the relative forces in the cervical spine area.

Statistical Methods

The paired-Wilcoxon signed rank method was implemented in this study at each frequency to investigate the significance of differences ($p < 0.05$, Wilcoxon) between different back-support conditions (rigid platform vs. board-litter) and the neck constraint condition (board-litter vs. board-litter-collar). A paired-Wilcoxon was used by other researchers for transmissibility of the supine human [16]. Although there may be inter-subject variability, paired methods test the difference in the value for each pair of observations. In addition, the Wilcoxon test does not need to assume a normal distribution of the paired differences [31]. To compare between single- and tri-axis input vibrations, the correlation of transmissibility for each input/output was computed using the R^2 coefficient of determination. The R^2 correlation provides a means to describe the amount of variation in tri-axis vibration that can be explained by single-axis vibration.

(a) Rigid-platform

(b) Board

(c) Board-litter

(d) Board-litter-collar

Figure 2-1. Example of experimental participant for each of the four support conditions: (a) rigid-platform; (b) long-board fixed to the platform; (c) addition of military litter; and (d) addition of cervical collar.

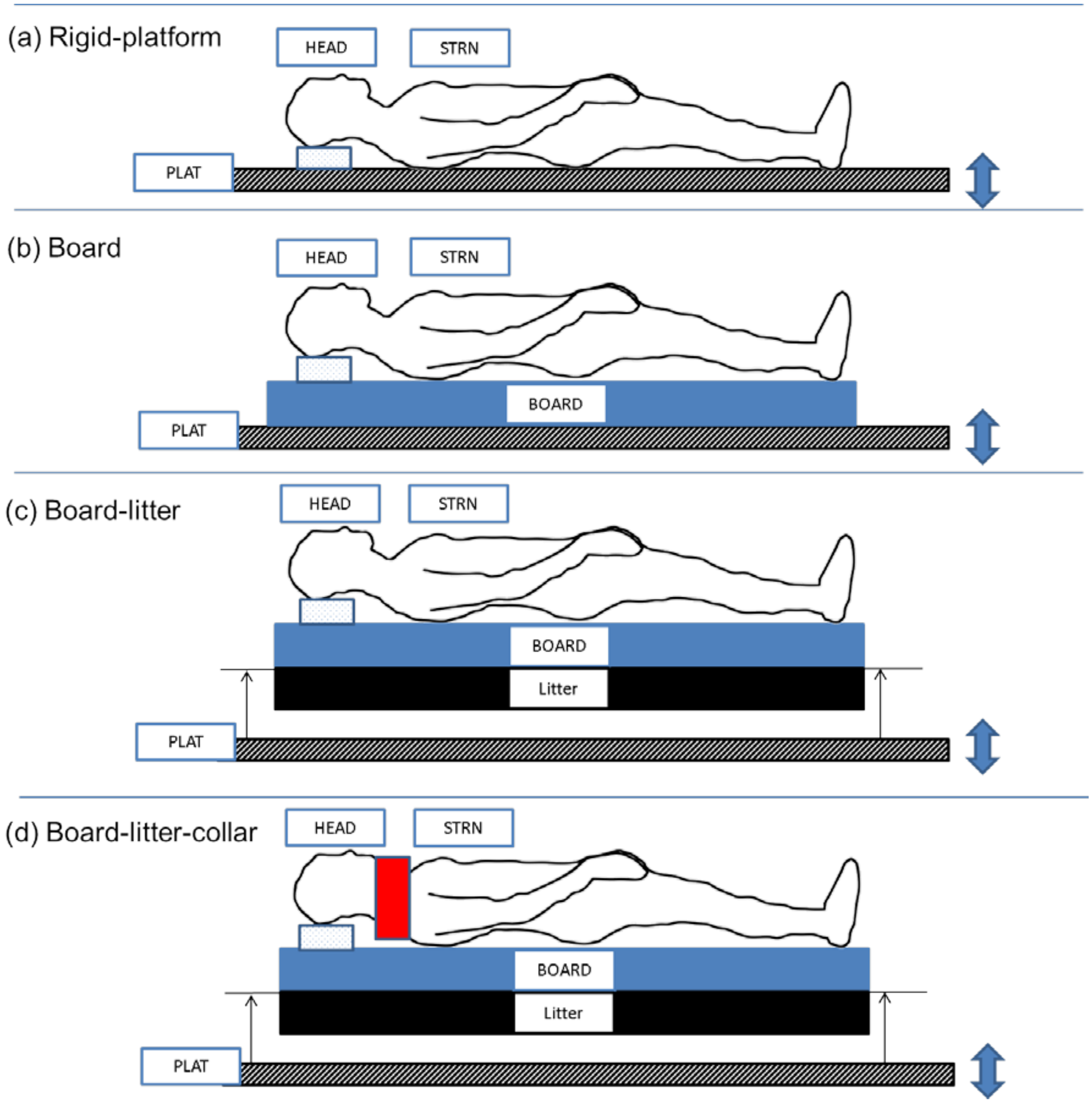

Figure 2-2. Illustration of the supporting conditions which include the (a) rigid-platform, (b) board, (c) board-litter, and (d) board-litter-collar. The box under the head represents the foam cushion support incorporated in the head immobilization device and the red square represents the cervical collar.

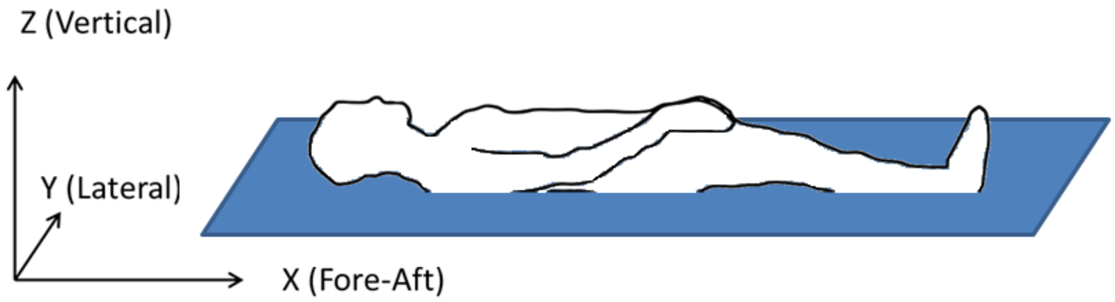

Figure 2-3. Axes definition in which vibration was applied with respect to the platform. For single-axis vibration, the random vibration was used in one axis independently. During tri-axis vibration, the stimuli were applied in each axis simultaneously. Vertical vibration primarily results in motion of the human in the anterior-posterior axis, fore-aft causes axial motion, and lateral vibration results in medial-lateral motion of the human.

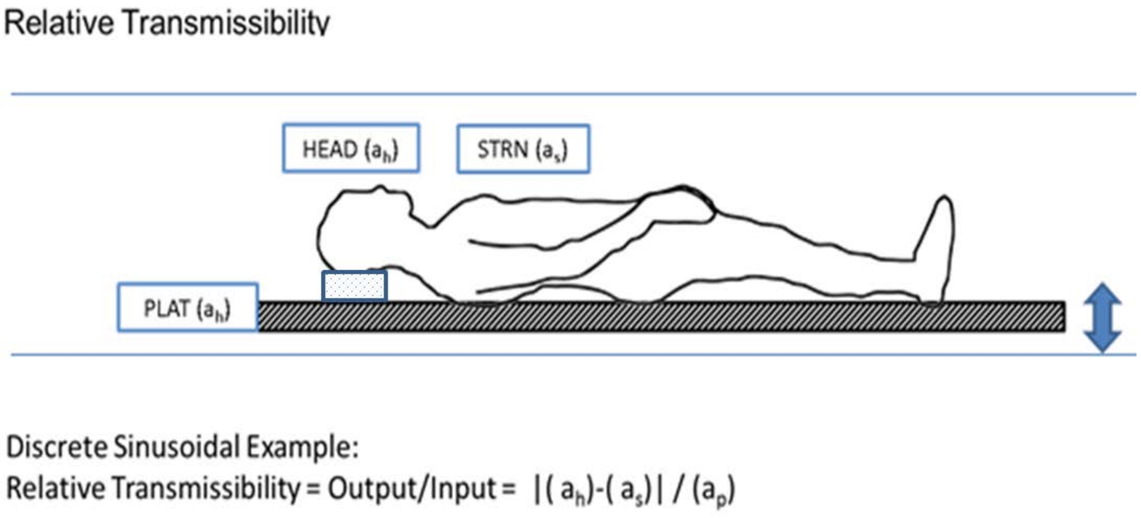

Figure 2-4. Example of relative transmissibility for discrete sinusoidal vibration. Acceleration at the head is subtracted from the sternum then divided by the input platform acceleration. The box under the head represents the foam cushion support incorporated in the head immobilization device.

CHAPTER III

RESULTS

Data Collection Validation

Inertial Acceleration vs. Baseline Accelerometer

The inertial system used to collect the acceleration data has a max sampling rate of 120 samples/s. Most accelerometers have the capability to sample at much higher rates above 500 samples/s. The frequency range of interest (0-20 Hz) is well below the Nyquist sampling rate [32] of 60 samples/s for the inertial system, however it is also important to verify the data with the gold standard. In this case the inertial sensor and standard accelerometer were rigidly fixed to the vibrating platform. Figure 3-1 displays a comparison between the inertial system and an accelerometer on the Moog platform system. The Moog platform accelerometer (Model 080A190, PCB Piezotronics, Depew, NY) is considered the baseline gold standard. In addition, the transmissibility was calculated between the Moog platform acceleration and the inertial system acceleration. The results showed that from 0.5 – 20 Hz the transmissibility was approximately 1 meaning there was no difference in the signals over that bandwidth or in other words the two accelerometers were rigid with each other giving the same measurement. This addresses manufactures concerns with mechanical vibration around the bandwidth limit of the sensor (30 Hz) and is not seen to affect the reliability of the data collected in this study.

Transmissibility Literature Comparison

Data for the supine human transmissibility to the sternum has been reported in the literature for vertical random vibration [16]. In the current study, the rigid-platform case (vertical component) serves as a control for comparison to previously reported results.

Spinal immobilization was not used in literature available, but constraining straps were applied. Figure 3-2 shows the literature comparison.

Single-Axis Input Vibration

Litter and Spinal Board

Baseline Transmissibility

The rigid-platform condition is used in this study as a baseline condition for the investigation of the supine-human transmissibility response to vibration under the no-back-support condition. In Figures 3-3 to 3-5, the column on the left represents the input in the X direction (fore-aft), the column in the middle represents the input in the Y direction (lateral), and the column on the right represents the input in the Z direction (vertical). The output components on the human body are represented by the lowercase letters x (axial), y (medial-lateral), and z (anterior-posterior) as shown in the figures. For single-axis input, vibration in the X, Y, and Z directions were applied independently. Taking the sternum as an example, Zz represents the transmissibility of vertical input (Z) acceleration on the platform to the vertical output (z) acceleration on the sternum.

For the baseline rigid-platform condition, the Zz component has indicated a 10 Hz natural frequency at the sternum (Figure 3-3) and a 17 Hz at the head (Figure 3-4). For the Xx component, the head showed a natural frequency around 3 Hz (Figure 3-4), which is very close to that of the sternum (Figure 3-3). For the Yy component, the head showed a natural frequency around 7 Hz (Figure 3-4), while the sternum showed a peak around 2.5 Hz (Figure 3-3). The addition of the board (board condition), which is directly attached to the rigid-platform, showed little effect on the characteristics of the median response of eight subjects for all transmissibility components. For clarity, the board condition was omitted from Figure 3-3 to Figure 3-6.

Platform-to-Sternum Transmissibility

The platform-to-sternum transmissibility (Figure 3-3) for the board-litter and the board-litter-collar conditions have shown clear magnifications for the Xx, Yy, Zz, and Zx components, with the remaining components of the transmissibility showing marginable contribution. The Xx components for the board-litter and the board-litter-collar conditions showed a resonance around 3.5 Hz. Similar characteristics were shown in the Yy component, with all conditions having a resonance around 3 Hz. The Zz component for the board-litter and the board-litter-collar conditions showed a transmissibility of magnitude around 3 and peaks around 5 Hz. For the Zx component, the board-litter and board-litter-collar conditions showed a peak around 6 Hz, with the board-litter-collar condition having a relatively higher magnitude than the board-litter condition.

When statistically comparing the board-litter with the rigid-platform condition, significant differences were seen in the Zz (Z – vertical platform input, z - anterior-posterior human output) component, with the board-litter causing a magnification at 0-6.7 Hz and attenuation at 8.1-20 Hz. For the Xx (X – fore-aft platform input, x – axial human output) component, significant magnification occurred in the frequency range of 0-7.6 Hz, and attenuation occurred from 11.8-20 Hz. The Zx component showed significant magnification from 0.7-7.9 Hz with some attenuation from 9.4-20 Hz.

Platform-to-Head Transmissibility

As shown in Figure 3-4, the Xx component for all conditions showed a resonance around 3 Hz. The Yy (Y – lateral platform input, y – medial-lateral human output) component for the board-litter and the board-litter-collar conditions showed two resonances around 2 Hz and 8 Hz. In the Zz component, the board-litter and the board-litter-collar conditions showed two resonances around 5 and 11 Hz. The Zx component was sensitive to the support conditions and showed peaks around 11 Hz for the board-litter condition and around 10 Hz for the board-litter-collar condition.

The comparison between the head transmissibility under the rigid platform and the board-litter condition (Figure 3-4) showed that the Zz component of the board-litter condition had significant magnification at 0-7 Hz and attenuation at 12.8-20 Hz. In addition, the Zx component showed significant amplification from 0-10 Hz and attenuation from 12.6-20 Hz. The Yy component had a small magnification from 0-2.1 Hz, and larger attenuation over the range of 3.9-8.7 Hz. In the Xx component, following the peak at 3 Hz, there was an increase in transmissibility at 11 Hz; significant differences were found from 8.25-15.5 Hz as well. Finally for the Xz component, the board-litter system showed significant amplification from 1.9-13.6 Hz and minimal attenuation from 16.5-20 Hz.

Platform-to-Sternum-Head Relative Transmissibility

Figure 3-5 shows the results of the relative sternum-head transmissibility under the three single-direction input motions of the platform X (fore-aft), Y (lateral), and Z (vertical); with output motions on the human in x (axial), y (medial-lateral), and z (anterior-posterior) directions. The Xx and Yy components of the board-litter and the board-litter-collar conditions showed the lowest relative transmissibility around 5 Hz; however, they showed the largest relative transmissibility around 7 Hz for the Zz component. The board-litter and the board-litter-collar conditions showed lower relative transmissibility for the Zx condition, but were higher for the Xz condition.

Differences were observed during the statistical comparison between the rigid-platform and board-litter conditions in the Zz, Yy, Xx, Zx, and Xz components. For the Zz component, significant magnification was shown in the board-litter conditions over 0-11.3 Hz and attenuation from 13.2-20 Hz. The peak Yy magnification was also significant from 3.5-6.7 Hz. Relative transmissibility was significantly lower in the Xx direction for the board-litter system over the range 0-11.2 Hz. Zx had significant amplification from 1.7-8.6 Hz and attenuation from 13.0-20 Hz. Also, the Xz component showed significant amplification from 8.8-14.1 Hz.

Platform-to-Pelvis Transmissibility

Figure 3-6a shows the median platform-to-pelvis transmissibility under vertical input vibration (Z). For the Zz component, the baseline transmissibility showed a resonance around 8 Hz. The board condition showed higher transmissibility around 10 Hz. The board-litter and the board-litter-collar conditions showed a similar trend, with a peak frequency around 5 Hz; the transmissibility showed lower magnitudes for the Zx and Zy components, with both cases showing relatively smaller peaks around 5 Hz.

Significant differences between the rigid-platform and board-litter conditions were found for the Zx (Z – vertical platform input, x - axial human output) and Zz (Z – vertical platform input, z - anterior-posterior human output) components. For the Zx component, the board-litter system showed significant attenuation from 9.1-20 Hz, while the Zz component showed significant amplification from 0-7.6 Hz and attenuation from 8.9-20 Hz.

Platform-to-Pelvis-Sternum Relative Transmissibility

The rigid platform relative transmissibility of the Zz component of the sternum-pelvis ascended steadily for the frequency under consideration but reached a steady state around 19 Hz (Figure 3-6b). The board-litter and the board-litter-collar showed a peak around 7 Hz but descended after that. While the Zy (Z – vertical platform input, y – medial-lateral human output) component showed transmissibility below 0.4, the Zx component depicted two peaks for the baseline rigid-platform around 10 and 15 Hz. The board-litter and the board-litter-collar conditions showed similar trends and peaked around 6 Hz, with the board-litter-collar showing a relatively higher transmissibility at that peak.

The comparison between the rigid-platform and board-litter conditions showed differences in the Zx and Zz components. The Zx of the board-litter conditions showed significant magnification from 0.6-7.5 Hz and attenuation from 9.3-20 Hz. In Zz, there was significant attenuation from 12.3-20 Hz.

Platform-to-Board Transmissibility

The platform-to-board transmissibility under three conditions—board, board-litter, and board-litter-collar—are shown in Figure 3-7. Most activities occurred in the diagonal directions. For the Zz component, both the board-litter and the board-litter-collar conditions showed a peak around 5 Hz with a magnification of 2.5. The Xx component of the board-litter and the board-litter-collar conditions showed attenuation around 5 Hz, but showed magnification after 15 Hz. For the board condition, the long spinal board was approximately rigidly moving with the platform. The statistical comparison between the board and the board-litter conditions (Figure 3-7) showed significant differences in the transmissibility. In the Zz component, there was significant magnification in the board-litter condition around 5 Hz and attenuation from 8.35-20 Hz. The Yy component showed small but significant attenuation from 2.1-13.4 Hz. Finally, the Xx component showed significant attenuation from 3.2-11.8 Hz and magnification after 15.6 Hz.

Cervical Collar

Platform-to-Head Transmissibility

Comparing the board-litter condition with the board-litter-collar condition (Figure 3-4), there were no meaningfully significant differences in the Zz, Yy, and Xx components for head transmissibility. Zx displayed significant attenuation with the cervical collar from 2.3-13.3 Hz; however, Xz showed amplification with significant differences in 0-20 Hz.

Platform-to-Sternum-Head Relative Transmissibility

For the head sternum relative transmissibility (Figure 3-5), the effects of the cervical collar were seen in the Zx and Xz components. For the Zx component, significant attenuation was presented from 6.7-14.1 Hz. Significant magnification was seen for the Xz condition from 0- 20 Hz. These findings were similar to the effect of the cervical collar on the head transmissibility.

Vibration Magnitude

For the head and sternum, the effect of vibration magnitude was investigated using single-axis vibration for the vertical direction. The results are presented in Figure 3-8 with columns representing (a) head transmissibility and (b) sternum transmissibility. Four cases are shown: rigid-platform, board, board-litter, and board-litter-collar.

Random vs. Sinusoidal Vibration

For the vertical direction, a comparison was made between using swept sinusoidal vibration and random vibration. Figure 3-9 displays (a) head transmissibility and (b) sternum transmissibility for four conditions: rigid-platform, board, board-litter, and board-litter-collar.

Tri-Axis Input Vibration

During the analysis of transmissibility for the supine human, single-axis vibration provides some significant information about the human response during WBV under various back-supporting conditions. However, in real-life situations, WBV more commonly occurs with input vibration over multiple axes. For vibration-suppression design, it may be easier to conduct experiments using single-axis analysis. Figures 3-10 and 3-11 display the transmissibility during tri-axis vibration for the sternum and head respectively. Three supporting conditions are displayed: rigid-platform, board-litter, and board-litter-collar.

Platform-to-Sternum Transmissibility Comparison

To compare the single- and tri-axis transmissibility, an R^2 correlation coefficient was computed. For example, a linear regression model was fitted between the (Xx) single-axis component and the (Xx) tri-axis transmissibility component for each support condition (rigid-platform, board, board-litter, and board-litter-collar). The model was fitted for the median of eight subjects during single-axis vs. tri-axis. Figures 3-12 to 3-15 display the single- and tri-axis transmissibility for the sternum and Table 3-1 summarizes the respective coefficient of correlation (R^2). Each figure represents a different supporting condition: rigid-platform, board, board-litter, and board-litter-collar.

Platform-to-Head Transmissibility Comparison

A linear regression model for the head transmissibility was fitted in the same manner as the sternum. Figures 3-16 to 3-19 illustrate the single- and tri-axis transmissibility to the head, while Table 3-2 summarizes the correlation coefficients. Each figure represents a supporting condition.

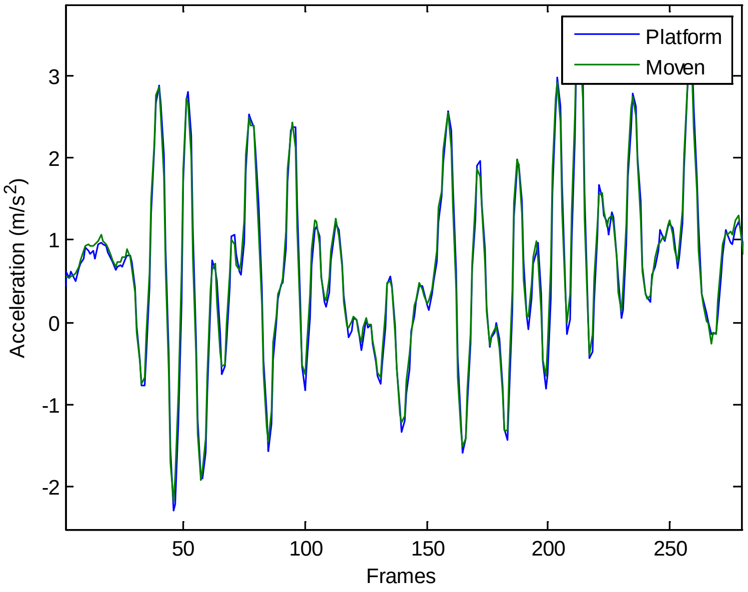

Figure 3-1. Fore-aft acceleration for the Moven inertial system (green line) and Platform accelerometer (blue line) during random vibration was used to verify the inertial system acceleration.

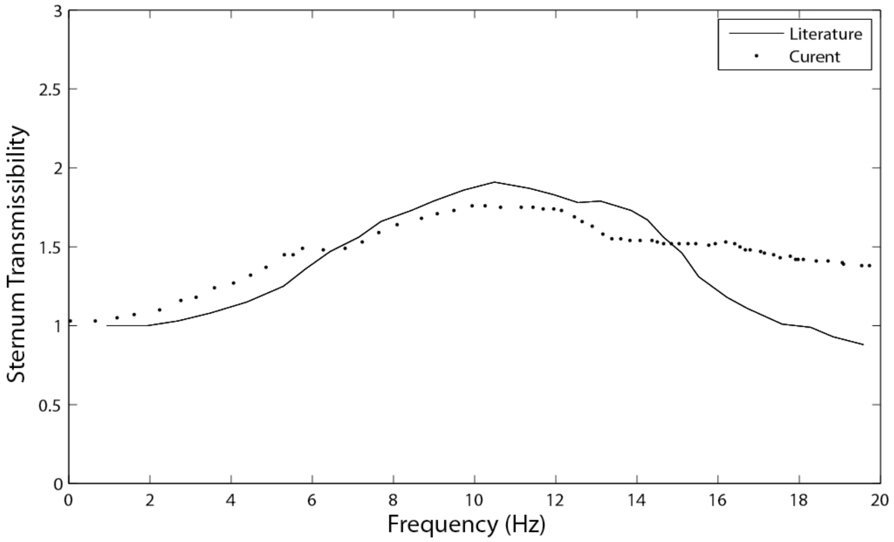

Figure 3-2. Vertical sternum transmissibility in the constrained semi-supine posture for the literature adapted from Huang and Griffin's 2009 study (solid line) and the current study (dotted line).

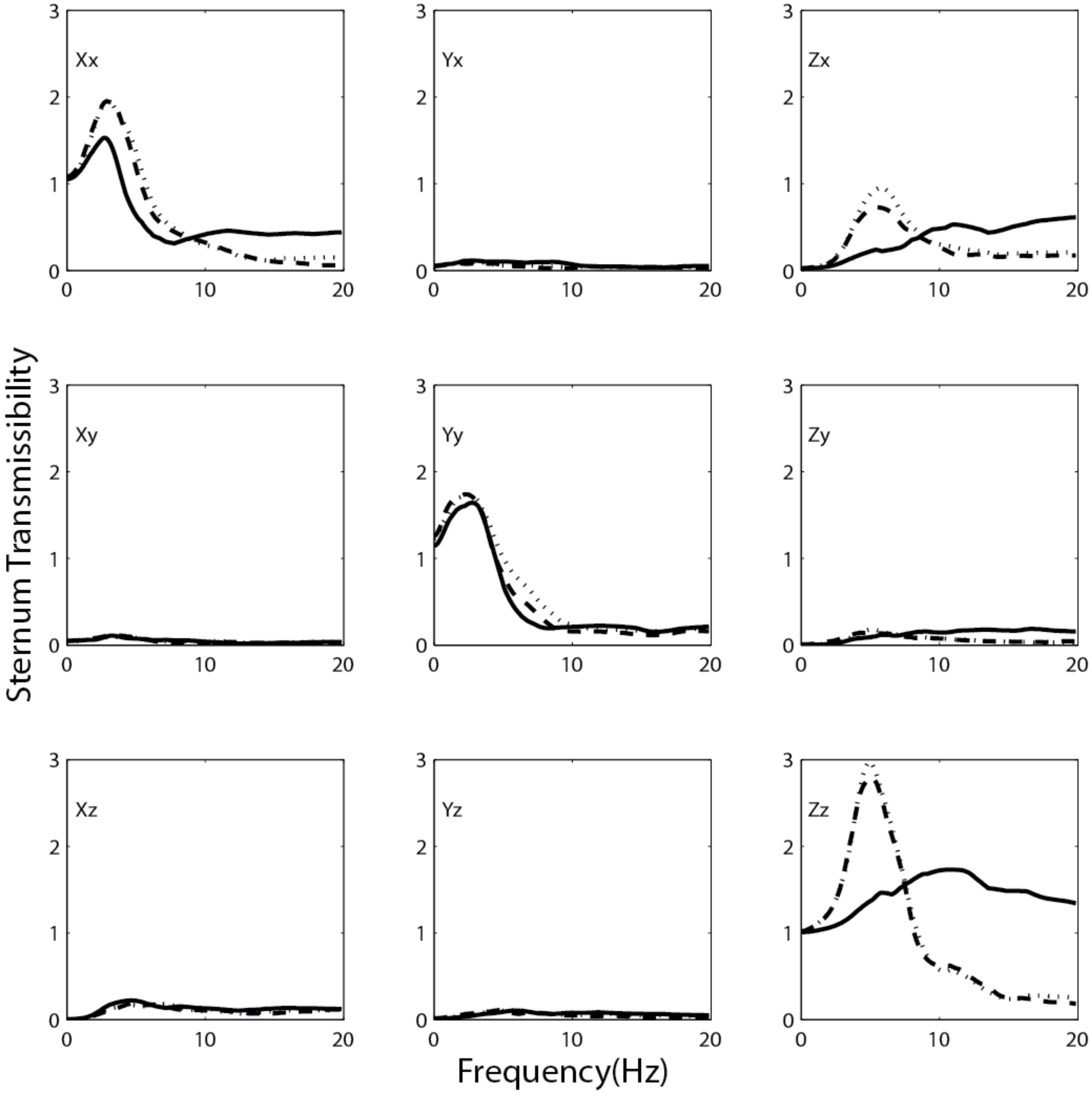

Figure 3-3. Platform-to-sternum transmissibility. Median of eight subjects is shown for three directions using single-axis input. For each direction the transmissibility is shown for the input direction as well as the orthogonal cross axis. Three support conditions are displayed: solid line (rigid-platform); dash (board-litter); and dotted (board-litter-collar). The uppercase direction represents the input motion of the platform: X – fore-aft, Y – lateral, Z - vertical and the lowercase direction represents the output motion on the human: x – axial, y – medial-lateral, and z – anterior-posterior. For example (Zz), the input platform motion (Z - vertical) mainly results in output human motion (z – anterior-posterior).

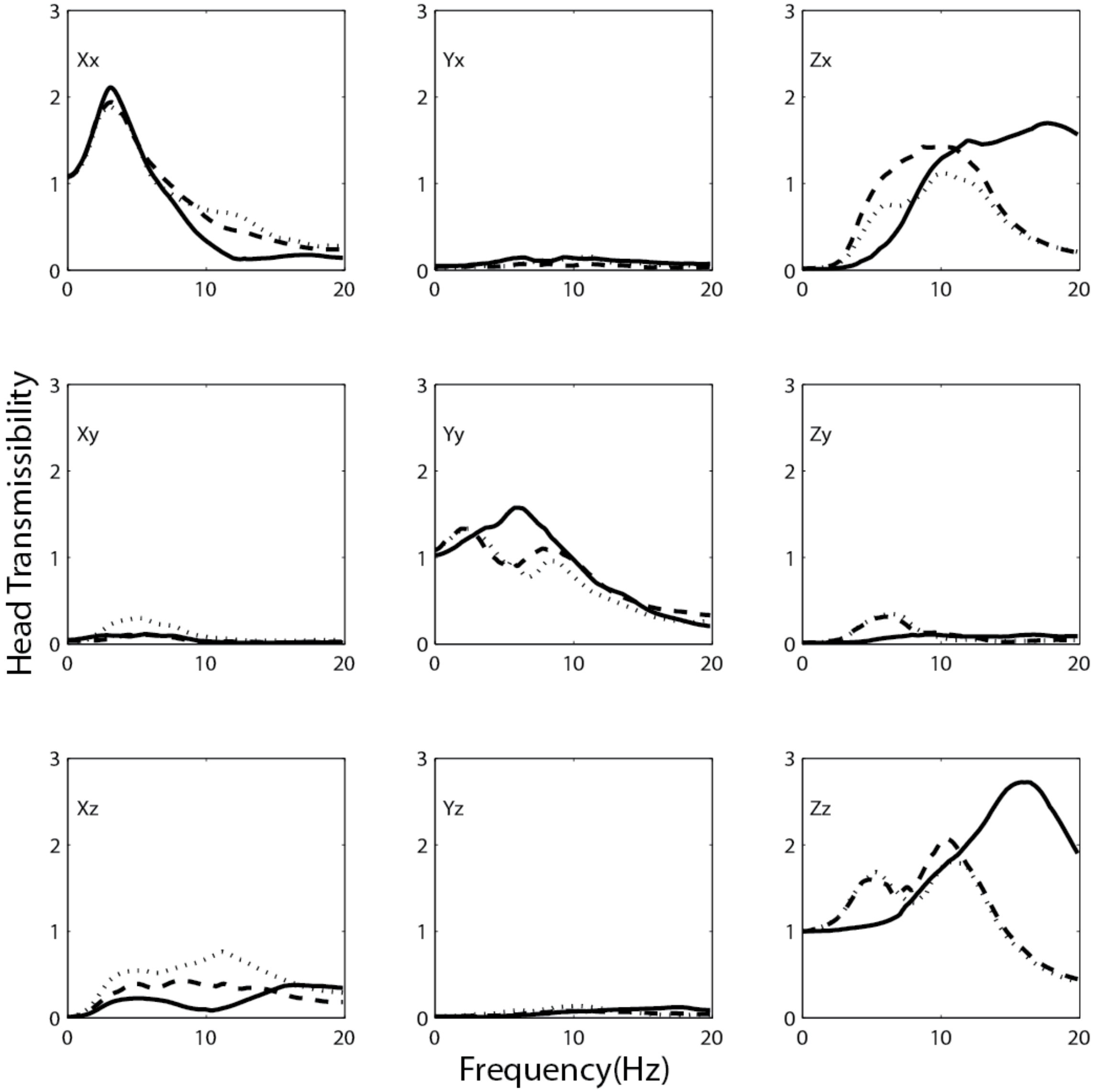

Figure 3-4. Platform-to-head transmissibility. Median of eight subjects is shown for three directions using single-axis input. For each the transmissibility is shown for the input direction as well as the orthogonal cross axis. Three support conditions are displayed: solid line (rigid-platform); dash (board-litter); and dotted (board-litter-collar). The uppercase direction represents the input motion of the platform: X – fore-aft, Y – lateral, Z - vertical and the lowercase direction represents the output motion on the human: x – axial, y – medial-lateral, and z – anterior-posterior. For example (Zz), the input platform motion (Z - vertical) mainly results in output human motion (z – anterior-posterior).

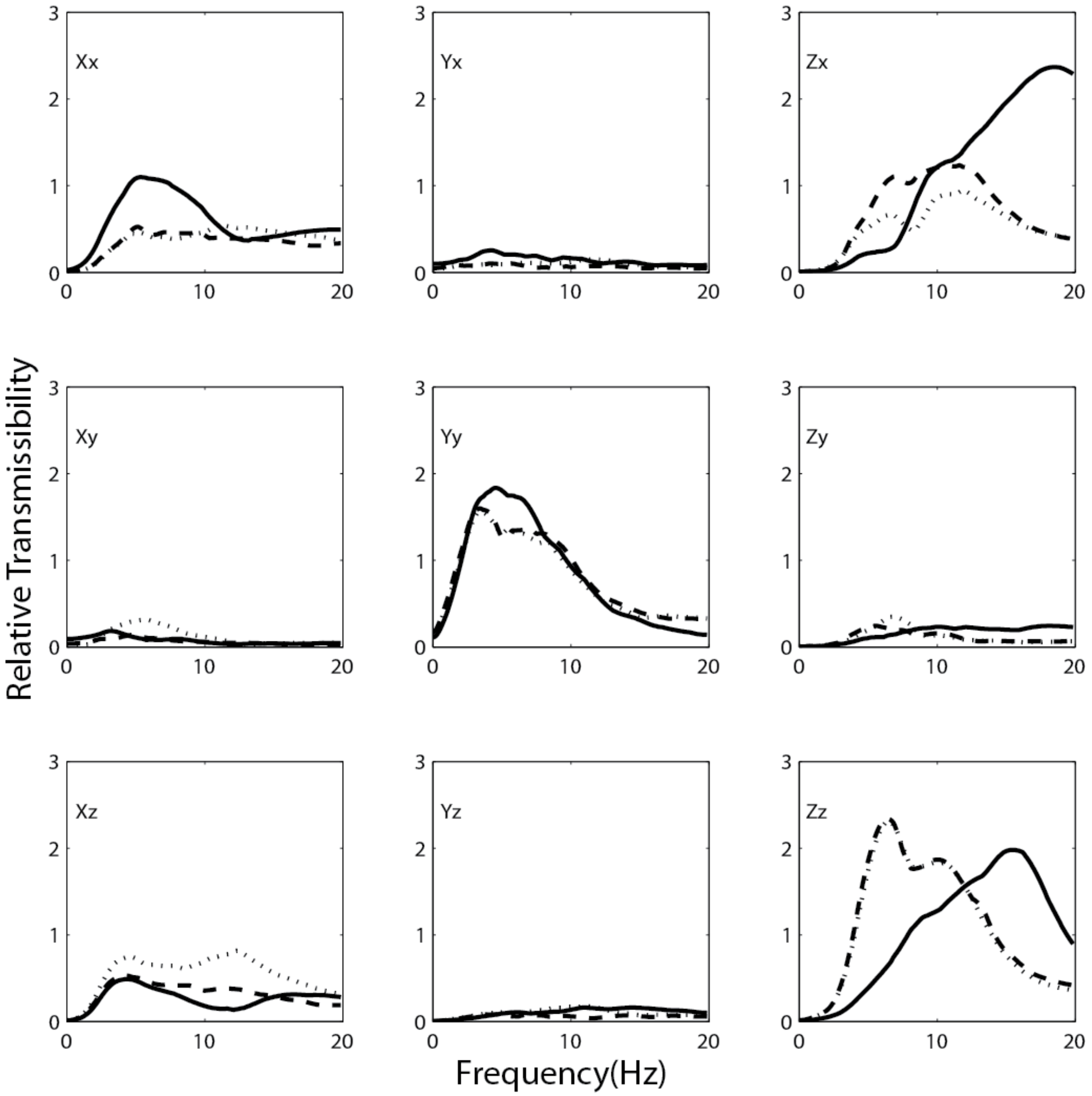

Figure 3-5. Sternum-to-head relative transmissibility. Median of eight subjects is shown for three directions using single-axis input. For each direction the transmissibility is shown for the input direction as well as the orthogonal cross axis. Three support conditions are displayed: solid line (rigid-platform); dash (board-litter); and dotted (board-litter-collar). The uppercase directions represents the input motion of the platform: X – fore-aft, Y – lateral, Z - vertical and the lowercase directions represents the output motion on the human: x – axial, y – medial-lateral, and z – anterior-posterior. For example (Zz), the input platform motion (Z - vertical) mainly results in output human motion (z – anterior-posterior).

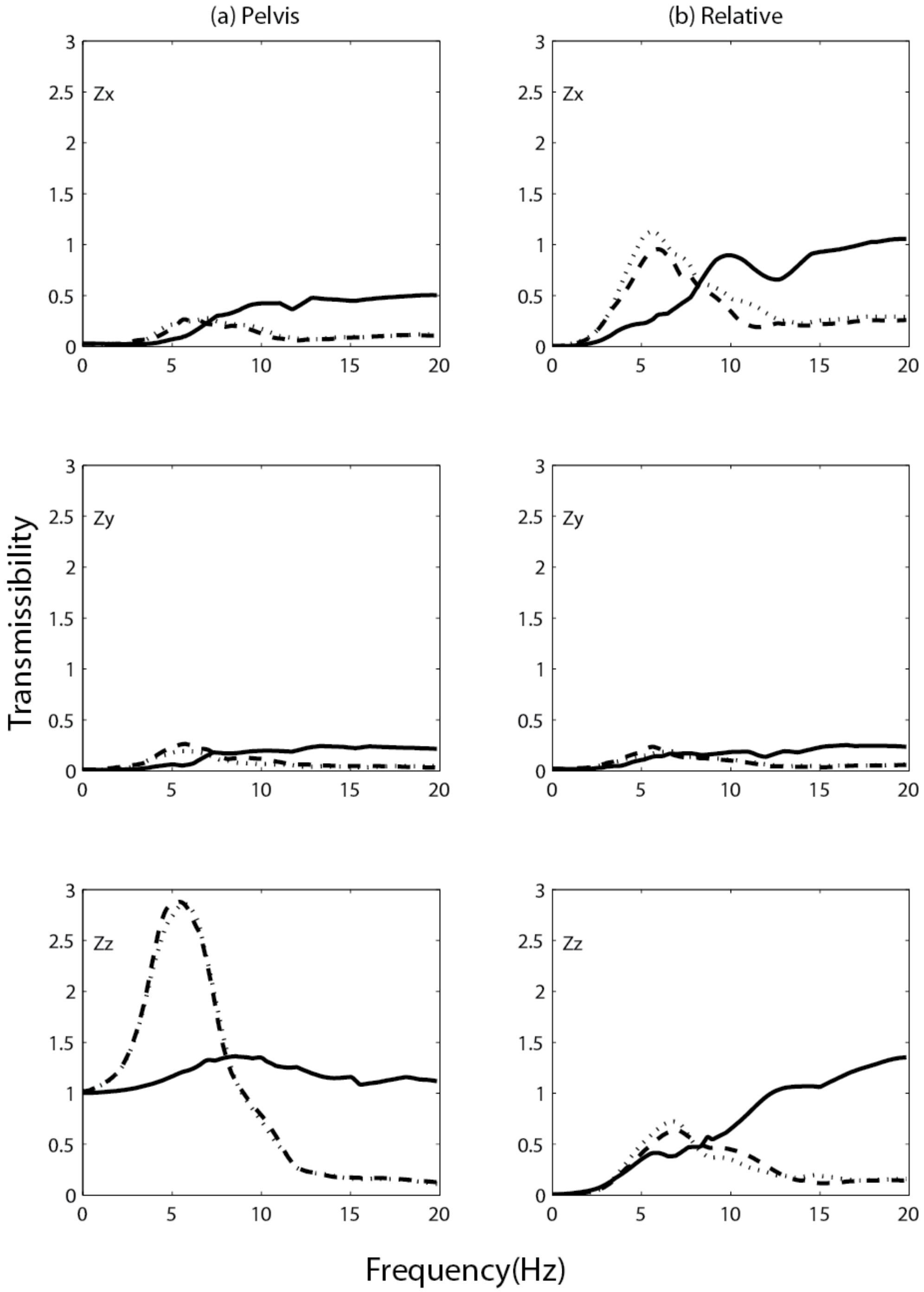

Figure 3-6. Median of eight subjects is shown for (a) platform to pelvis and (b) platform to relative (pelvis-sternum) transmissibilities during single-input vertical vibration. Three support conditions are displayed: solid line (rigid-platform); dash (board-litter); and dotted (board-litter-collar). The uppercase direction represents the input motion of the platform (Z - vertical) and the lowercase direction represents the output motion on the human (z – anterior-posterior).

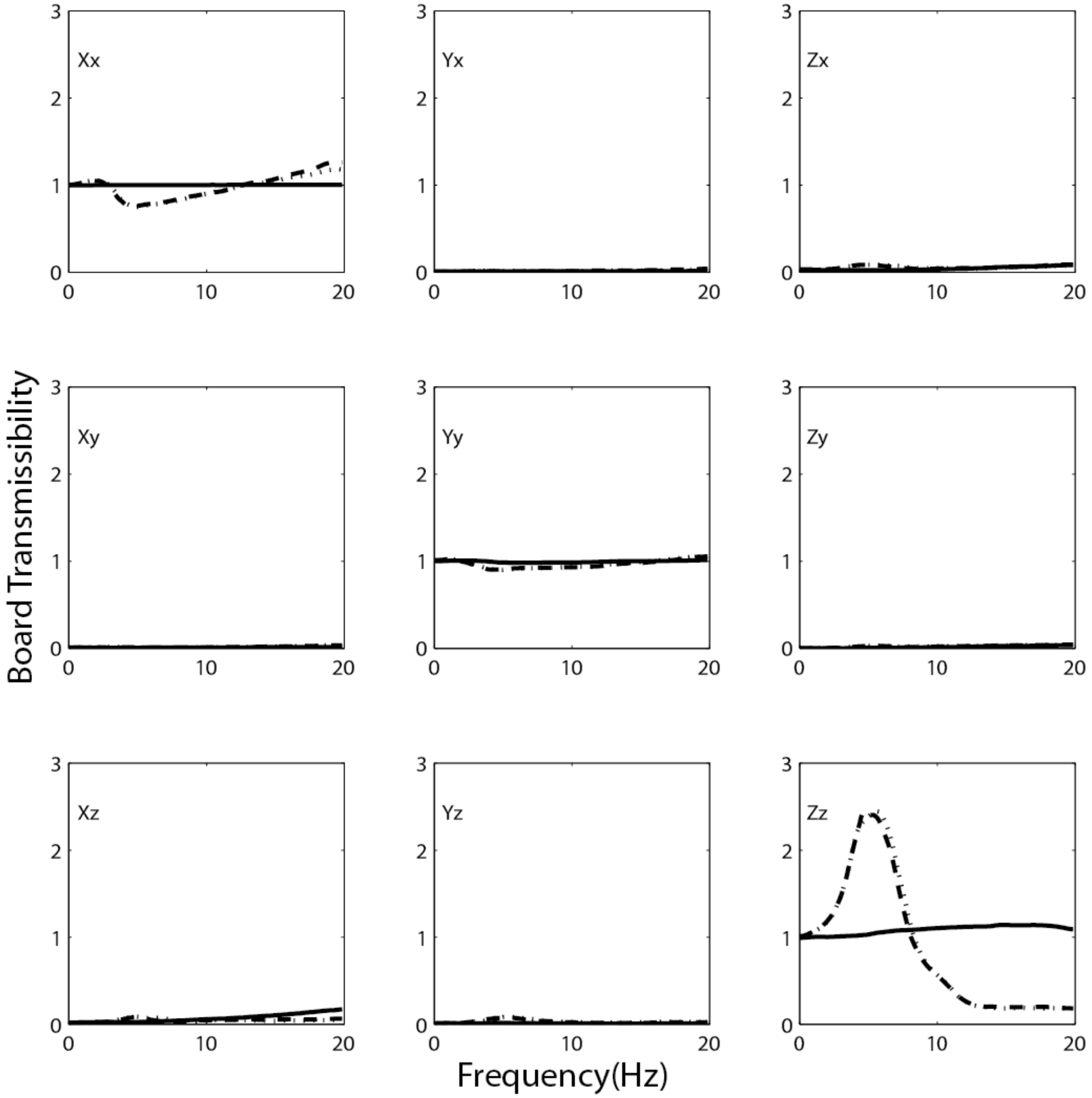

Figure 3-7. Platform-to-board transmissibility. Median of eight subjects is shown for three directions using single-axis input. For each direction the transmissibility is shown for the input direction as well as the orthogonal cross axis. Three support conditions are displayed: solid line (board); dash (board-litter); and dotted (board-litter-collar). The uppercase directions represents the input motion of the platform: X – fore-aft, Y – lateral, Z - vertical and the lowercase directions represents the output motion on the center of the spinal board: x – axial, y – medial-lateral, and z – anterior-posterior. For example (Zz), the input platform motion (Z - vertical) mainly results in output board motion (z – anterior-posterior).

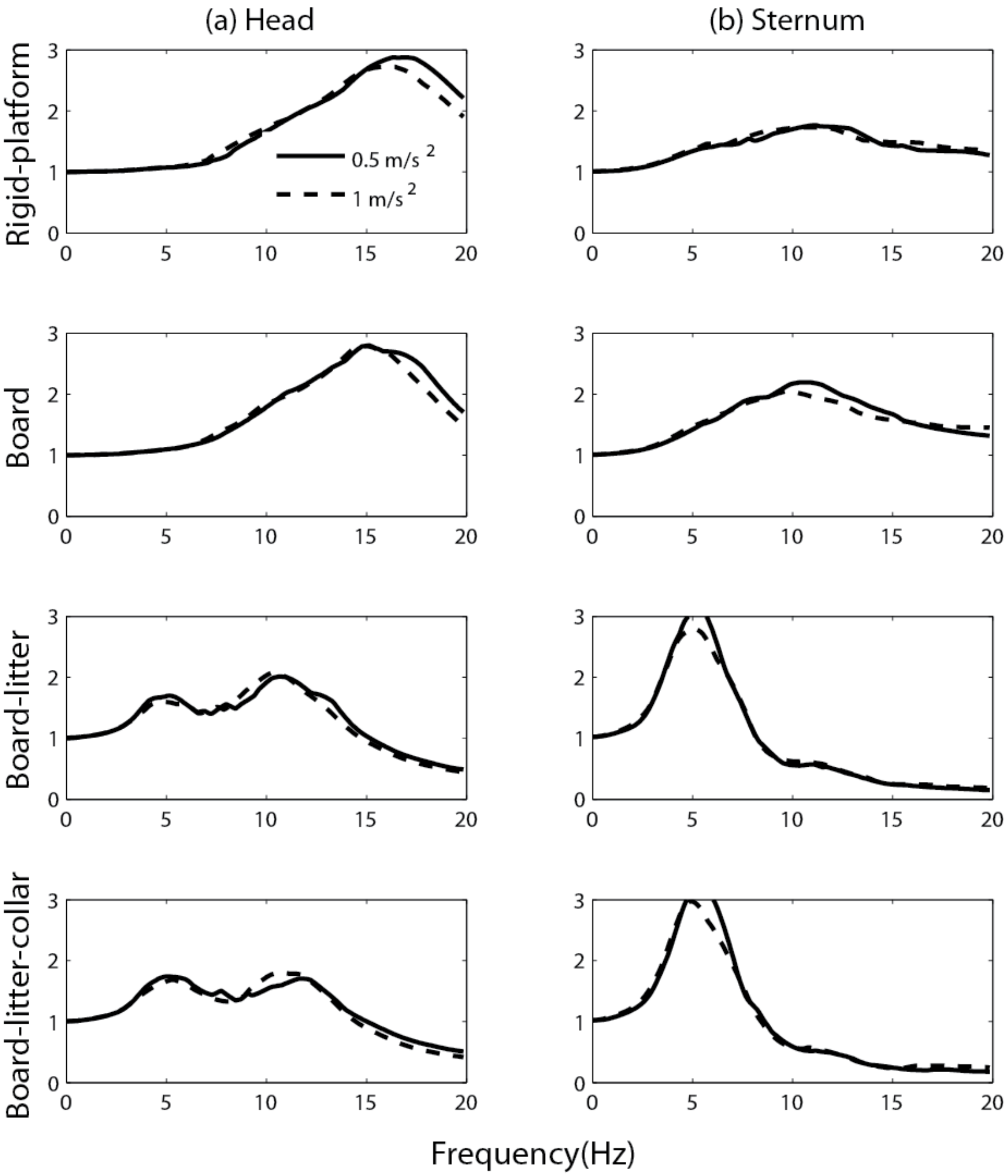

Figure 3-8. Platform to (a) head and (b) sternum transmissibilities are shown for four support conditions (rigid-platform, board, board-litter, and board-litter-collar). The solid line represents 0.5 m/s^2 random input vibration, and the dashed line represents 1.0 m/s^2 random input vibration. Median of eight subjects is shown for vertical vibration using single-axis input. Transmissibility is shown for the Zz direction (Z – vertical platform input, z – anterior-posterior human output).

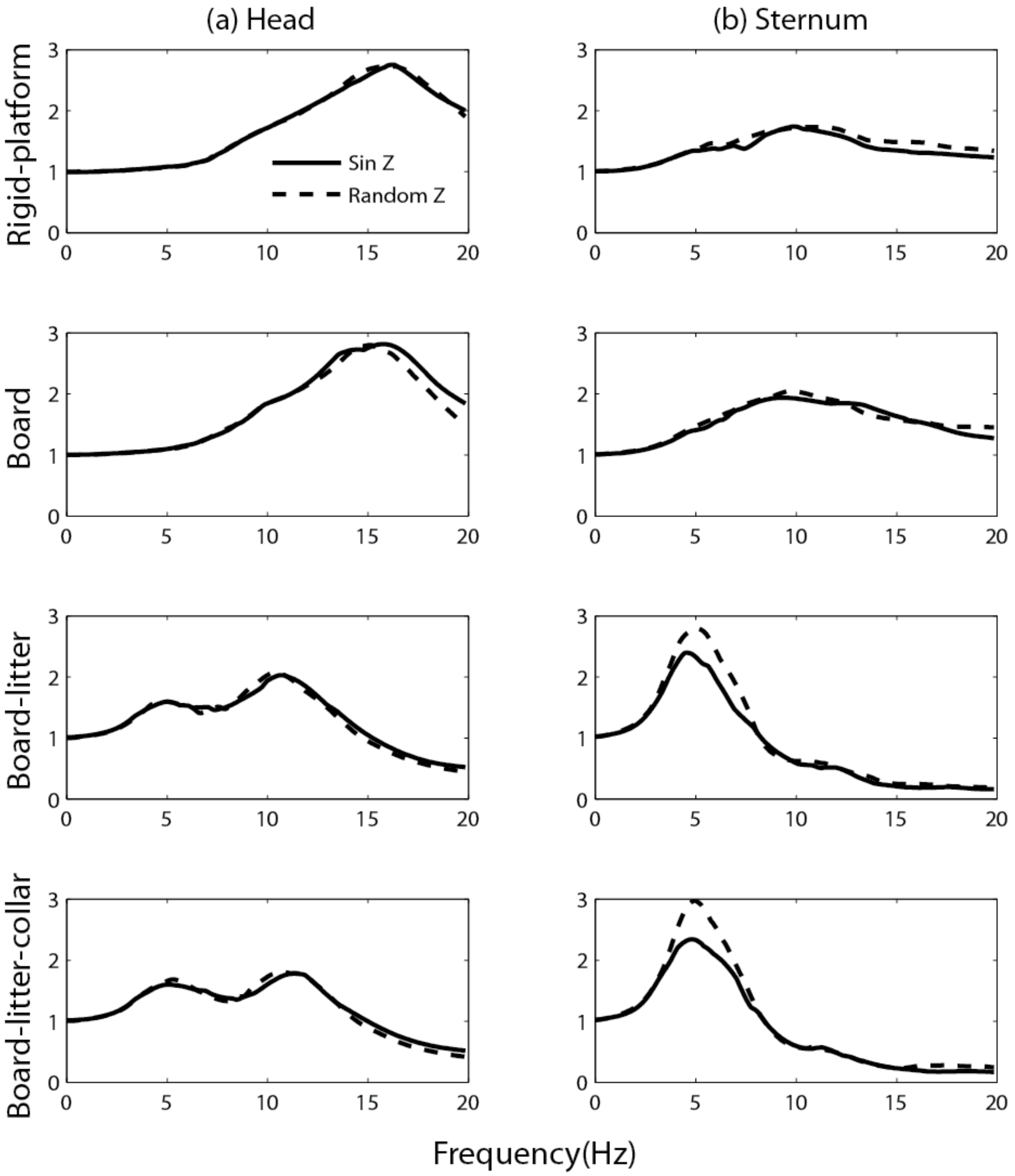

Figure 3-9. Platform to (a) head and (b) sternum transmissibilities are shown for four support conditions (rigid-platform, board, board-litter, and board-litter-collar). The solid line represents 1.0 m/s^2 sinusoidal input vibration, and the dashed line represents 1.0 m/s^2 random input vibration. Median of eight subjects is shown for vertical vibration using single-axis input. Transmissibility is shown for the Zz direction (Z – vertical platform input, z – anterior-posterior human output).

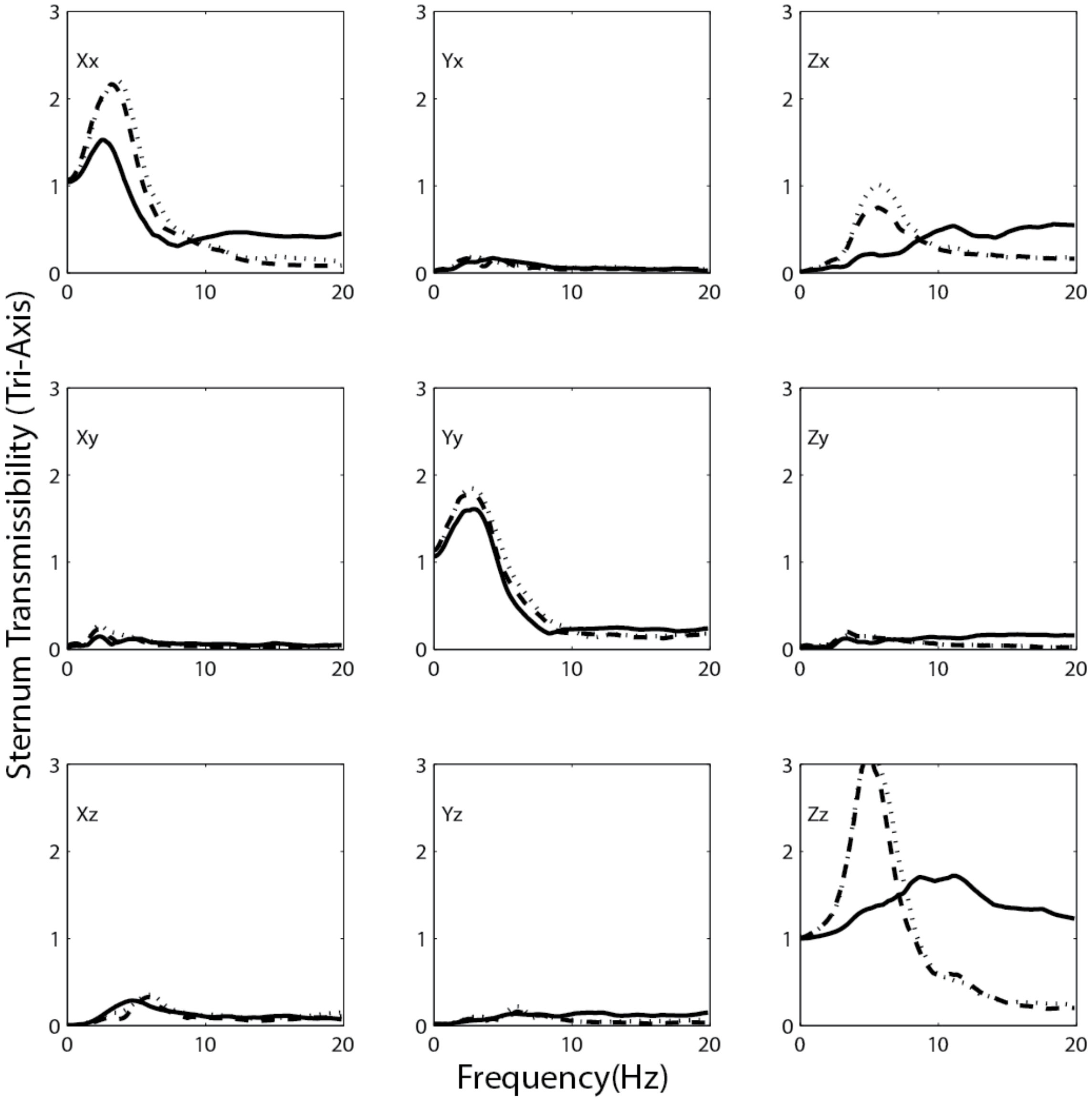

Figure 3-10. Platform-to-sternum transmissibility. Median of eight subjects is shown for three directions using tri-axis input. For each direction the transmissibility is shown for the input direction as well as the orthogonal cross axis. Three support conditions are displayed: solid line (rigid-platform); dash (board-litter); and dotted (board-litter-collar). The uppercase direction represents the input motion of the platform: X – fore-aft, Y – lateral, Z - vertical and the lowercase direction represents the output motion on the human: x – axial, y – medial-lateral, and z – anterior-posterior. For example (Zz), the input platform motion (Z - vertical) mainly results in output human motion (z – anterior-posterior).

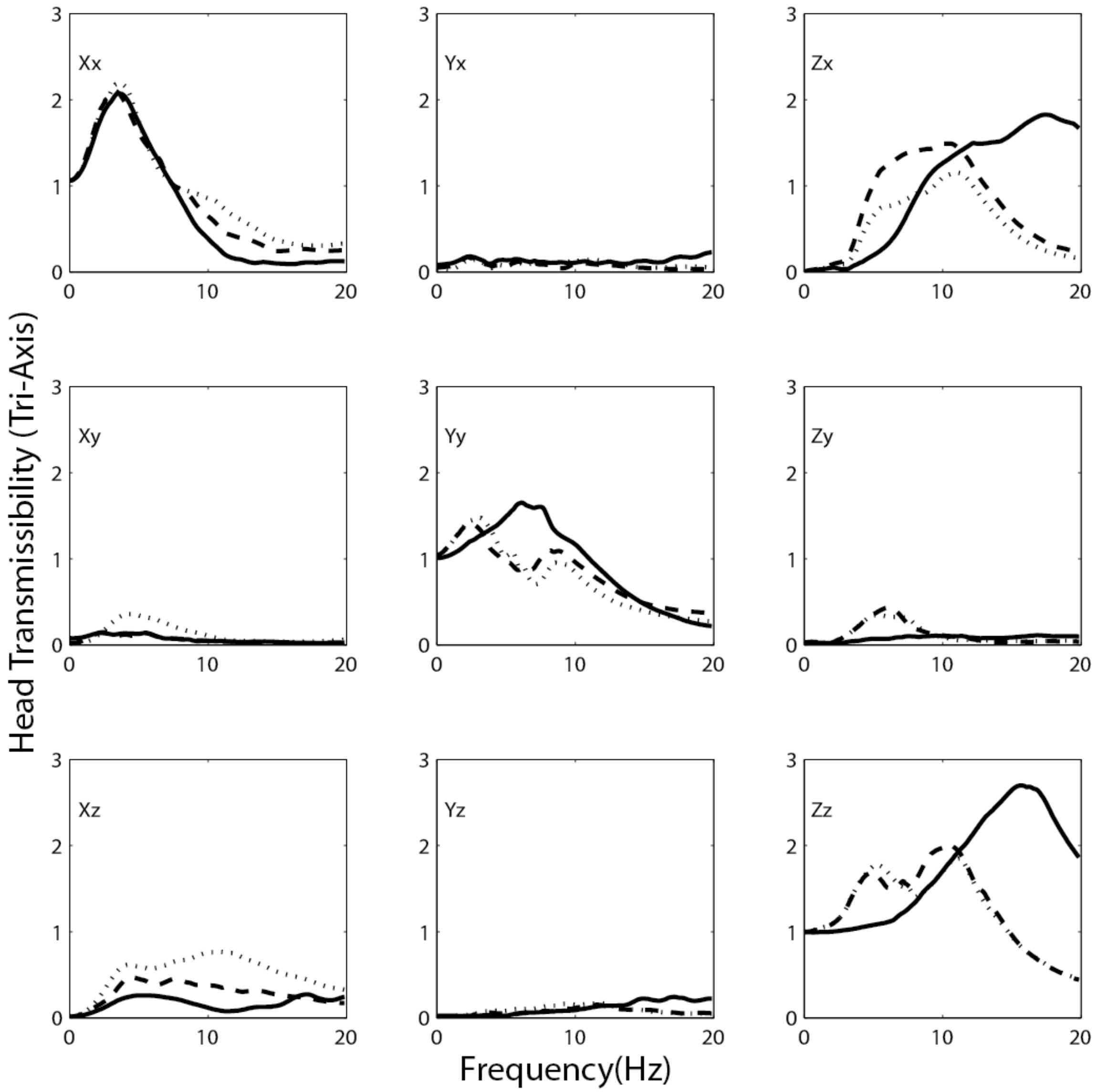

Figure 3-11. Platform-to-head transmissibility. Median of eight subjects is shown for three directions using tri-axis input. For each the transmissibility is shown for the input direction as well as the orthogonal cross axis. Three support conditions are displayed: solid line (rigid-platform); dash (board-litter); and dotted (board-litter-collar). The uppercase direction represents the input motion of the platform: X – fore-aft, Y – lateral, Z - vertical and the lowercase direction represents the output motion on the human: x – axial, y – medial-lateral, and z – anterior-posterior. For example (Zz), the input platform motion (Z - vertical) mainly results in output human motion (z – anterior-posterior).

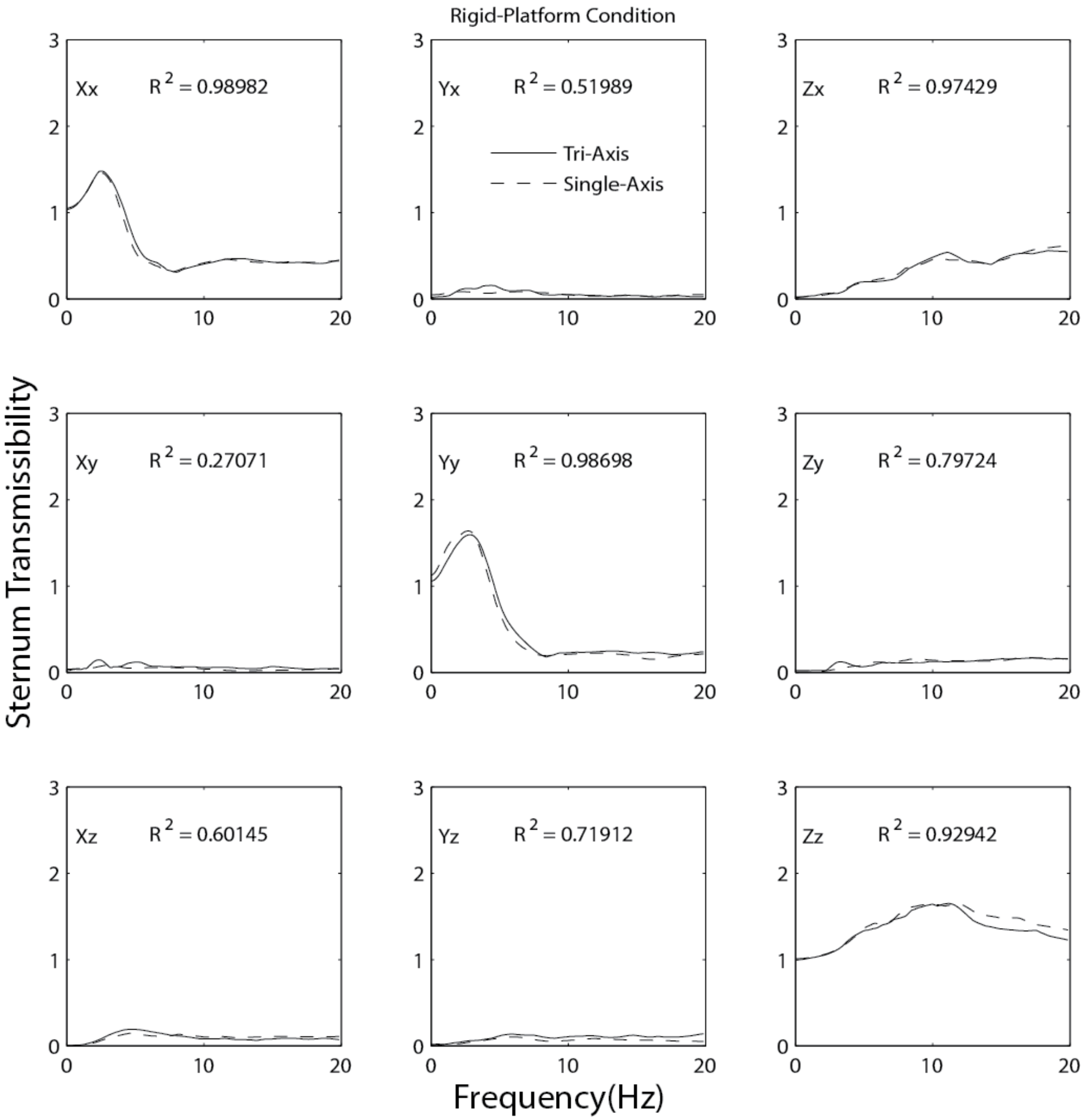

Figure 3-12. Platform-to-sternum transmissibility for tri- and single- axis vibration input. Median of eight subjects under rigid-platform support. The uppercase direction represents the input motion of the platform: X – fore-aft, Y – lateral, Z - vertical and the lowercase direction represents the output motion on the human: x – axial, y – medial-lateral, and z – anterior-posterior. For example (Zz), the input platform motion (Z - vertical) mainly results in output human motion (z – anterior-posterior).

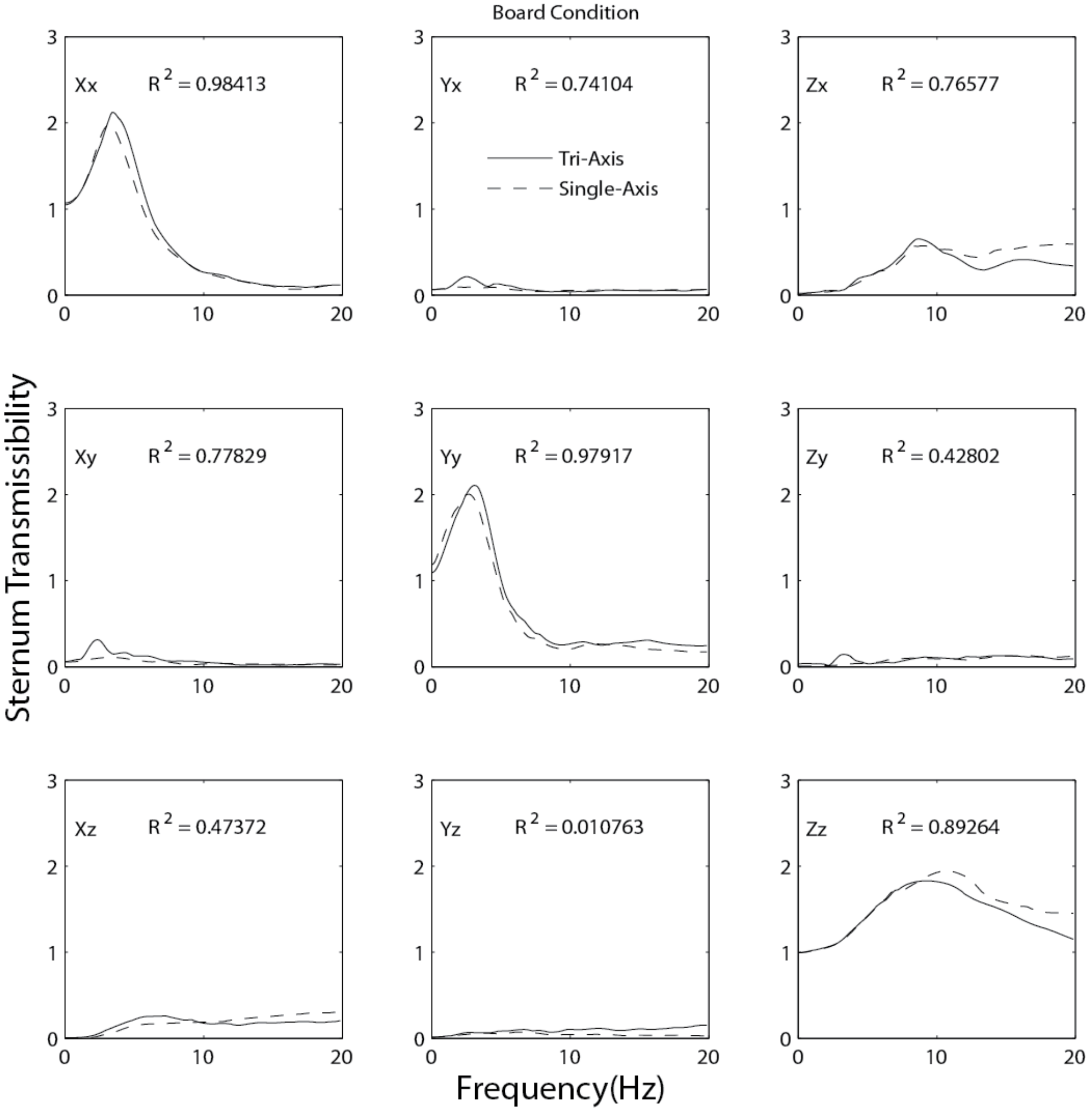

Figure 3-13. Platform-to-sternum transmissibility for tri- and single- axis vibration input. Median of eight subjects under spinal board support. The uppercase direction represents the input motion of the platform: X – fore-aft, Y – lateral, Z - vertical and the lowercase direction represents the output motion on the human: x – axial, y – medial-lateral, and z – anterior-posterior. For example (Zz), the input platform motion (Z - vertical) mainly results in output human motion (z – anterior-posterior).

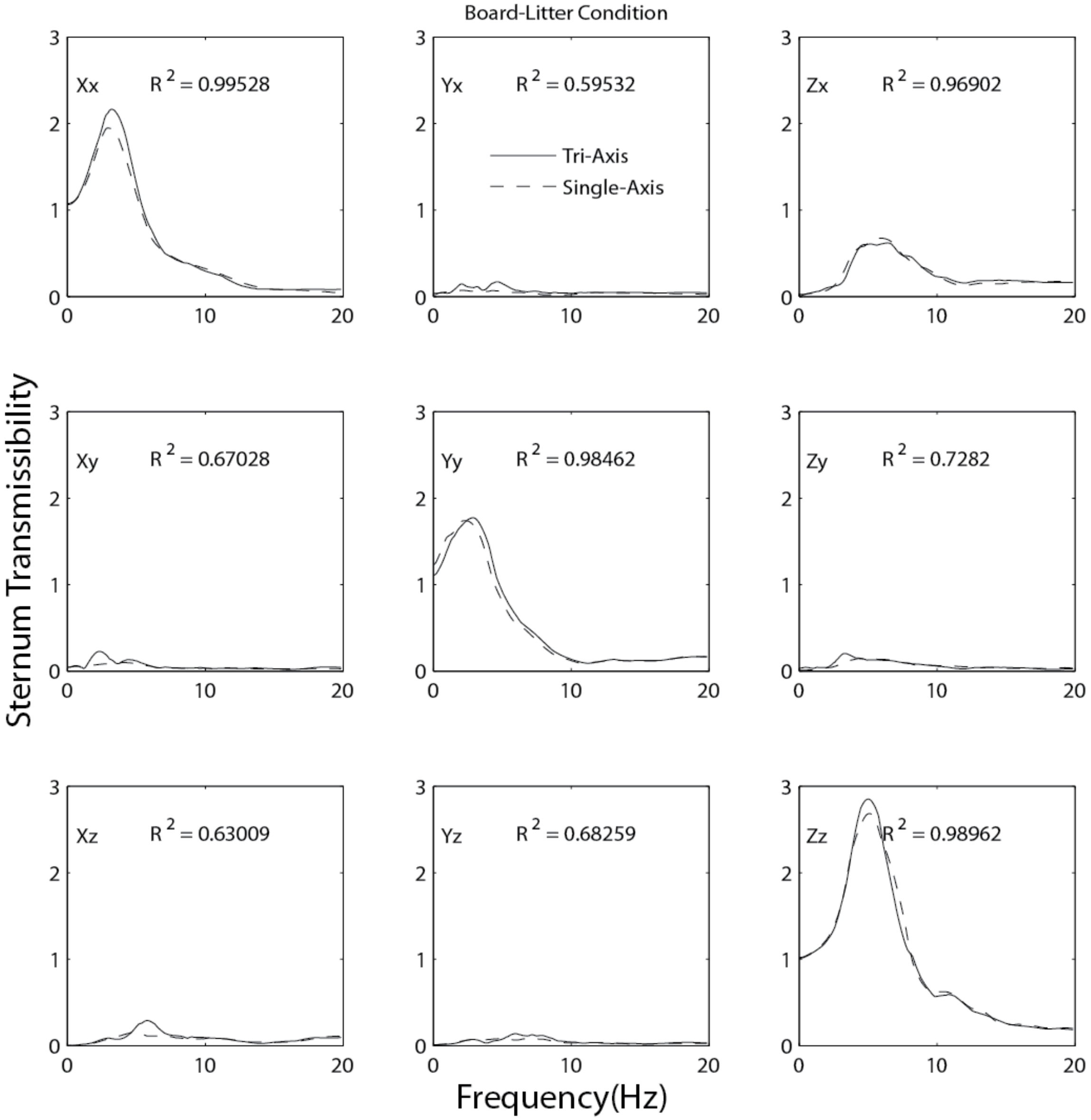

Figure 3-14. Platform-to-sternum transmissibility for tri- and single- axis vibration input. Median of eight subjects under spinal board and litter support. The uppercase direction represents the input motion of the platform: X – fore-aft, Y – lateral, Z - vertical and the lowercase direction represents the output motion on the human: x – axial, y – medial-lateral, and z – anterior-posterior. For example (Zz), the input platform motion (Z - vertical) mainly results in output human motion (z – anterior-posterior).

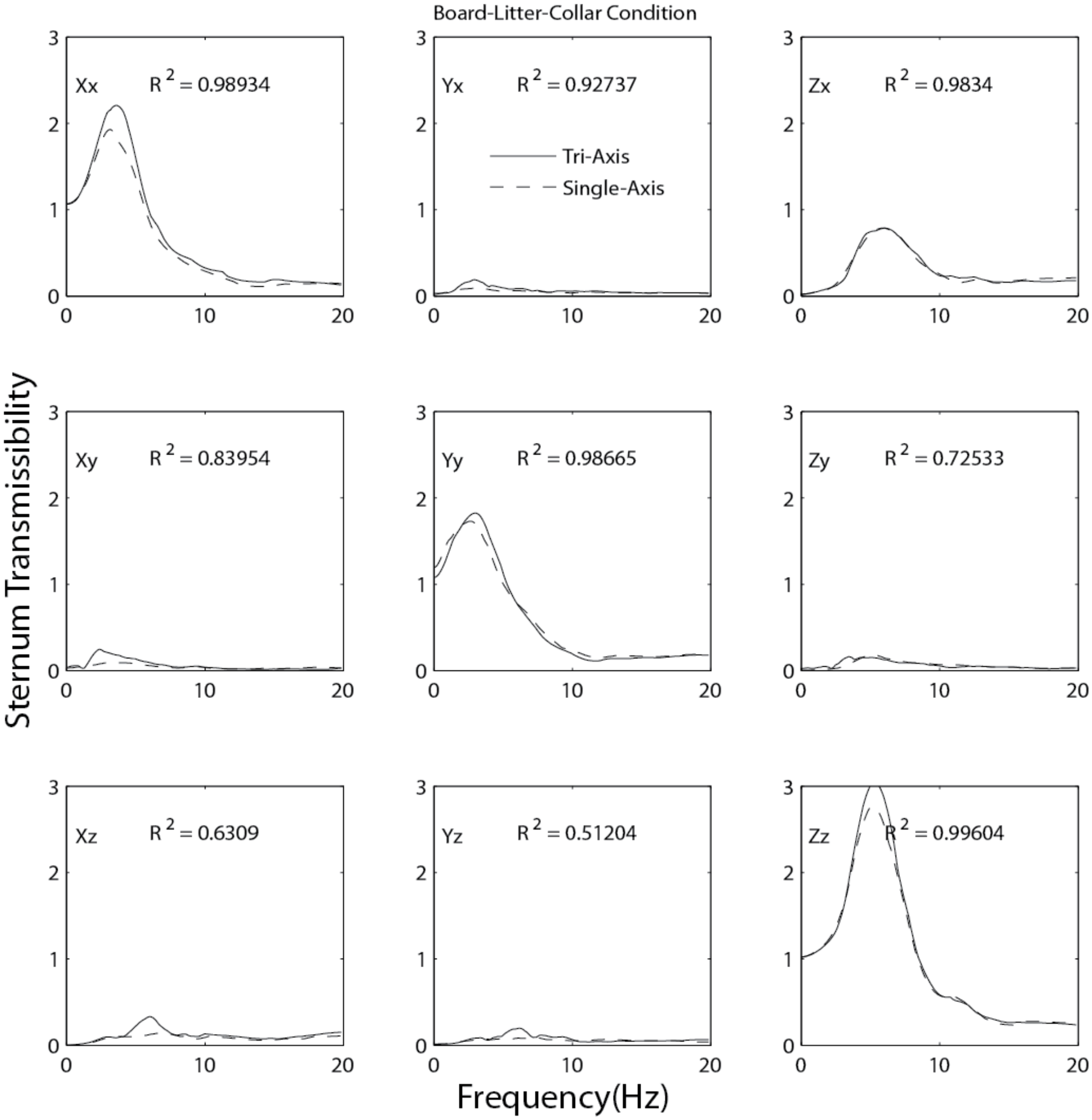

Figure 3-15. Platform-to-sternum transmissibility for tri- and single- axis vibration input. Median of eight subjects under spinal board, litter, and cervical collar support. The uppercase direction represents the input motion of the platform: X – fore-aft, Y – lateral, Z - vertical and the lowercase direction represents the output motion on the human: x – axial, y – medial-lateral, and z – anterior-posterior. For example (Zz), the input platform motion (Z - vertical) mainly results in output human motion (z – anterior-posterior).

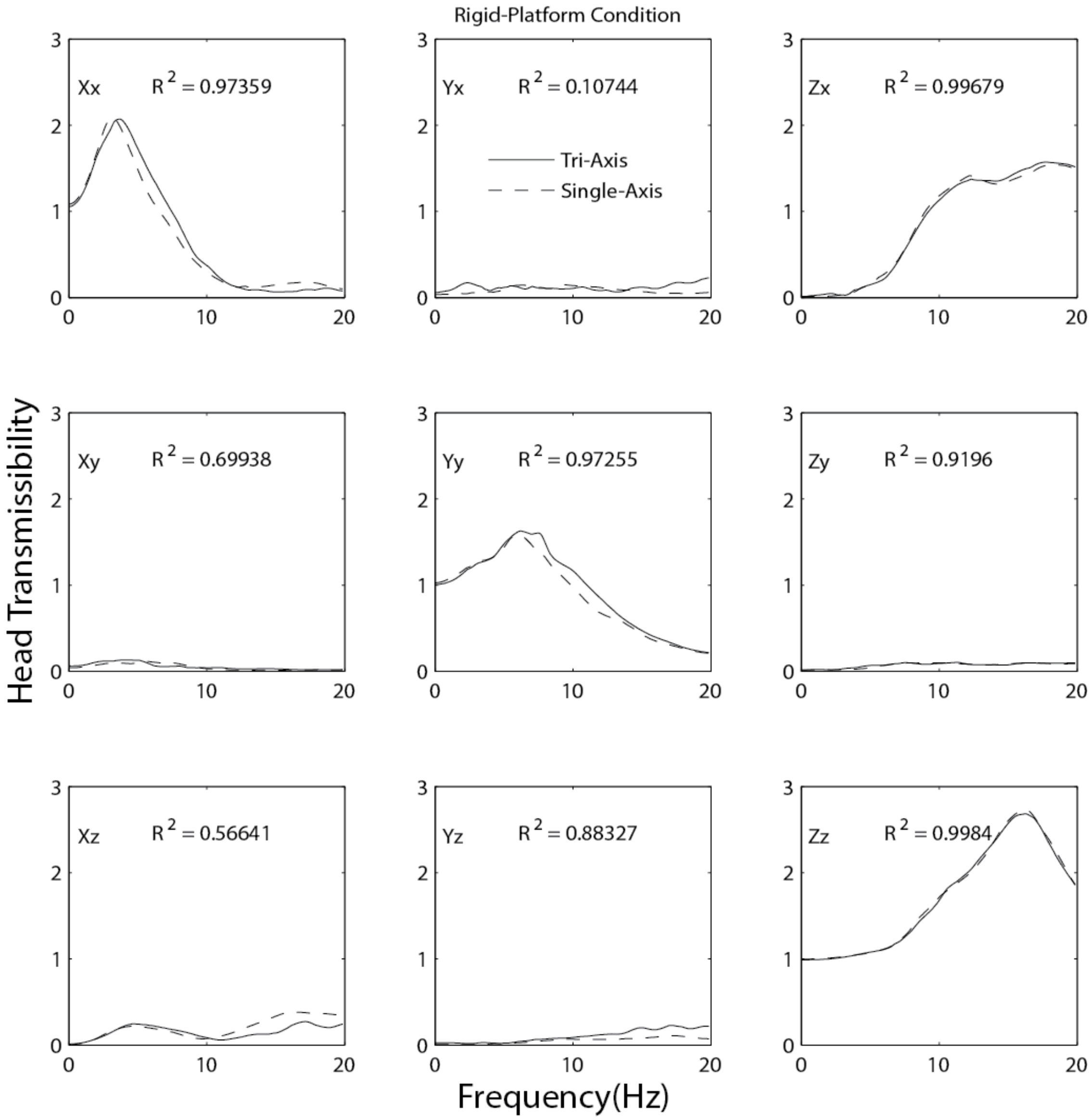

Figure 3-16. Platform-to-head transmissibility for tri- and single- axis vibration input. Median of eight subjects under rigid platform support. The uppercase direction represents the input motion of the platform: X – fore-aft, Y – lateral, Z - vertical and the lowercase direction represents the output motion on the human: x – axial, y – medial-lateral, and z – anterior-posterior. For example (Zz), the input platform motion (Z - vertical) mainly results in output human motion (z – anterior-posterior).

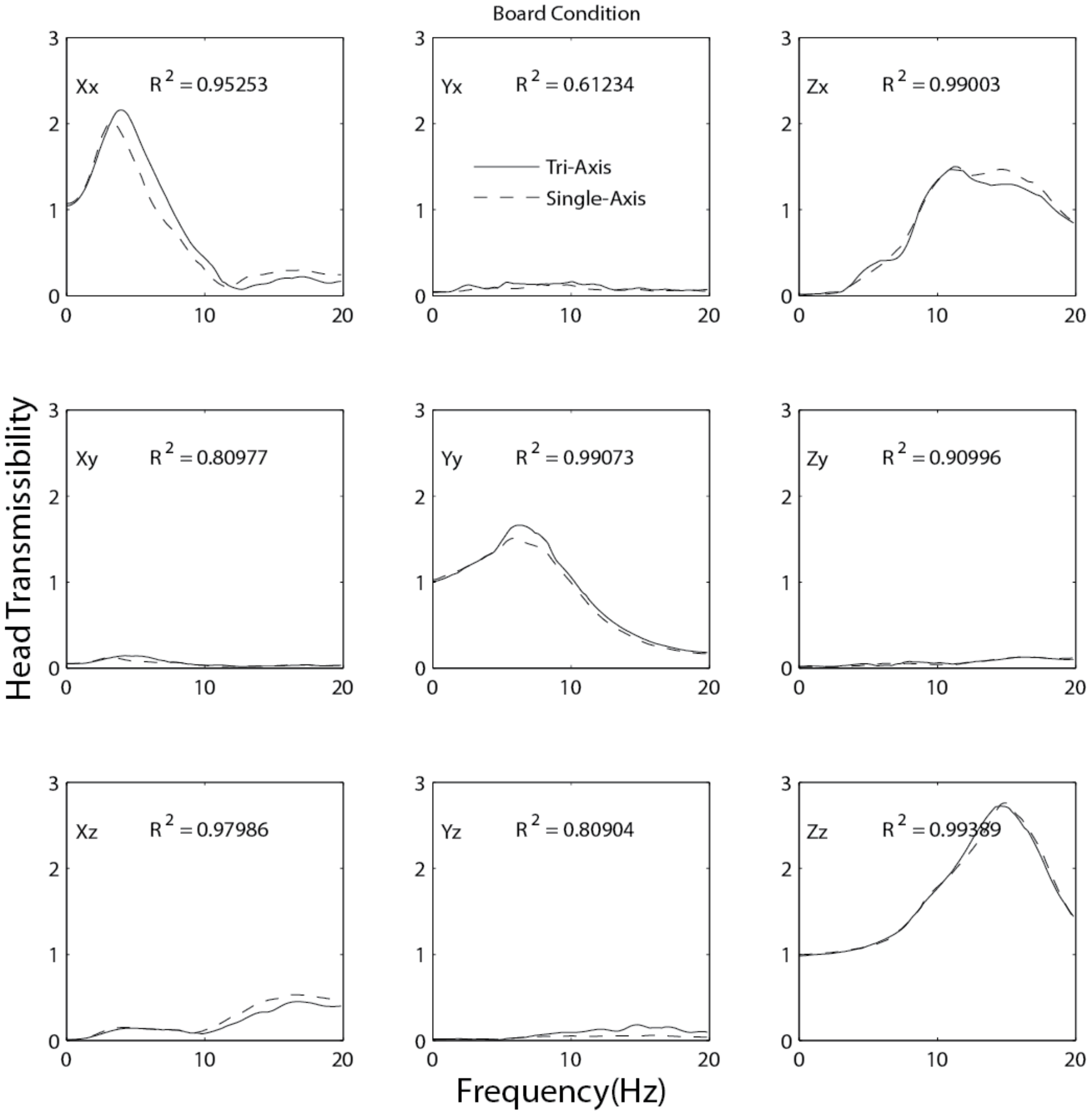

Figure 3-17. Platform-to-head transmissibility for tri- and single- axis vibration input. Median of eight subjects under spinal board support. The uppercase direction represents the input motion of the platform: X – fore-aft, Y – lateral, Z - vertical and the lowercase direction represents the output motion on the human: x – axial, y – medial-lateral, and z – anterior-posterior. For example (Zz), the input platform motion (Z - vertical) mainly results in output human motion (z – anterior-posterior).

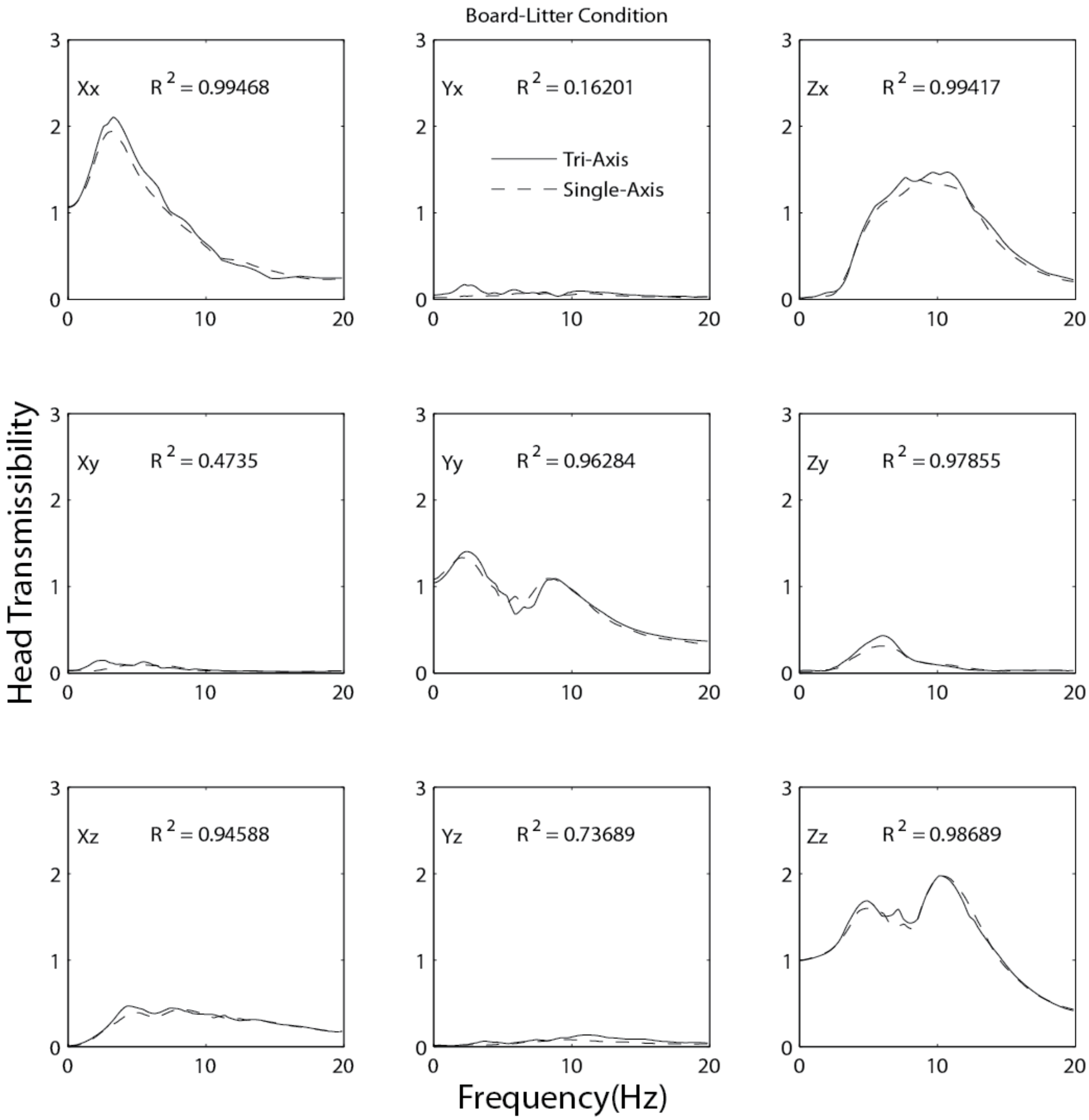

Figure 3-18. Platform-to-head transmissibility for tri- and single- axis vibration input. Median of eight subjects under spinal board and litter support. The uppercase direction represents the input motion of the platform: X – fore-aft, Y – lateral, Z - vertical and the lowercase direction represents the output motion on the human: x – axial, y – medial-lateral, and z – anterior-posterior. For example (Zz), the input platform motion (Z - vertical) mainly results in output human motion (z – anterior-posterior).

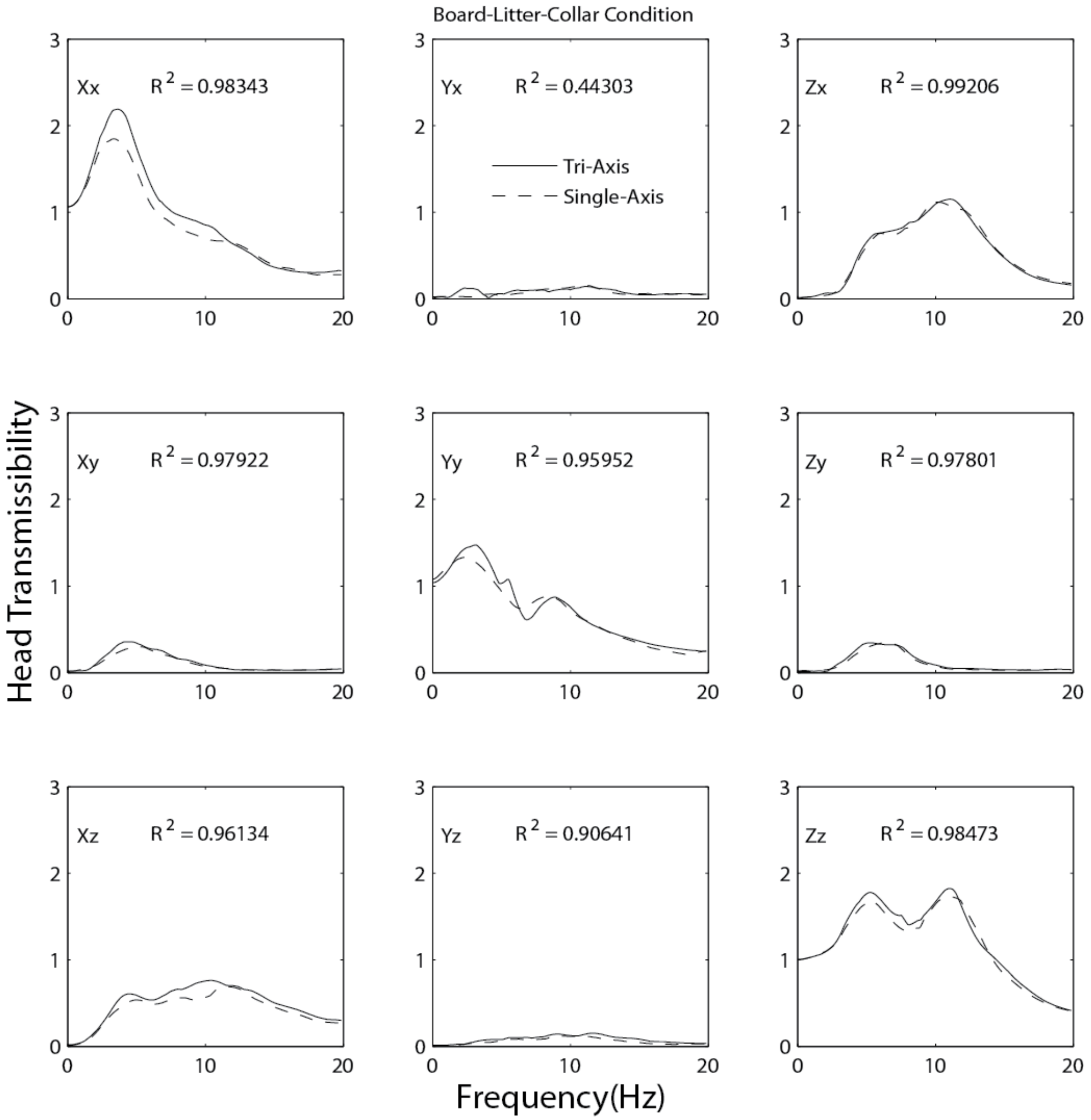

Figure 3-19. Platform-to-head transmissibility for tri- and single- axis vibration input. Median of eight subjects under spinal board, litter, and cervical collar support. The uppercase direction represents the input motion of the platform: X – fore-aft, Y – lateral, Z - vertical and the lowercase direction represents the output motion on the human: x – axial, y – medial-lateral, and z – anterior-posterior. For example (Zz), the input platform motion (Z - vertical) mainly results in output human motion (z – anterior-posterior).

Table 3-1. R^2 correlation coefficient between the median of eight subjects for (a) single- and (b) tri-axis platform-to-sternum transmissibility for each supporting condition. The uppercase direction represents the input motion of the platform: X - fore-aft, Y - lateral, Z - vertical and the lowercase direction represents the output motion on the human: x - axial, y - medial-lateral, and z - anterior-posterior. For example (Zz), the input platform motion (Z - vertical) mainly results in output human motion (z - anterior-posterior).

Sternum Transmissibility R^2									
Component	Xx	Xy	Xz	Yx	Yy	Yz	Zx	Zy	Zz
Rigid-platform	0.99	0.27	0.60	0.52	0.99	0.72	0.97	0.80	0.93
Board	0.98	0.78	0.47	0.74	0.98	0.01	0.77	0.43	0.89
Board-litter	0.99	0.67	0.63	0.59	0.98	0.68	0.97	0.73	0.99
Board-litter-collar	0.99	0.84	0.63	0.93	0.97	0.51	0.98	0.73	0.99

Table 3-2. R^2 correlation coefficient between the median of eight subjects for (a) single- and (b) tri-axis platform-to-head transmissibility for each supporting condition. The uppercase direction represents the input motion of the platform: X - fore-aft, Y - lateral, Z - vertical and the lowercase direction represents the output motion on the human: x - axial, y - medial-lateral, and z - anterior-posterior. For example (Zz), the input platform motion (Z - vertical) mainly results in output human motion (z - anterior-posterior).

Head Transmissibility R^2									
Component	Xx	Xy	Xz	Yx	Yy	Yz	Zx	Zy	Zz
Rigid-platform	0.97	0.70	0.57	0.11	0.97	0.88	0.99	0.92	0.99
Board	0.95	0.81	0.98	0.61	0.99	0.81	099	0.91	0.99
Board-litter	0.99	0.47	0.95	0.16	0.96	0.74	0.99	0.98	0.99
Board-litter-collar	0.98	0.98	0.96	0.44	0.96	0.91	0.99	0.98	0.98

CHAPTER IV

DISCUSSION

In designing vibration-suppression systems, information about the relationship between the input ground motion and the resulting motion on the human body is very important. In seated and standing positions, the information about selected points on the human body (the head, for example) could be sufficient to reduce the motion at different segments as the energy is transferring through the body from the seat or feet to the head, but the situation in supine positions is more complicated. For supine subjects, if the motion of the head in response to the input motion is minimized, then that may not solve the problem at the cervical spine area, as the latter may have been affected by the motion of the adjacent segments as well (Figure 3-5).

Platform to the sternum transmissibility (Zz in Figure 3-3; Z – vertical platform input, z – anterior-posterior human output) and platform to the pelvis transmissibly (Zz in Figure 3-6a) are similar to some degree, especially up to 7 Hz, with both of them resonating around 5 Hz; thus, their relative transmissibility (Zz in Figure 3-6b) in this range is small, meaning that the segments are moving together and the relative motion between them is minimal. However, the small difference between the sternum and pelvis motions may become larger if the vibration-suppression systems targeted only one of them, for example.

The sternum and the head have shown different baseline resonances in different directions, which can be attributed to the differences in their mass, stiffness, and constraint conditions; however, most of these frequencies are still greater than 10 Hz and therefore are expected to be attenuated by the board-litter system. Clear examples are shown in the Zz and Zx (Z – vertical platform input, x – axial human output) cases of Figures 3-3 and 3-4. Below 10 Hz, the sternum motion is affected directly by the board-litter system at 5 Hz as shown in (Zz in Figure 3-3; Z – vertical platform input, z –

anterior-posterior human output); however, it appears that the head is affected by the board-litter system at 5 Hz as well 10 Hz (Figure 3-4).

The effect of the board-litter system on the motion during fore-aft X (axial) and lateral Y (medial-lateral) vibrations is not as prominent as that in the vertical (anterior-posterior) Z direction. While it looks like the board-litter system is moderately magnifying the motion of the sternum around 3 Hz in Xx (X – fore-aft platform input, x – axial human output), the relative transmissibility between the sternum and the head was attenuated in the Xx direction.

Still the prominent frequency due to the board-litter system at 5 Hz was very clear, indicating the board-litter system is magnifying the transmitted motion for the whole-body segments at 5 Hz in the vertical (Zz) direction. The magnification, however, is not the same for all segments but depends on the segment mass and stiffness. Therefore, the effect of the board-litter system can be captured by the relative transmissibility, which can demonstrate what is happening between the segments and how segment motions are affecting each other.

The effect of vibration magnitude in the vertical direction on the human sternum and head natural frequencies showed softening characteristics for the four support conditions (Figure 3-7) similar to those observed by [16] for the sternum. The resonance frequency was shifted by 1-2 Hz when the input vibration magnitude was increased from 0.5 m/s^2 to 1 m/s^2.

The results have in general shown insignificant changes in the transmissibility magnitude when sinusoidal input signals were used instead of random input signals (Figure 3-8). The Zz component of the sternum showed a less than 5% difference in the peak for the human response during random and sin sweep signals, while the board-litter system showed an approximately 15-25% higher peak value for random vibration. These differences were not seen in peak head transmissibility.

With the current spinal board dimensions and material type, it was expected that the board would show some flexibility, especially along its longitudinal axis. The transmissibility between the rigid platform and the output motion at three locations on the board (under the head, under the sternum, and under the pelvis) was investigated. The results showed similar characteristics at these three locations in terms of the resulting peaks, however, the one under the pelvis showed a magnitude that is slightly higher than the one under the sternum. The one under the head showed a smaller peak (around 5 Hz) in comparison to the other two points.

For verification purposes the acceleration from both the inertial system and gold standard accelerometer were compared, Figure 3-1. The results showed minimal differences. In addition, the transmissibility to the sternum (Figure 3-2) from the rigid-platform case was compared with previously reported results showing a good trend match from 0-15 Hz, while from 15-20 Hz the literature results tapered off at a faster rate than data collected in this study. This difference is likely attributed to the constraints of spinal immobilization.

Limitations

In this pilot study there are some limitations that should be considered when interpreting the results. A small sample size may reduce the effectiveness of the statistical test. Only healthy male college subjects that were reasonably fit participated in the study. The data collection was associated with some difficulties. The usage of the inertial system for a supine-human facilitated to a certain degree the transformation of the acceleration components from the local to the global reference frames; however, the system was sensitive to possible interference with ferro-magnetic conditions, which could affect the z rotation angle. In this study, the local to global z rotation was approximated as zero, as the sensors were approximately aligned on the participant’s body. Although, the z rotation was affected, orientation about the x and y axes were not affected and subtraction of the gravity component was not seen to be affected. There were also some difficulties associated with strapping the relatively large, flat sensor to the subject's curved forehead using the head immobilization. Other researchers have noted challenges with sensor placement on the head [12].

Future Work

Vibration Suppression

Based on the current study, the stiffness properties in the spinal board and litter should be investigated. Adjusting the board stiffness will alter the vibration and shock characteristics. While the current spinal board and litter act a low pass filter that attenuates higher frequency vibration, it is clear that resonance occurs differently based on the direction. An optimal design will take into account the resonance in each direction as well as the relative motion between segments seen with relative transmissibility. Since each segment has different vibration characteristics, materials placed below each individual segment may provide a method of synchronizing the segments. Other technologies such semi-active and active dampers should be investigated as well.

Motion Capture

Using passive optical motion capture technologies, the displacement may also be recorded to analyze relative motions between segments of the supine human. Considering the limitations in resolution, at higher frequencies the displacement recorded may be less accurate; however, the supine human provides a small capture volume and a properly calibrated system may give accurate results beyond 10 Hz. Using motion capture to track displacement, biomechanical modes can then be used to gain information about the muscle activity. This would require collecting force data as well. Another aspect of using motion capture is the ability to capture the effects of posture, which may be valuable in understanding the dynamics of the human upon the litter.

Other Dynamic Measures

Impedance and apparent mass are two other dynamic measures used to characterize the human response to vibration. These measures may also provide valuable feedback for the evaluation of vibration suppression systems.

CONCLUSION

In this study, the effect of the spinal board upon the military litter has resulted in an amplification of vertical (anterior-posterior) acceleration to the segments with resonance around 5 Hz. The advantage of the long spinal board coupled to the military litter is that the transmission of higher frequency vibration may be reduced after 12 Hz for the head and after 6 Hz for the sternum. Yet, these advantages are also coupled with an increase in vibration transmission to both the head and sternum at 5 Hz. Use of the military litter created amplification 3 times the input vibration level at the sternum and 1.5 times the input at the head during vertical resonance in the anterior-posterior axis of the subject. Compared to full-rigid support, the long spinal board strapped to a standard military litter system showed a 50% increase in transmission of the vibration to the head and a 100% increase to the sternum at its resonant frequency of 5 Hz ($p < 0.05$, Wilcoxon) for vertical vibration in subject's anterior-posterior axis.

The neck-collar showed, in general, little effect on the relative motion between the head and the sternum, but showed significant magnification in response to the axial (fore-aft) motion. In other words, using the cervical collar during immobilization increased the head nodding and the relative head-sternum flexion-extension as a result of the axial platform fore-aft whole-body vibration. Yet, head nodding was reduced from vertical (anterior-posterior) platform input vibration.

Results showed good correlation between single- and tri-axis transmissibilities to both the head and sternum. In the components with the largest transmissibility most directions showed minimal differences.

The response to vibration of the human, spinal board, and litter system, is inherently complex. The frequency of aerial, ground, and hand vibration content as well as the transmission of vibration through the human, spinal board, and military litter should be considered with caution to find an optimal design which considers the relative dynamics between human segments as well as the transmission of vibration to each segment. This task, however, is also complicated with various resonant frequencies among human segments and vibration directions.

A novel approach, called relative transmissibility, was introduced and presents a good tool for the designers of vibration-suppression systems to target the relative motion between the segments and the input ground motion at specific locations on the spine.

APPENDIX A

SPINAL IMMOBILIZATION

The local EMS was consulted for the proper spinal immobilization procedure.

Figure A-1 displays the demonstrated immobilization. Below is the full protocol [33].

1. Indications

A. Mandatory mechanisms that require immobilization.
  1. High impact vehicle crashes that include:
    a. Significant passenger compartment intrusion.
    b. Ejection of the patient.
    c. Rollover.
    d. Traumatic death of another occupant of the vehicle.
  2. Pedestrian hit at 20mph or greater.
  3. Falls from 20 feet or greater.
  4. Gunshot or other severe wound near the spine.
  5. Blast injuries.
  6. Shallow water diving accidents.

B. If you are unsure if the mechanism of injury indicates immobilization, Paramedic Specialists may follow the following to consider immobilization. All others must follow the procedures for spinal immobilization.
  1. Patient has posterior spine pain or tenderness- immobilize.
  2. The motor/sensory exam is abnormal-immobilize.
  3. The patient/exam is unreliable- immobilize.
  *If all three of the above are negative, no immobilization is required.

C. If you are sure that the mechanism of injury is not significant, no immobilization is required.

2. Procedure

A. Assure that the scene is safe and free of any potential hazards to rescuer or patient.
B. Assess the scene for mechanism and potential severity of injuries.
C. Rapidly gain access to the patient without endangering rescuer or patient.
D. Gain initial control of the spine manually. Unless contraindicated by pain or muscle spasm, move the head into a neutral, in-line position and provide manual stabilization. If unable to move head to neutral position with gentle traction, stabilize it as found.
E. Rapidly perform a primary assessment including auscultation of lung fields. Begin appropriate interventions as indicated. If potential life threatening conditions are identified, scene time must be kept to a minimum.
F. Apply an appropriate, effective and properly fitted/sized cervical collar. Collars that are too large may cause dangerous hyperextension; collars that are too small are ineffective. Note: Do not rely on the collar alone to effectively immobilize the patient's

C-spine, always maintain in-line stabilization until the patient's head and body are secured to long spine board.
G. If time permits, complete the patient assessment and provide any additional interventions as indicated.
H. Select the appropriate interim method or device that can safely and effectively facilitate the moving of the patient to a supine position on a long spine board. In non-life threatening situations, time may allow the use of a KED device. The need for additional resuscitation or shortened scene time or an unstable environment dictates the use of the PHTLS rapid manual extrication method for movement of a seated patient.
I. Once on the long spine board, the patient must be effectively secured to prevent movement. Straps must be secured in ax-pattern over the shoulders and under the armpits to secure the upper chest. Additional straps are placed across the iliac crest and above the knees to prevent potential movement. Attempts should be made to maintain Normal Anatomical Alignment (NAA) of the spine on all patients (except those with abnormal spines, i.e. kyphosis).
J. The head must be completely immobilized in normal anatomical position. In most cases, 1-1.5 inches of non-compressible padding should be placed under the head. Few cases will not require such padding to maintain neutral position. Towel rolls or other bulky, lightweight material may be placed around the head to stabilize it. Do not use sand bags. A wide strip of adhesive tape across the forehead to form an "X" effectively secures the head to the board. The use of chinstraps is not advised due to the potential for aspiration if the patient vomits.
K. The feet are secured together with tape to prevent rotation of the legs. Rotation may cause anterior pelvic thrust, which results in undesirable movement of the spine and flexion of the cervical spine. In addition, it is also desirable to secure the arms at the patient's sides to prevent movement of the shoulder girdle.

3. Special Considerations

A. Large bore suction equipment must be at hand for a patient placed on a spine board in the event of vomiting. The backboard may have to be rolled to the side to clear the patient's airway.
B. When moving the immobilized patient, move them as a unified package versus moving the patient or device alone.
C. It is best to immobilize the patient's torso first, and then immobilize the head to the device.
D. Do not attempt to follow a rigid, detailed technique when immobilizing or extricating a patient. Adjustments must be made to accommodate any number of variables to attain the general objectives as outlined.
E. Immediate interventions to maintain the ABC's must be quickly met while also protecting the patient's spine.
F. Conditions that relate to an unreliable patient/exam are:

1. Drugs or alcohol intoxication.
2. Acute stress reaction.
3. Chronic alteration of mental status.
4. Brain injury.

5. Distracting injuries.
6. Inability of the patient to communicate.


[redacted]

Figure A-1. EMS spinal immobilization demonstration.

APPENDIX B

MOTION PLATFORM SPECIFICATIONS

The vibrating platform (Moog-FCS E-CUE 624-1800 electrical system, Ann Arbor, MI) used in this study can produce 6 DOF motion. Tables B-1 and B-2 present public manufacture specifications although individual systems may vary [34].

Table B-1. Maximum excursion for the E-CUE 624-1800 motion platform.

DOF	**Excursion Limits**	
	Single DOF	**Maximum**
Surge	-0.46/+0.57 m	-0.57/ +0.57 m
Sway	+- 0.46 m	+- 0.49 m
Heave	+- 0.39 m	+- 0.39 m
Roll	+- 23.2 deg	+- 23.8 deg
Pitch	-23.0 deg/+25.6 deg	-27.4 deg/+31.6 deg
Yaw	+- 24.3 deg	+- 27.5 deg

Table B-2. Maximum velocity and acceleration for the E-CUE 624-1800 motion platform.

DOF	**Velocity**	**Acceleration**
Surge	+- 0.7 m/s	+- 7 m/s^2
Sway	+- 0.7 m/s	+- 7 m/s^2
Heave	+- 0.5 m/s	+- 10 m/s^2
Roll	+- 34 deg/s	> 225 deg/s^2
Pitch	+- 35 deg/s	> 225 deg/s^2
Yaw	+- 36 deg/s	> 225 deg/s^2

APPENDIX C

INFORMED CONSENT DOCUMENT

The following pages reflect an unsigned informed consent document. The study was approved by the University of Iowa Institutional Review Board (ID # 200811705) for human subject studies, and informed consent was obtained for each participant prior to the study.

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INFORMED CONSENT DOCUMENT

Project Title: **Comfort Weighting Curve for Seated Machine Operators**

Principal Investigator: **Salam Rahmatalla**

Research Team Contact: **Salam Rahmatalla, 1 319 335-5614**

John Meusch
Jonathan DeShaw

This consent form describes the research study to help you decide if you want to participate. This form provides important information about what you will be asked to do during the study, about the risks and benefits of the study, and about your rights as a research subject.

- If you have any questions about or do not understand something in this form, you should ask the research team for more information.
- You should discuss your participation with anyone you choose such as family or friends.
- Do not agree to participate in this study unless the research team has answered your questions and you decide that you want to be part of this study.

WHAT IS THE PURPOSE OF THIS STUDY?

This is a research study. We are inviting you to participate in this research study because you are a healthy, adult who does not have a history of muscle or bone disease or injury.

The purpose of this research study is to determine a proper shape of the comfort weighting curve for seated machine operators. This comfort curve will serve seat manufacturer in understanding the impact of machine changes on human comfort in single and multiple directions and therefore, help them in designing better and safer seats.
The study may also investigate the motion of people in supine position during emergency transportation with the goal of achieving better litter designs.

HOW MANY PEOPLE WILL PARTICIPATE?

Approximately 100 people will take part in this study at the University of Iowa.

HOW LONG WILL I BE IN THIS STUDY?

If you agree to take part in this study, your involvement will last for 3-6 hours in a single visit with no follow-up. If there are technical problems, you may be scheduled for second visit to complete the study procedures.

WHAT WILL HAPPEN DURING THIS STUDY?

If you agree to participate, you will be scheduled to return to the Engineering Research Facility, 330 South Madison Street, Iowa City, Iowa the morning of the test day. Inside the facility, you will change in to shorts and a tank-top so that the motion measurements can be obtained. The clothing will be supplied to you at the test site.

Preparation and Set-Up

Marker placement and calibration: Your body motion will be monitored using infrared cameras (VICON). Up to 90 reflective markers will be attached to your body. Each marker is about a half inch sphere attached to a soft rubber base of about 1 ½ inch x 1 ½ inch. The rubber base will be attached to your body using non-allergenic, double-sided tape. The markers on your head will be attached to an adjustable head band which you will wear on your head. Markers will be attached to your skin over bony landmarks, such as the elbow, the knee, the collar bone, or back bone. If you have considerable body hair, we will shave the small area of skin under each marker to minimize pain with removal of the markers. Markers may also be attached using athletic pre-wrap instead of adhesive tape. In some parts of the experiment, you may be dressed in a motion capture suit (a black cloth suit to which markers will be attached); in this case, the markers will be directly stuck to the suit instead of your skin.

Inertial sensors: Inertial sensors are devices that can measure acceleration in three and six directions. Inertial sensors are small devices that can sense movement. Inertial sensors will also be attached to your body at the same time the above markers are attached. Inertial sensors will be placed on you on up to 8 locations. The Inertial sensors will be attached to your skin using medical-grade, double-sided adhesive tapes, after cleaning your skin with rubbing alcohol.

The placement of the markers and inertial sensors will take about one to two hours.

In addition to the recordings for motion tracking, we will videotape the study procedure.

Testing

After this preparation stage, you will be instructed to sit on a chair or lay on a litter similar to those used in patient's transportation that is attached to a table that vibrates, called a shaker table. During the experiments, you will experience the physical conditions of a heavy construction machinery operator who is performing tasks in the real world or a person on a litter in an emergency transport vehicle.

Motion Capture Calibration: The first step in the motion capture process is to calibrate the system and ensure that the cameras see only the reflected markers (no artifact). The second step involves calibrating you by having you stand still for 30 seconds. The motion capture system will use this information to obtain your measurements, such as the length of your legs and arms.

Task Simulation: In order for you to keep your attention focused, we may provide a task for you to work on. The task consists of a video-game like simulation of the operation of a piece of heavy equipment. You will control the piece of equipment using the arm-rest controls you will be holding during the testing.

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Experimental Protocol:
You will be tested under one of the following conditions:

Condition A) You will be asked to sit in the shaker table chair. The experiments to be conducted will include using a shaker table to provide vibration typical of operation of common heavy equipment.

You may be tested under the following scenarios:

1. Back on seatback and hands on armrests
2. Back on seatback and hands on lap
3. Back on seatback and hands on steering wheel
4. Back off seatback and hands on lap, and looking back (twisted posture)
5. Back off seatback and hands on armrests, and looking back (twisted posture)
6. Back off seatback and hands on lap
7. Back off seatback and hands on steering wheel
8. Back off seatback and hands on armrests
9. In some of the above cases, you may be asked to sit on a seat with your trunk constrain to the seatback using a life-Vest jacket; however, your arms will be freely to move. The reason for these cases is to isolate your head-neck motion from your trunk motion. By doing this, we will be able to more accurately analyzing the contribution of your head-motion to your discomfort level.

In all above cases, your feet will remain on the ground/pedals.

Condition B) You will be asked to take a supine position on a litter with a backboard similar to those in patient's transportation.
The following procedure will be used as recommended by the Local EMS provider (Johnson County):
1. Apply an appropriate, effective and properly fitted/sized cervical collar.
2. Position participant on the long spine board and center.
3. Place straps in an x-pattern over the shoulders and under the armpits to secure the upper chest.
4. Additional straps are placed across the iliac crest and above the knees to prevent movement.
5. Normal Anatomical Alignment of the spine should be maintained.
6. Immobilize the head in the normal anatomical position. 1-1.5 inches of non-compressive occipital padding may be used.
7. Towel rolls or other bulky, lightweight material may be placed around the head to stabilize.
8. Place a wide strip of adhesive tape across the forehead to form an "X" securing the head.
9. Secure the feet with tape to prevent leg motion.

The following cases will be considered:
- i. Using traditional backboard.
- ii. Using traditional backboard with cushions.

We will conduct a series of tests to collect information about your body's responses to the movement of the shaker table seat and to test whether or not we are tracking the markers attached to you. You will experience up to 200 bouts of typical ride vibration on the shaker table each lasting up to 60 seconds with total of up to 100 minutes. The test will be repeated for each of the above twoconditions.. The

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“rides” will consist of vibration in one or multiple directions. Normally, up to 100 minutes (for each of the two above mentioned conditions) of that time will consist of exposure to typical "ride" vibration. If up to half of the tests need to be repeated, you could be exposed to up to 150 minutes of "ride" vibration.

In the event a test is stopped before all the data are collected or data are lost due to computer failure, the test will be repeated, up to a maximum of half of the possible tests. It is unlikely that more than one or two tests will actually require repetition, but all estimates of total daily vibration and shock exposure have included these additional tests. In the event data recording systems fail to acquire data during a test, the test will be repeated. This may take an additional six hours during a separate visit.

As mentioned above, it is possible that some tests may need to be further repeated in the event results are not stored properly (data lost due to computer error, etc.). The duration of the testing procedures should require no longer than 6 hours (with breaks). The expected total duration of exposure to the vibration is 100 minutes, but could be as high as 150 minutes in the event half of the tests require repeating.

During the tests, you will be asked by the investigators to rate your discomfort level either using verbal forms or paper based forms.

You may be asked to complete more visits if additional testing is required.

Audio/Video Recording or Photographs

One aspect of this study involves taking some pictures and video movies during the testing procedures. The motion capture cameras can only “see” infrared light reflected from markers. In addition to the motion capture camera images, we will take photographs and video of you using traditional still and video cameras to know where the markers are located on your body. The pictures and video movies will help us in identifying the location of the markers on the body during the experiments; otherwise, it would be very difficult to recognize the real markers’ locations on the body by just looking to the motion capture data. In the event these materials are used in reports or publications, the images will be altered so that no personally-identifiable information will appear.

These recordings and photographs will be used to document the test protocol. These recordings will not be erased or destroyed as they will provide valuable documentation of the study.

WHAT ARE THE RISKS OF THIS STUDY?

You may experience one or more of the risks indicated below from being in this study. In addition to these, there may be other unknown risks, or risks that we did not anticipate, associated with being in this study.

You may feel some irritation from the preparation for, the use of, and the removal of the reflective markers, and accelerometers. We will try to minimize this risk by using only medical-grade tape meant for use on human skin and shaving any areas that have substantial hair. We will try to make the time that the devices are attached as short as possible consistent with the data to be gathered. We will monitor you

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carefully by sight and by asking questions about how you feel. We will ask you if you are allergic to adhesive tape before placing the markers and accelerometers on your skin.

You may be at risk for developing dizziness. You will have a switch that will immediately stop the ride in the event you feel you need to stop. You can also take breaks as needed throughout the test protocol. We will monitor you carefully by sight and by asking questions about how you feel. If you are prone to motion sickness, have a history of vestibular (inner ear) problems, or do not tolerate simulation rides at Amusement Parks, you should not enroll in this study.

The vibration involved in this study may pose a risk for muscle or back pain with extended exposures. However, one day of testing is unlikely to result in any chronic vibration or shock injuries. The front to back vibrations you will experience should be no worse than those felt while riding a tractor on a rough field or operating typical heavy construction equipment for a period of time. We have analyzed the vibration for the conditions you will experience using international standards to be sure that the total exposure is within acceptable levels. If you have a history of neck or back pain, you should tell the researchers before enrolling in the study.

There is a risk that you could faint during the test. Sitting for extended periods of time, coupled with the simulated ride, could result in feeling like you could faint. Before fainting, people have reported experiencing weakness, lightheadedness, nausea, sweating, hyperventilation, blurred vision and/or impaired hearing. Sitting or lying down can reverse the symptoms. To minimize the risk of fainting, regular rest intervals are planned, where you will be asked to get up out of the seat and stand and move your arms and legs. Further you will be monitored closely for any signs of intolerance listed above, by sight and by asking questions about how you feel throughout the test. If you have any history of fainting or have a cardiac condition you should not enroll in this study.

If you have a history of neck or back pain, heart problems, neurological problems, balance problems or dizziness, motion sickness, or are taking over-the-counter drugs, prescribed drugs, or have consumed alcohol or recreational drugs within 24 hours of the study, you should not enroll in this study.

There is a risk that you may experience a fear of falling or being unable to maintain your balance in the seat. We will minimize this situation by monitoring you carefully by sight and by asking questions about how you feel. If you have any history of fear, then you should not enroll in this study.

WHAT ARE THE BENEFITS OF THIS STUDY?

You will not benefit from being in this study. However, we hope that, in the future, other people might benefit from this study because the result of this study may help seat and machine designers to develop more comfortable seats for heavy machinery operators.

WILL IT COST ME ANYTHING TO BE IN THIS STUDY?

You will not have any cost for being in this research study.

WILL I BE PAID FOR PARTICIPATING?

You will be paid for being in this research study. You will need to provide your social security number (SSN) in order for us to pay you. You may choose to participate without being paid if you do not wish to provide your social security number (SSN) for this purpose. You may also need to provide your address if a check will be mailed to you. If your social security number is obtained for payment purposes only, it will not be retained for research purposes.
You will be paid at a rate of $12 per hour of a total of up to $72. The average amount per visit is $48.

DO THE RESEARCHERS HAVE PERSONAL FINANCIAL INTEREST IN THIS STUDY?

No.

WHO IS FUNDING THIS STUDY?

Departmental Funding from the University of Iowa, Center for computer aided design.

WHAT IF I AM INJURED AS A RESULT OF THIS STUDY?

- If you are injured or become ill from taking part in this study, medical treatment is available at the University of Iowa Hospitals and Clinics.
- No compensation for treatment of research-related illness or injury is available from the University of Iowa unless it is proven to be the direct result of negligence by a University employee.
- If you experience a research-related illness or injury, you and/or your medical or hospital insurance carrier will be responsible for the cost of treatment.

WHAT ABOUT CONFIDENTIALITY?

We will keep your participation in this research study confidential to the extent permitted by law. However, it is possible that other people such as those indicated below may become aware of your participation in this study and may inspect and copy records pertaining to this research. Some of these records could contain information that personally identifies you.

  - federal government regulatory agencies,
  - auditing departments of the University of Iowa, and
  - the University of Iowa Institutional Review Board (a committee that reviews and approves research studies)

To help protect your confidentiality, we will assign you an identification number that does not include any personally identifiable information. All data will be stored on password-protected computer files using this number and not your name. Your name and personal information will be linked to your study identification number in a separate document and kept by the principal investigator in electronic and hard-copy formats separately from the rest of the data. All data will be kept in a locked lab or office or

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in password protected computer files, with appropriate backup. The motion data will be available to other researchers for future model development; however no personal identification of any kind will be linked to the data sets.

If we write a report or article about this study or share the study data set with others, we will do so in such a way that you cannot be directly identified.

IS BEING IN THIS STUDY VOLUNTARY?

Taking part in this research study is completely voluntary. You may choose not to take part at all. If you decide to be in this study, you may stop participating at any time. If you decide not to be in this study, or if you stop participating at any time, you won't be penalized or lose any benefits for which you otherwise qualify.

Will I Receive New Information About the Study while Participating?

If we obtain any new information during this study that might affect your willingness to continue participating in the study, we'll promptly provide you with that information.

Can Someone Else End my Participation in this Study?

Under certain circumstances, the researchers might decide to end your participation in this research study earlier than planned. This might happen because in our judgment it would not be safe for you to continue or because the funding for the research study has ended.

WHAT IF I HAVE QUESTIONS?

We encourage you to ask questions. If you have any questions about the research study itself, please contact: Salam Rahmatalla at (319) 335-5614 or salam-rahmatalla@uiowa.edu If you experience a research-related injury, please contact Salam Rahmatalla at (319) 335-5614 or salam-rahmatalla@uiowa.edu

If you have questions, concerns, or complaints about your rights as a research subject or about research related injury, please contact the Human Subjects Office, 105 Hardin Library for the Health Sciences, 600 Newton Road, University of Iowa, Iowa City, IA 52242-1098, (319) 335-6564, or e-mail irb@uiowa.edu. General information about being a research subject can be found by clicking "Info for Public" on the Human Subjects Office web site, http://research.uiowa.edu/hso. To offer input about your experiences as a research subject or to speak to someone other than the research staff, call the Human Subjects Office at the number above.

This Informed Consent Document is not a contract. It is a written explanation of what will happen during the study if you decide to participate. You are not waiving any legal rights by signing this Informed Consent Document. Your signature indicates that this research study has been explained to you, that your questions have been answered, and that you agree to take part in this study. You will receive a copy of this form.

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Subject's Name (printed): ____

Do not sign this form if today's date is on or after **EXPIRATION DATE: 08/05/12** .

______________________________ (Signature of Subject)

______________________________ (Date)

Statement of Person Who Obtained Consent

I have discussed the above points with the subject or, where appropriate, with the subject's legally authorized representative. It is my opinion that the subject understands the risks, benefits, and procedures involved with participation in this research study.

______________________________ (Signature of Person who Obtained Consent)

______________________________ (Date)

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