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Comparison of Whole-body Vibration Biodynamics between Healthy Human Subjects And Injured Swine Models Subjected to Similar Ground Medical Evacuation Transports

Rachel Kinsler & Amy Lloyd

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14. ABSTRACT
The overall objective of this project was to compare data sets from studies using healthy human subjects and studies using injured animal models subjected to similar ground transport insults to determine feasibility and suitability of using the injured animal model as a reasonable approximation for an injured human patient during ground medical evacuation transport. The biodynamic response of the swine model and the biodynamic response of a healthy human model exhibit similar patterns to the same ground ambulance excitations. Anthropometric measures, root-mean-square acceleration analyses, power spectral density calculations, and transmissibility calculations from each study were provided. Examination of the data and comparison of the swine with an existing supine human model for whole body vibration response indicates it is reasonable to conclude the swine is an acceptable model for the biodynamic response of humans subjected to ground transport, if appropriate scaling factors can be defined and applied.

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Summary

Purpose: The overall objective was to compare data sets from studies using healthy human subjects and studies using injured animal models subjected to similar ground transport insults to determine feasibility and suitability of using the injured animal model as a reasonable approximation for an injured human patient during ground medical evacuation transport.

Subject population: Data was collected from healthy humans and injured swine in previous studies.

Study design type: This was a correlational design study comparing human and animal biodynamics during similar ground ambulance transport inputs.

Procedures: Analyses of linear acceleration and rotational velocity vibration data collected from similar anatomical landmarks on healthy human subjects and injured swine subjected to the same ground transport insults were performed. These analyses included examination of the amplitude, energy content at certain frequencies, and transmissibility of linear acceleration. Identified patterns of biodynamic response suggested the possibility of translation between the existing biodynamics of these populations (human and animal). Extrapolation to injured humans, through use of a preliminary digital model, was explored.

Results: Anthropometric measures, root-mean-square (RMS) acceleration analyses, power spectral density (PSD) calculations, and transmissibility calculations from each study for the various common track segments were provided.

Discussion: The sum RMS accelerations for the two animal studies are in relatively good agreement across the common track segments tested. The human subjects data showed a similar trend, though the magnitude of the transmitted vibration is larger than all equivalent animal data. The PSD data was not a direct one-to-one comparison between the human study or either animal study but there are similar patterns of energy peaks present in the vertical direction of the animal spine board data as seen in the human head and sternum data across the gravel track segment. There are still commonalities to be seen in the data patterns such as exacerbation of the energy in the frequency ranges that were identified in the PSDs previously. The eventual goal of the comparison between the human and animal datasets would be the construction of a model that could be extrapolated to address injured humans using the combination of healthy human, healthy animal, and injured animal data. An example of a two-dimensional (2D) supine human model being transported on a litter and spine board is presented.

Conclusions: The biodynamic response of the swine exhibits similar patterns to that of the healthy human biodynamic response to the same ground ambulance excitations. As the example 2D model of the human shows, this biodynamic response is dependent on the mass and spring/damper coefficients of the human or equivalent subject, and a scaling process must be used for humans of different anthropometry. Given these considerations, it is reasonable to conclude that the swine is an acceptable model for the biodynamic response of humans subjected to ground transport, if appropriate scaling factors can be defined and applied.

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Table of Contents

List of Figures

Table of Contents (continued)

List of Figures (continued)

List of Tables

Introduction

Traumatic brain injuries (TBI) and hemorrhagic shock (HS) were the leading causes of death from Operation Iraqi Freedom and Operation Enduring Freedom. Physicians and neuroscientists have referred to TBI as the signature injury of Operation Iraqi Freedom and Operation Enduring Freedom. Blast has been implicated in upwards of 70% of all trauma, with rapid accelerative and decelerative force from tertiary blast injury often resulting in TBI (Eastridge et al., 2012). Similarly, approximately 90% of all preventable mortalities involve HS (Mayer et al., 2019). Forces transmitted during the transport of patients can have severe consequences, especially for neurotrauma patients (e.g., those who have suffered a TBI) sensitive to increased intra-cranial pressure (Ratanalert et al., 2004; Reno, 2010) and those suffering from the complications of HS.

Collecting data from actual injured patients during transport in theater is difficult, but there have been a few controlled studies on the effects of transport on healthy supine humans (DeShaw & Rahmatalla, 2016; Rahamatalla et al., 2017; Wang & Rahamatalla, 2013). A recent study was completed by the U.S. Army Aeromedical Research Laboratory (USAARL) to evaluate the effect of patient weight as a factor when using an immobilization system versus no immobilization system (litter only) during patient transport. Significant differences were found between weight groups and immobilization configurations within weight groups, with respect to z-axis transmissibility, area under z-axis transmissibility curve, z-axis transmissibility resonance frequency, root mean square (RMS) z-axis acceleration, and RMS rotational velocity (Conti et al., 2019).

A collaboration between USAARL, the Mind Research Network, and Lovelace Biomedical Research Institute (LBRI) was formed to examine the effects of transport on injuries (e.g., TBI) and clinical states (e.g., HS) in an animal model. An elliptical ride-quality course was designed and built on the LBRI South campus. The ride course was built in collaboration with the Aberdeen Test Center and designed based on data collected in theater from military ground evacuation vehicles. To date, two studies with animal models have been conducted using ground ambulance transport on this course (Kinsler et al., 2019; Mayer et al., 2022). One study examined the effects of transport on spinal cord-injured (SCI) animals versus healthy controls during ground ambulance transport on the course (Kinsler et al., 2017; Wanner et al., 2017). The second study investigated a polytrauma TBI and HS injured Yucatan swine model to determine whether a drug therapy, EE-3-SO4, prolongs survival time after rough ground transport relative to sham (Lloyd et al., 2020; Mayer et al., 2021). A USAARL study examined gender and anthropometry in healthy humans on the same ride-quality course as the animal studies (Kinsler et al., 2019).

The U.S. Army has a goal of becoming a multi-domain operations (MDO) -capable force by 2028 and will require medical capabilities to meet warfighter needs prior to that time (U.S. Army Training and Doctrine Command [TRADOC], 2018a; TRADOC, 2018b). Examination of the effects of ground ambulance transport is critical because it is directly applicable to several aspects of MDO, which anticipates conflicts with near-peer adversaries. MDO reduces many of the advantages enjoyed the U.S. military in recent conflicts including air superiority. Increased use of ground ambulance transport vehicles means that medical evacuation research must emphasize this mode of transport. Biodynamically valid substitutes for injured humans should be identified for performing future studies on mitigation of ground transport effects on casualties.

Military Relevance

Medical evacuation of Soldiers with head and spinal injuries, or polytrauma, is essential to obtain life- and function-saving treatment in a medical facility with specialized surgical capabilities. Vehicle shock and vibration during ground and air medical evacuation make it challenging to restrict patients' body movements during transport. When vehicle shocks and vibrations act on the body, they can aggravate SCI, TBI, and polytrauma. Materiel developers and vibration subject matter experts do not have a thorough understanding of the characteristics and magnitude of the vibration transmitted to supine humans in military medical evacuation ambulances because these types of mechanical inputs in the combat environment with real patients can be extremely challenging to measure. Investigating this critical gap, with the identification of a translatable animal injury model to determine dose-response relationships and develop vibration mitigation technologies, will lead to safer ground transport of casualties with head, spine, and other traumatic injuries. Future conflicts are expected to occur with near-peer adversaries, reducing the likelihood of an uncontested airspace. This is expected to shift much of the initial medical evacuation need to ground transport platforms.

Objective and Specific Aim

Objective: The overall objective of this paper is to compare de-identified data sets from studies using healthy human subjects and studies using injured animal models subjected to similar ground transport insults to determine feasibility and suitability of using the injured animal model as a reasonable approximation for an injured human patient during ground medical evacuation transport.

Specific aim: The team will characterize the biodynamic response of healthy human subjects compared to injured swine exposed to similar ground transport conditions. The transmissibility concept is a very well-established biodynamic measure in the field of whole-body vibration (Matsumoto, 2000). Transmissibility has effectively been used to quantify vibration transmitted to and through mechanical and biological systems, to effectively design vibration suppression systems, and as a guide for safety standards.

Hypothesis

Null Hypothesis: Vibration transmissibility values are significantly different between healthy supine humans and recumbent injured swine on a litter and spine board during ground transport.

Methods

The healthy human study "2016-012 Supine Human Response to Repeated Shock and Vibration during Ground En Route Care Transport" collected complete data sets from 26 human subjects. Data analyses conducted under this protocol discovered statistically significant differences in response to vehicle shock and vibration can be defined with respect to subject anthropometry and mass. The animal model study "FY13-100 Improved Field Management and Safe Transport of Patients with Head and Spine Injuries" collected full data sets for 10 healthy and 13 injured animals. The animal study "FY17-077 Increasing Survival Rate Following Hemorrhagic

Shock and Traumatic Brain Injury in Austere Environments" collected full data sets for 26 injured animals. The animal studies were collected with the same type of ground ambulance on the same track at the same speeds as the healthy human subjects study, indicating direct comparisons can be made with this data set that has already produced statistically significant findings.

Subject Population

The population for which the findings may be generalized are casualties/patients transported on military ground ambulances over bumpy terrain. The study includes data from healthy humans and injured swine subjected to very similar ground ambulance transport events.

Sample Characteristics

All data files were collected during previous USAARL studies "FY13-100 Improved Field Management and Safe Transport of Patients with Head and Spine Injuries," "2016-012 Supine Human Response to Repeated Shock and Vibration during Ground En Route Care Transport," and "FY17-077 Increasing Survival Rate Following Hemorrhagic Shock and Traumatic Brain Injury in Austere Environments." These data files characterize the linear acceleration and rotational velocity vibration inputs from the vehicle ride to the subjects/animals. The data also includes general body dimensions. Data files must have been collected during ground ambulance transport on the track located at LBRI at Kirtland Air Force Base, New Mexico. Any data files collected during sham or control treatments, such as when an animal was loaded into the ground vehicle, but not actually transported, were not included in analyses.

Research Design

This study is retrospective in design and consists of analyses of existing biodynamic and body dimension data collected during previous Institutional Review Board (IRB) and/or Animal Care and Use Review Office (ACURO) approved studies. The data was collected on healthy human subjects and injured swine subjected to ground transport in the same type of ground ambulance on the same structured track.

Figure 1 describes the layout of the test track as well an example of lap sequences and direction of travel. The vehicle entered the track as shown in the lower left corner of the figure and stopped at the beginning of the gravel straight away, and the first set of passes began. For each lap in the set of passes, there was a condition that changed. In this example, the vehicle started on the gravel section at 20 miles per hour (mph) (bottom of Figure 1), turned the corner, and then reached the track sections described in Table 1. The vehicle drove at 5 mph on each of the track sections, and completed the half round at 10 mph. The bumpy tracks refer to non-periodic bumps on the road meant to simulate an approximately 2-inch root mean square (RMS) average ride roughness. Straddle indicates the tires on one side of the vehicle are on one track section and the other tires are on another track section at the same time (either straddling both bumpy sections or one bumpy section and the smooth shoulder beside the bumpy track sections). The half round is a steel pipe embedded in the concrete, with a six-inch rise, which created a significant mechanical shock when driven over. Each study included some combination of all of these elements (gravel, bumps, straddle, smooth, and half-round).

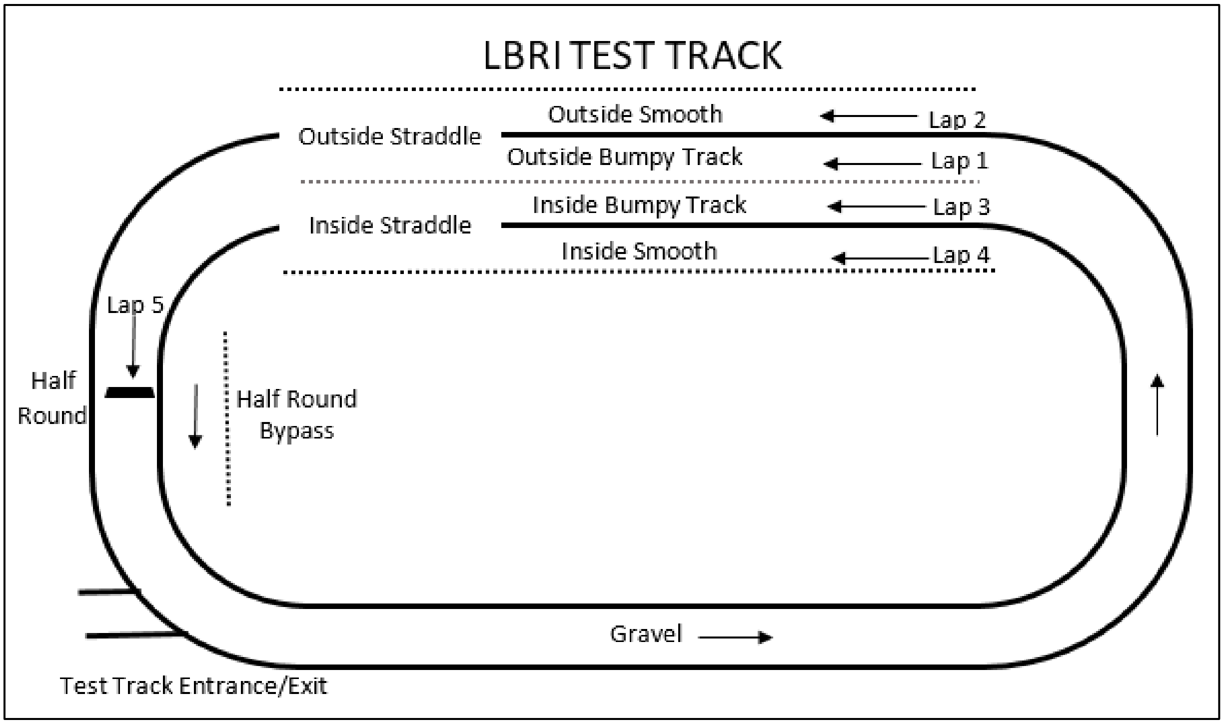


Figure 1. Test track with an example of lap sequences and direction of travel.

The ground ambulance vehicle used for data collection for all studies was an M997A3 High Mobility Multipurpose Vehicle (HMMWV) Ground Ambulance. This ambulance is capable of transporting four litter patients, plus two seated personnel, or up to eight seated personnel in the back cabin. Figures 2 through 4 show the ambulance on various sections of the track as described in Figure 1.

Figure 2. Vehicle passing on inside bumpy section.

Figure 3. Vehicle passing on inside smooth section.

Figure 4. Vehicle passing on outside half straddle section.

The human subjects and swine were immobilized while lying on a spine board. Human subjects lay supine, while the swine were in dorsal (FY13-100) or lateral recumbency (FY17-077), depending on the study. The subject/swine was secured to the spine board using immobilization straps, head blocks, and rolled blankets as bolsters as needed. The subject-spine board combination was then secured to a standard U.S. Army Decontaminable litter. The litter was loaded into the left lower litter berth of the ground ambulance. Figure 5 shows an example of a human subject secured to the spine board and loaded into the ground ambulance. For human subjects, sensors were placed on the head, chest, pelvis, knee, backboard, and litter berth. Figure 6 shows an example location of the sensors on the animal model, as well as the backboard and litter berth.

Figure 5. Subject secured in the ground ambulance.

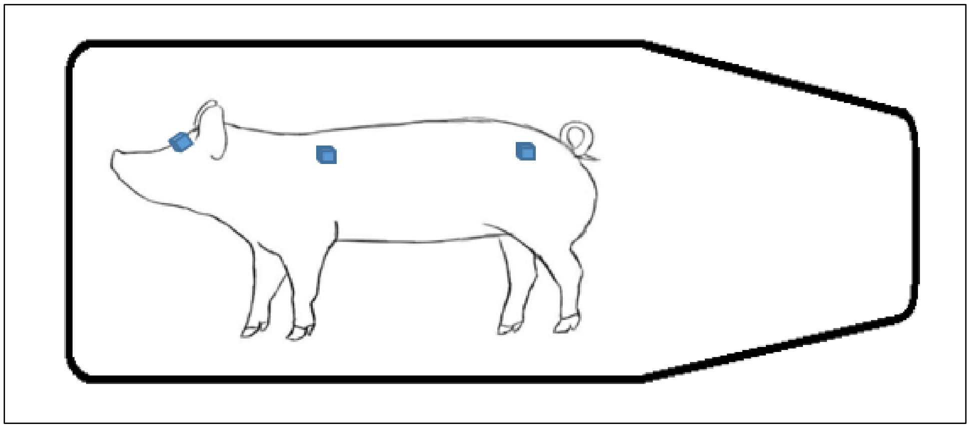


Figure 6. Example of animal sensor locations.

The sensors used during testing were triaxial accelerometers that measure linear acceleration in three directions and 6 degree-of-freedom (6DOF) sensors that measure linear acceleration and rotational velocity. The sensor values were recorded using CoCo-90 data acquisition (DAQ) devices, manufactured by Crystal Instruments. The DAQs collected data in separate channels for each axis of each sensor. Each DAQ had 16 channels available. The first 15 channels of the DAQ were used to collect sensor data, and the 16th channel on each device was used to record a common square wave so the data could be synchronized between the two DAQ devices. Data was collected at 500 samples per second. Figure 7 shows an example of the linear vertical acceleration time history of a single pass on all track sections. From 0 to 550 seconds, the sequence of track sections is: gravel surface, outside bumpy, inside smooth at 10 mph, inside bumpy, inside smooth at 15 mph, half straddle, and half round shock. The colored boxes on the time history correspond to the same colors on the track sections.

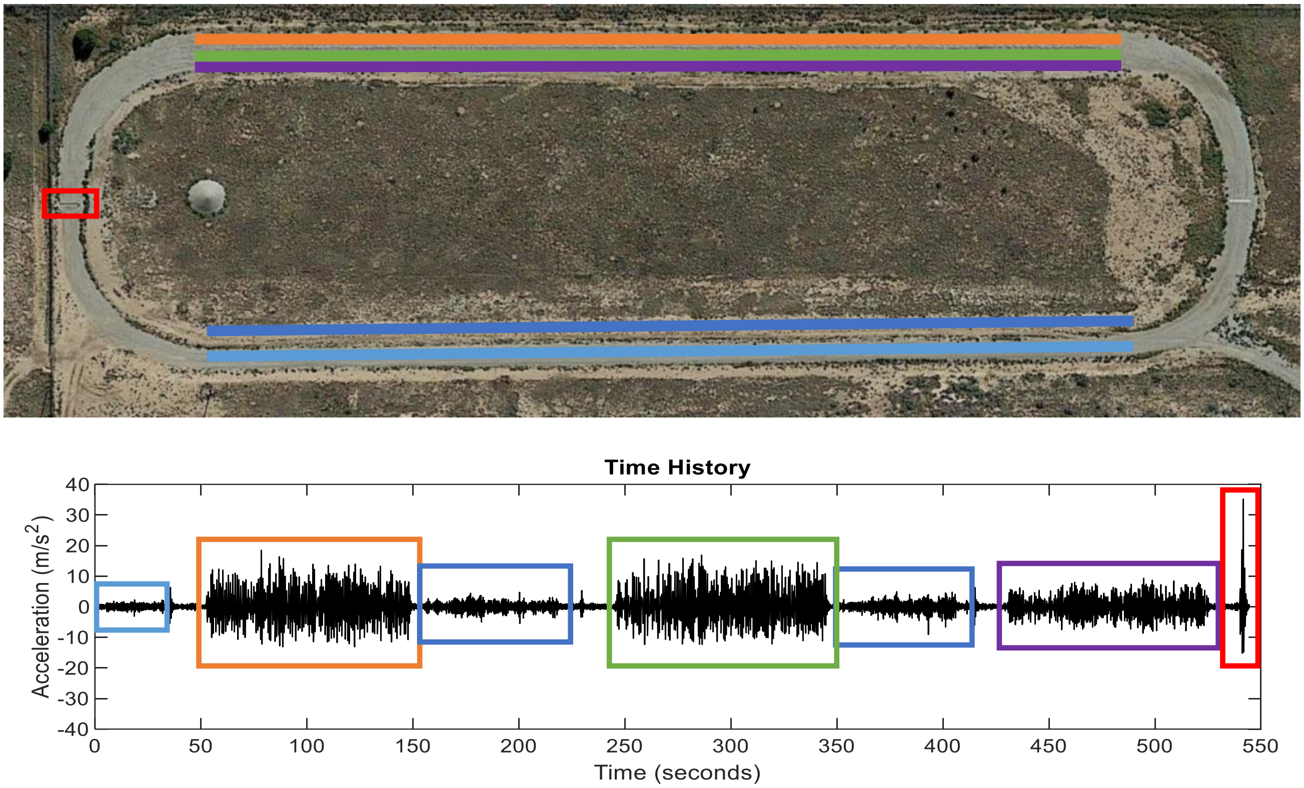
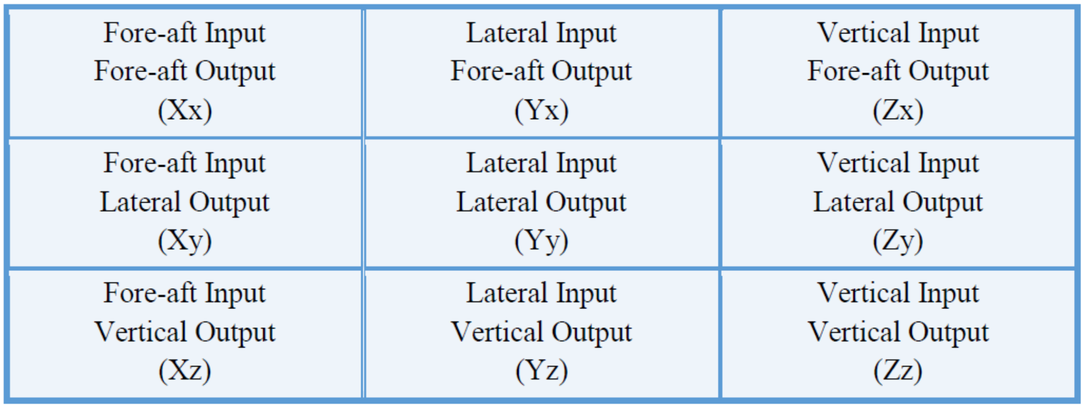


Figure 7. Vertical acceleration data example for all track sections.

The primary data analyzed under this protocol were acceleration data, gyroscopic data, and body dimension measures. The individual and summed components of the acceleration data (x-, y-, and z-axes) of the backboard were averaged and standard deviations calculated across all subjects for each track segment, in order to verify that vibration excitation was consistent across all groups. A processing technique called a Fast Fourier Transform was also applied to the data set, allowing the calculation of a power spectral density function. When plotted across specific frequency bands, this function describes the frequencies at which energy is present and at what levels. This is of particular interest when higher levels of energy are present in frequency bands that are known to have possible health effects on humans during whole body vibration.

Analysis of acceleration data allows characterization of the frequency and amplitude of transmitted vibration at various points in the human (or animal)-litter system, which is used for the calculation of vibration transmissibility. Transmissibility calculations are quantitative metrics that define how vibration is altered by passing through a material or structure, attenuating, amplifying, or shifting energy to different frequencies. Transmissibility above 1.0 indicates amplification in the system, while transmissibility below 1.0 indicates attenuation. The transmissibility will be calculated for each input-output directional combination as well as in three-dimensional (3D) space (3 input/3 output). Table 2 shows the matrix of transmissibility combinations. For this analysis, the input acceleration is the backboard. The output acceleration is the acceleration at each body segment; therefore, there are multiple matrices for each subject.

Table 1. Directional Transmissibility Combinations



Fore-aft Input Fore-aft Output (Xx)	Lateral Input Fore-aft Output (Yx)	Vertical Input Fore-aft Output (Zx)
Fore-aft Input Lateral Output (Xy)	Lateral Input Lateral Output (Yy)	Vertical Input Lateral Output (Zy)
Fore-aft Input Vertical Output (Xz)	Lateral Input Vertical Output (Yz)	Vertical Input Vertical Output (Zz)

The accelerations may also be computed into a 3D resultant sum by taking root-sum-squared of the three components by using the function:

$$SUM\ XYZ = \sqrt{(X_{acceleration}^{2} + Y_{acceleration}^{2} + Z_{acceleration}^{2})}$$

After this resultant vector is calculated, the root-mean-square (RMS) will be taken for each subject, body location, and track segment. This resultant vector sum allows an indication of the total vibrational energy experienced by the subject. These sums will be averaged, and standard deviations calculated across subject type, body location, and track segment groupings. Additional descriptive statistics may also be performed specific to the body dimension measures for the human and animal subjects.

Data Types

The types of data that were collected, their sources, and operational specifications are listed in Table 2.

Table 2. Types and Sources of Data Collected

Data Element/Variable	Source	Operational Specification
Acceleration data	Human subjects/animal subjects (previously collected)	200 mV/g (+/- 5 g) or similar
Gyroscope data	Human subjects/animal subjects (previously collected)	1 mV/deg/s (+/- 1000 deg/s) or similar
Acceleration data	Ground vehicle, spine board, and litter (previously collected)	174 mV/g (+/- 5 g) or similar
Body dimension data	Human subjects/animal subjects (previously collected)	Weight, height (length), other body dimension measurements (kg/cm)

Note. mV = millivolt(s), g = unit(s) of gravity (9.81 meters [*m*]/second [*s*]^{2}), deg = degree(s), kg = kilogram(s), cm = centimeter(s)

Results

Multiple anthropometric measures were collected from the human subjects prior to testing. Table 3 summarizes the basic anthropometric measures for all subjects. One subject, marked with a single asterisk, was excluded from the data analyses due to a sensor failure.

Table 3. Human Subject Anthropometric Measures for Study 2016-012

Subject ID	Weight (kg)	Height (m)
01	87.2	1.870
02	82.0	1.802
03	78.5	1.774
04	87.5	1.778
05	75.6	1.683
06	87.8	1.816
07	65.2	1.664
08	73.6	1.708
09	110.5	1.870
10	82.5	1.763
11	58.5	1.568
12	72.6	1.725
13	94.5	1.747
14*	64.4	1.608
15	86.6	1.731
16	57.4	1.625
17	82.1	1.700
18	99.3	1.806
19	64.8	1.671
20	74.0	1.706
21	79.4	1.720
22	98.2	1.726
23	118.0	1.887
24	89.0	1.692
25	70.8	1.701
26	55.5	1.567
27	97.2	1.713
Average	81.9	1.731
SD	15.6	0.082

*Excluded from average and SD.

Equivalent metrics were collected from the animal subjects in studies FY13-100 and FY17-077. In this case, the total length of the animal from the tip of their nose to the hind end is considered the equivalent of human height. This length is the same long axis along the spine board as the human length corresponding to their height.

Table 4. Animal Anthropometric Measures for Study FY13-100

Animal ID	Weight (kg)	Length (m)
42-101	26.2	0.90
42-115	23.4	0.84
42-121	22	0.86
47-018	23.2	0.88
42-131	27.2	0.89
42-132	23.2	0.84
43-090	24.8	0.91
46-030	21	0.86
46-091	24.6	0.93
46-101	18.8	0.84
46-149	23	0.90
47-050	19.8	0.95
47-051	21.4	0.89
47-052	22.8	0.88
47-094	20.6	0.86
Average	22.8	0.88
SD	2.31	0.034

An equivalent listing of anthropometric measures for the animal population from study FY17-077 is not available. The animal population was somewhat heavier than those in FY13-100, with an average approximate weight of 30.4 kg, but exhibit a similar range of lengths.

By proportion, the human subjects are heavier per unit of length than the animal subjects, with an average of 47.3 kg/m, while the animals (FY13-100 only) averaged 26.0 kg/m. However, the human subjects also occupy a larger volume, suggesting that density (with units of kg/m^3) may be much closer to proportionate. Most mammals have a density close to that of water (1000 kg/m^3). Insufficient anthropometric measures were collected to calculate the exact volume of each population.

RMS Acceleration

Table 5 presents the average RMS acceleration for various track sections collected at the level of the litter berth. These values represent the input energy associated with the linear acceleration into the litter through the feet or stirrups of the litter. These values were calculated from acceleration readings in the vertical direction, using this equation (Eq. 1):

$$rms = \sqrt{\frac{1}{N}\sum_{i=1}^{N} x(i)^2} \qquad (1)$$

Table 5. Representative Average Vertical RMS Acceleration for Track Sections

Track Section	**Approx. speed (mph)**	**RMS acceleration (m/s^2)**
Gravel	20-25	0.599
Outside bumpy	5	5.576
Inside smooth	10	0.982
Inside bumpy	5	5.895
Inside smooth	15	1.315
Half straddle	5	3.248

The human subjects averaged RMS accelerations values at each anatomical location are shown below. The labels on the graphs' x-axis denote the tracks. For labeling purposes, GR = gravel, OB = outside bumpy, IS10 = inside smooth at 10 mph, IB = inside bumpy, IS15 = inside smooth at 15 mph, and HST = inside half-straddle.

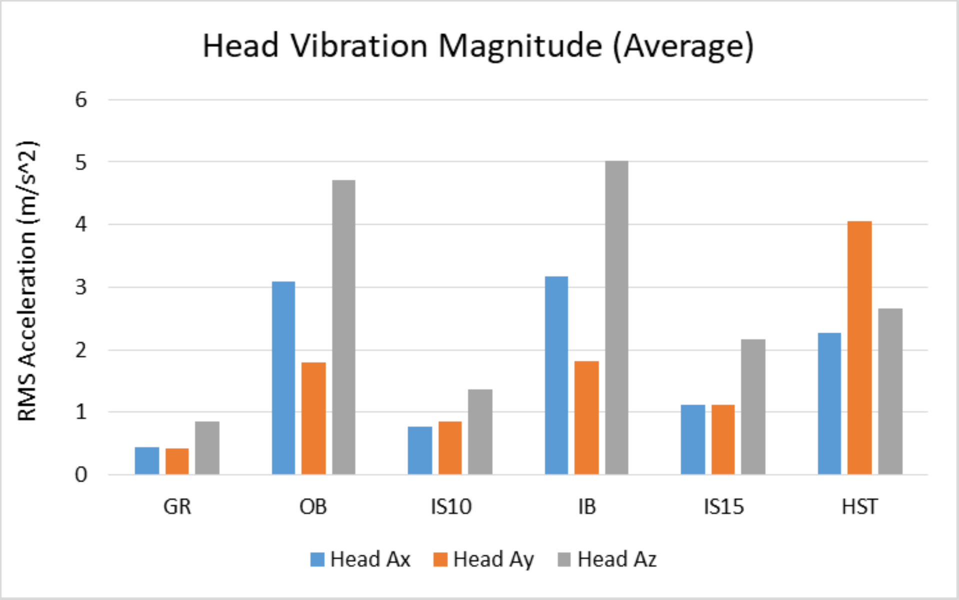


Figure 8. Average head vibration magnitude (human).

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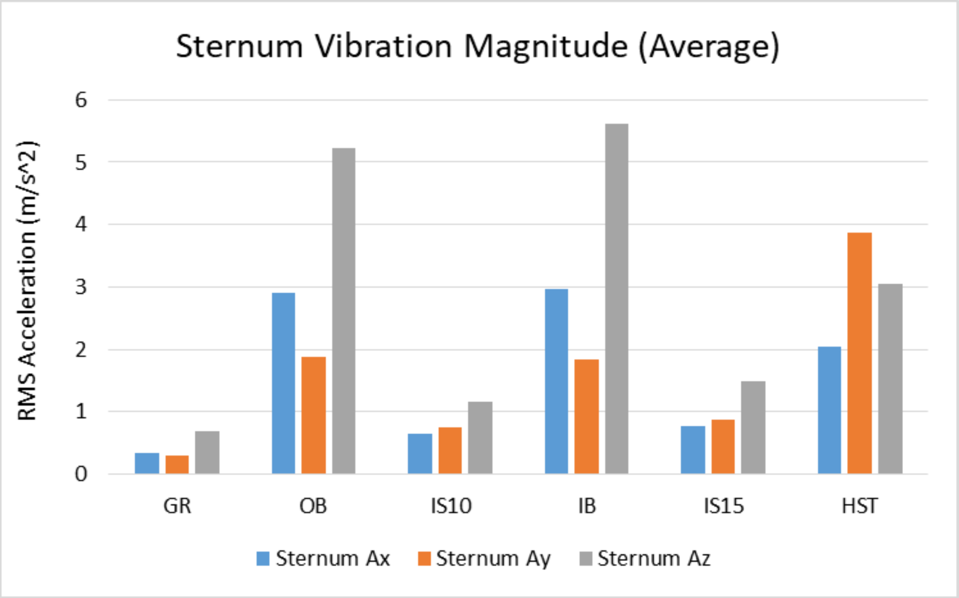

Figure 9. Average sternum vibration magnitude (human).

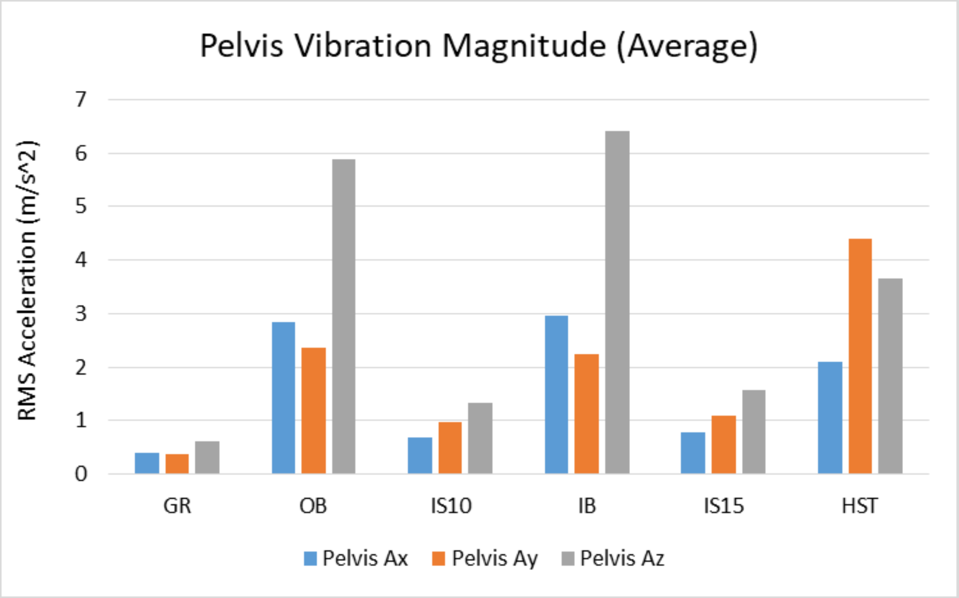

Figure 10. Average pelvis vibration magnitude (human).

Using these values, we can find the resultant (sum) acceleration at each location and track section. These values are summarized in Table 6.

Table 6. Resultant Acceleration for Track Sections (Human)

Track Section	**Head RMS acceleration (m/s^2)**	**Sternum RMS acceleration (m/s^2)**	**Pelvis RMS acceleration (m/s^2)**
Gravel	1.063	0.832	0.820
Outside bumpy	5.911	6.272	6.939
Inside smooth (10 mph)	1.789	1.535	1.779
Inside bumpy	6.209	6.613	7.405
Inside smooth (15 mph)	2.680	1.885	2.074
Half straddle	5.350	5.342	6.101

Animal study FY13-100 adhered to a different sequence of testing but used the same track segments as in the human subjects study. These segments are OT (outside bumpy), IT (inside bumpy), OS (outside smooth ~ 5mph), IS (inside smooth ~5mph), and ST (straddle). HR refers to half-rounds, which are not being analyzed for equivalence in this report. The original study divided transported animals into healthy shams and injured animals, but there were no significant statistical differences between these two groups.

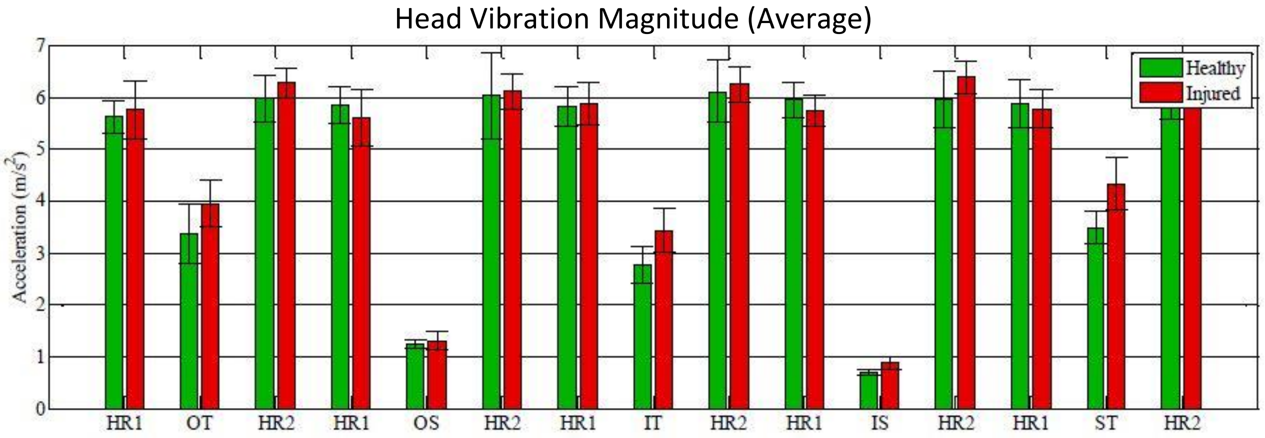

Figure 11. Average head vibration magnitude (study FY13-100).

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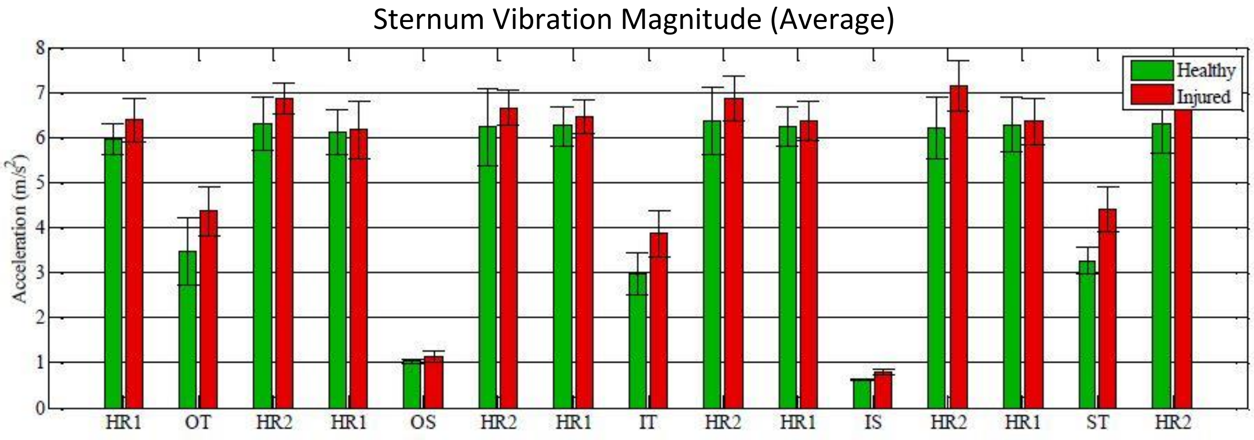
Sternum Vibration Magnitude (Average)

Figure 12. Average sternum vibration magnitude (study FY13-100).

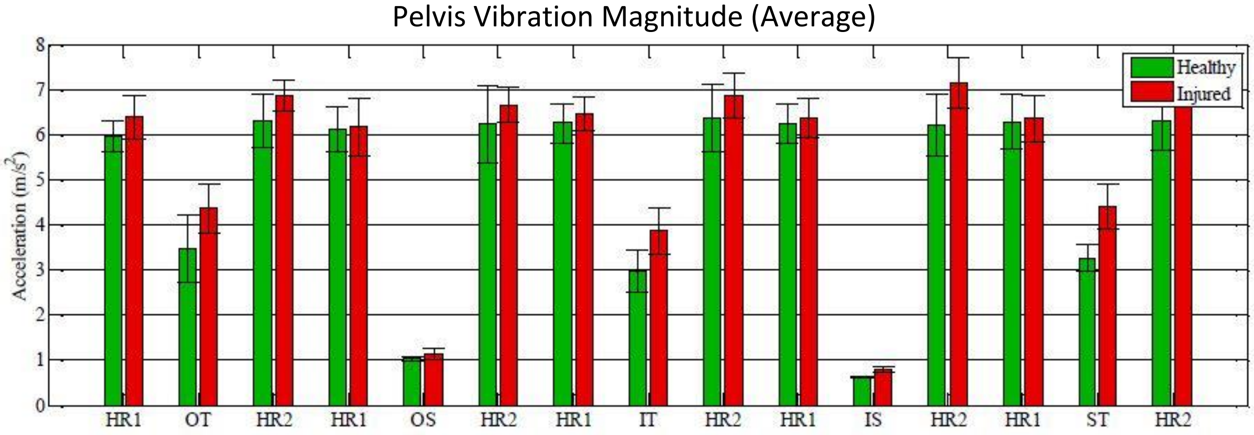
Pelvis Vibration Magnitude (Average)

Figure 13. Average pelvis vibration magnitude (study FY13-100).

Animal study FY17-077 adhered to a testing sequence similar to the order of track segments as in the other animal study. These segments are OB (outside bumpy), IB (inside bumpy), OS (outside smooth ~ 5mph), IS (inside smooth ~5mph), and OST/IST (half-straddle). Again, HR refers to half-rounds, which are not being analyzed for equivalence in this report.

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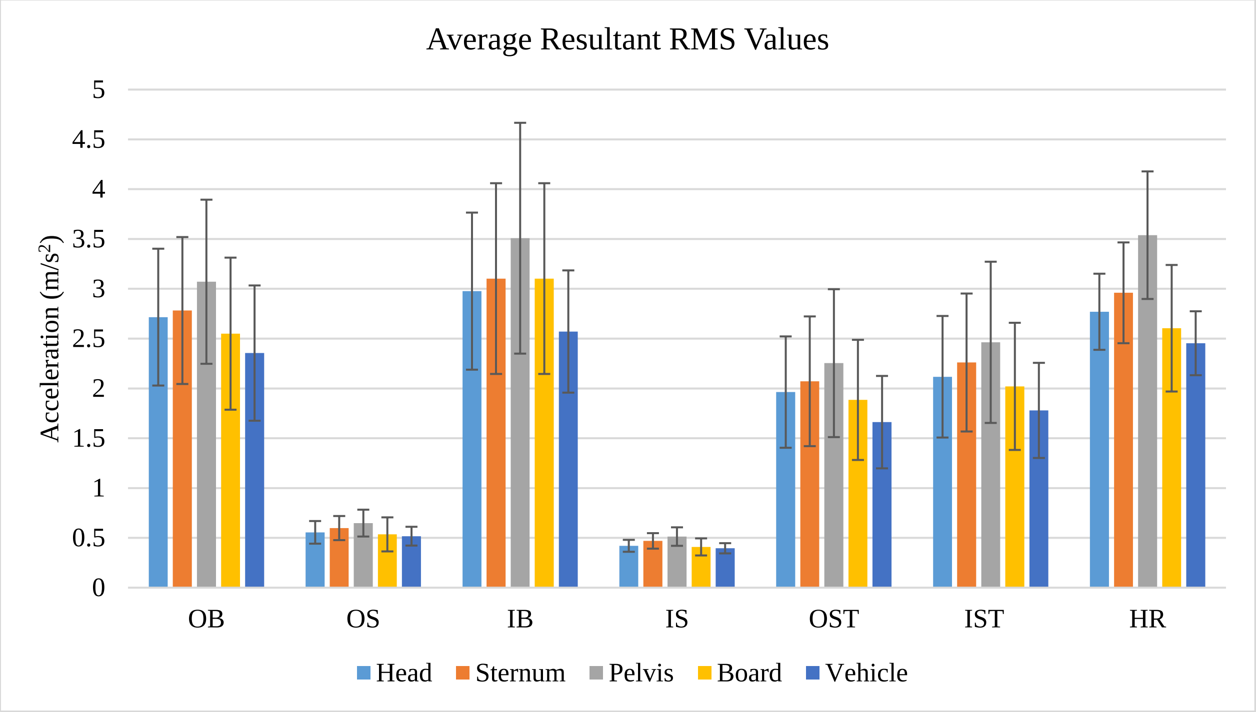

Figure 14. Average resultant vibration magnitude (study FY17-077).

Power Spectral Density

The power spectral density (PSD) for the human response is seen in Figures 15 through 17 during the gravel track segment. These data were originally analyzed with respect to gender, but the mean response (black line) is of interest for this analysis. The power spectral density represents the magnitude of the acceleration plotted across the frequency spectra, indicating where most energy is present. For significant health effects, we are interested in frequencies below 20 Hertz (Hz).

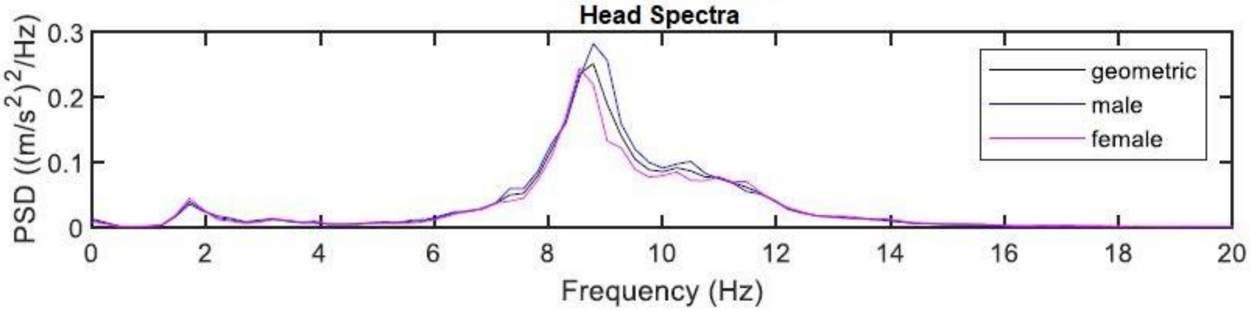

Figure 15. PSD for head (study 2016-012).

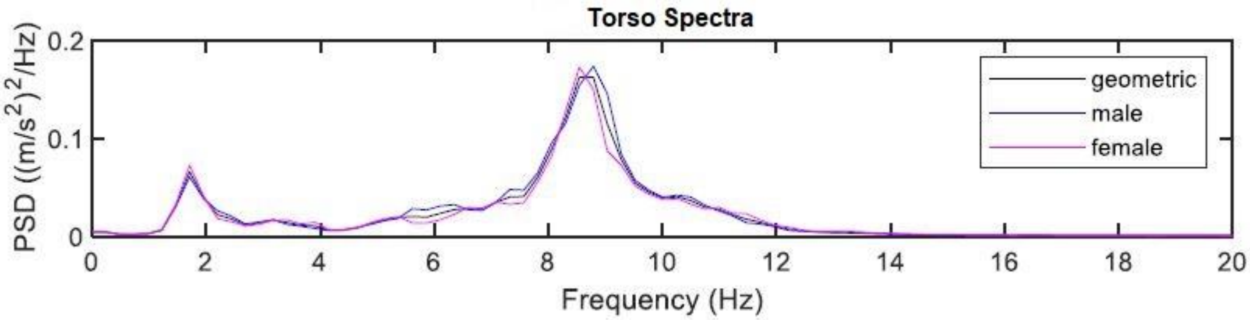

Figure 16. PSD for sternum (study 2016-012).

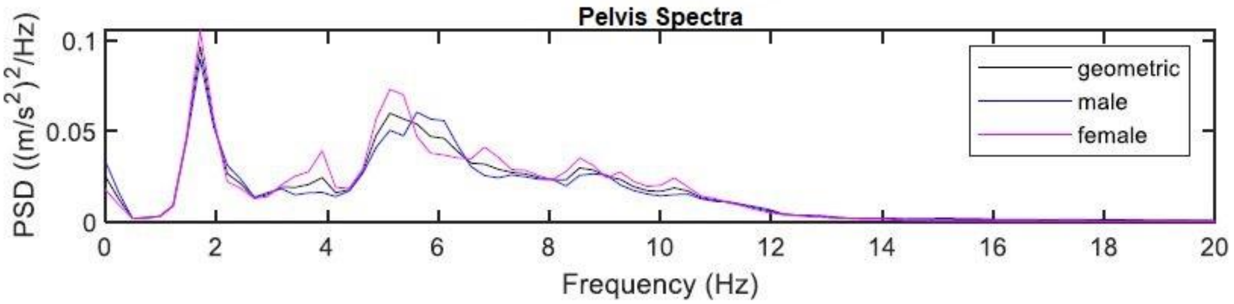

Figure 17. PSD for pelvis (study 2016-012).

The PSD for study FY13-100 was graphed with respect to one-third octave bands for the gravel segment of the track at the level of the spine board.

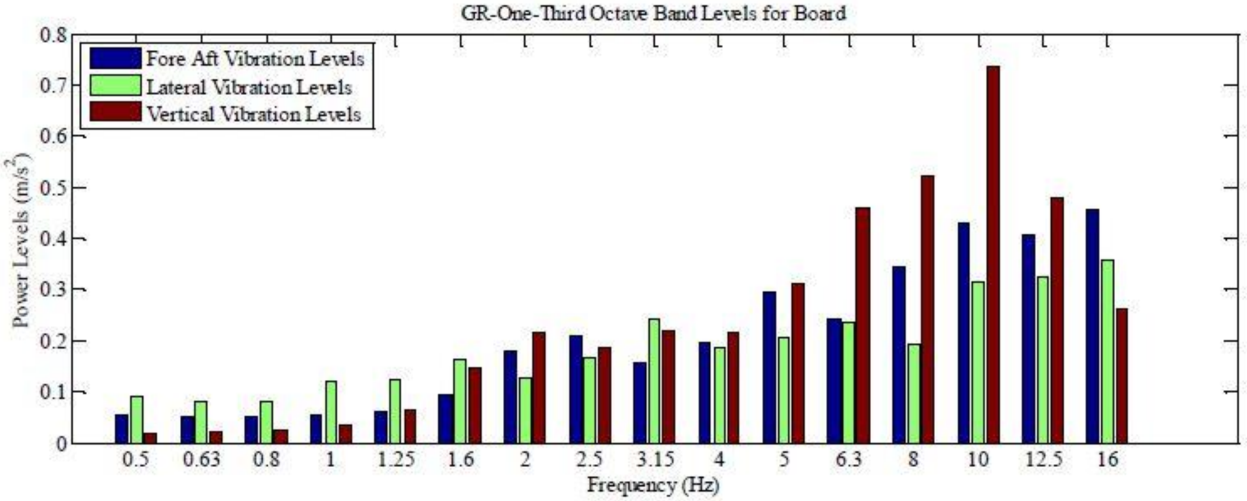

Figure 18. PSD for spine board (study FY13-100).

An example PSD for study FY17-077 is provided for the outside smooth segment of the track (the gravel track segment was not examined in this study). All sensors were graphed on the same graph for each axis of motion.

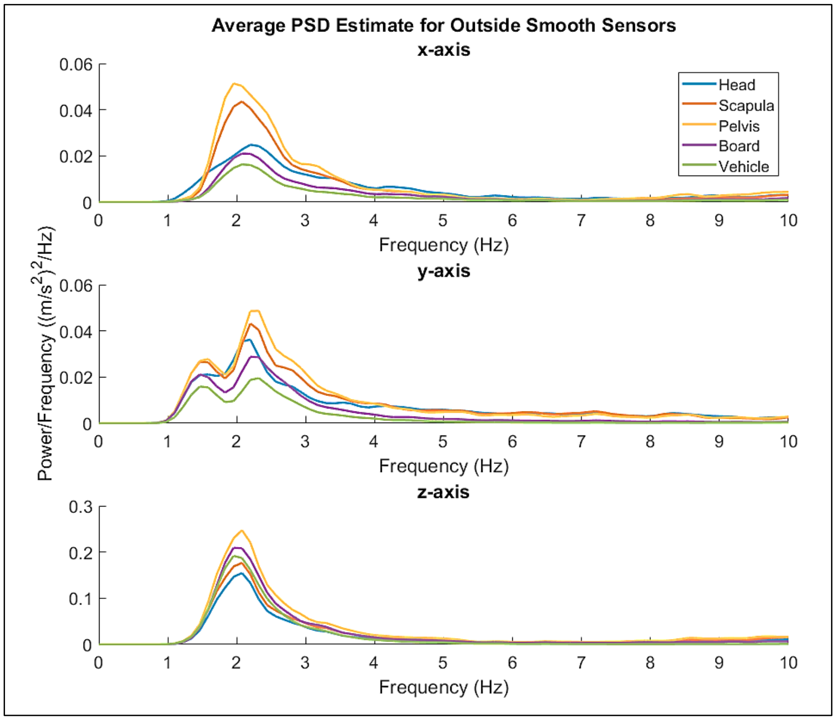

Figure 19. Average PSD estimate for each sensor for the Outside Smooth section.

Transmissibility

For study 2016-012, the transmissibility was calculated between the litter berth (input) and the surface of the human body (output) at the head, sternum (or torso), and pelvis. Values above 1.0 indicates exacerbation of the input energy and values below 1.0 indicate dampening. The acceleration values used in these transmissibility calculations were collected during the gravel track segment in the vertical direction. The black line is the mean of all subjects' graphs.

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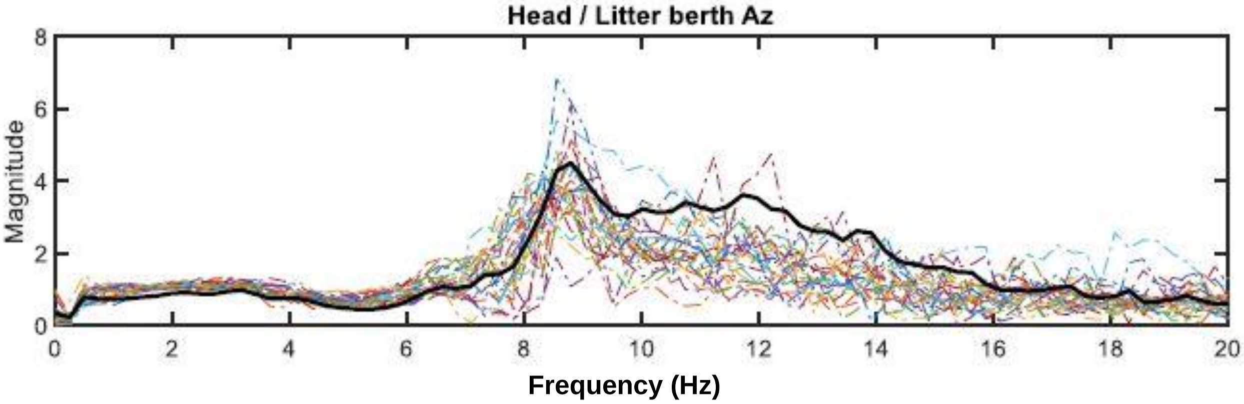

Figure 20. Transmissibility for the head in the vertical direction.

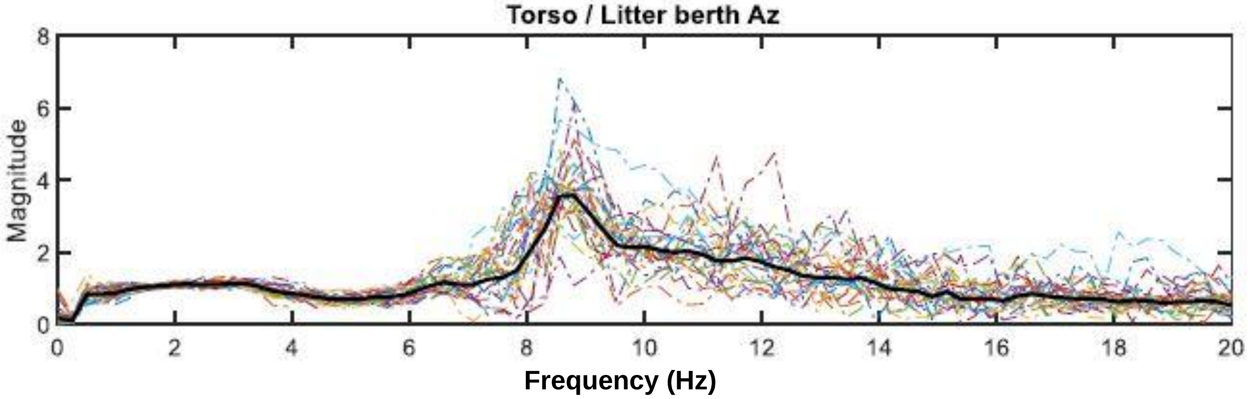

Figure 21. Transmissibility for the sternum in the vertical direction.

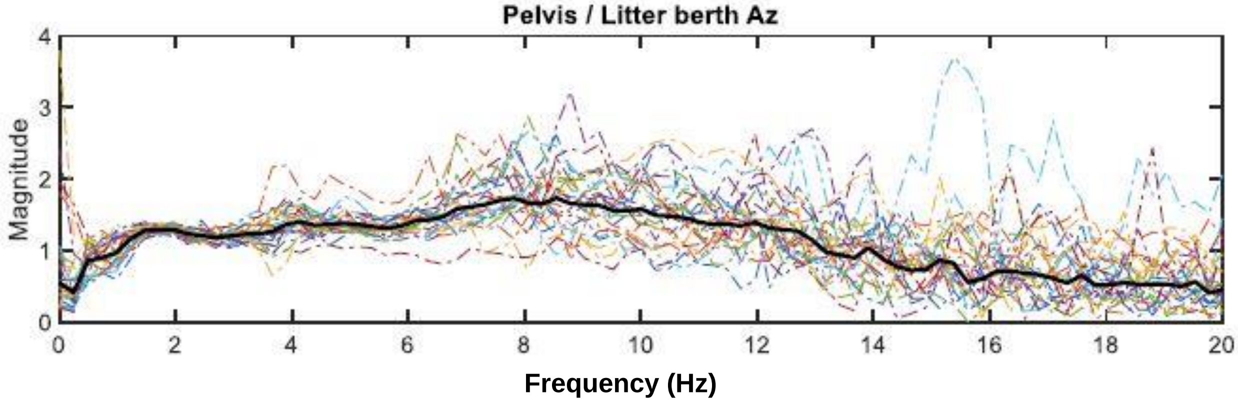

Figure 22. Transmissibility for the pelvis in the vertical direction.

Transmissibility data was not calculated in an equivalent way for study FY13-100. The transmissibility was calculated with respect to the spine board (input) and the on-the-body sensors (output). The different plotted lines represent the various cohorts (healthy, injured, sham). An example of this transmissibility calculation is shown in Figure 22 for the outside smooth and inside smooth track segments (the closest equivalent to the gravel road section shown above for the human subjects). Other graphs from this study show a similar trend of pass through (~ equal to 1.0), followed by a gradual dampening behavior as the frequency increases.

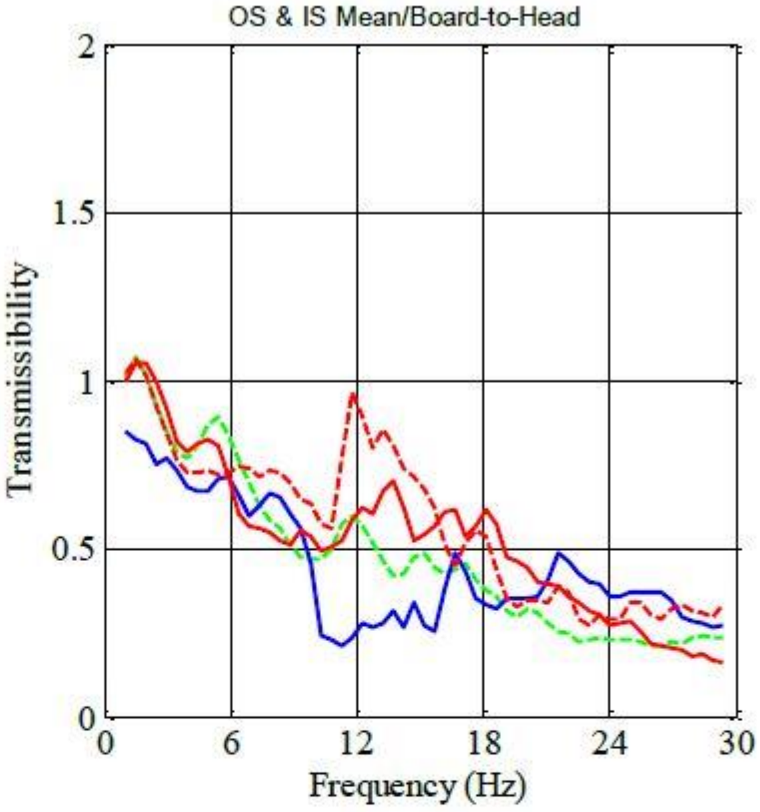

Figure 23. Example transmissibility for the head in the vertical direction (study FY13-100).

Transmissibility was calculated in study FY17-077 with respect to the vehicle (input) and the on the body sensor locations. Each axis of motion was compared to all axes of the output acceleration. This directional transmissibility is captured in a matrix for specific track segments, with each on the body sensor drawn on the same graphs. The graphical matrices for the outside and inside smooth track sections are presented.

The outside smooth track transmissibility graphs are shown in Figure 23, for the vertical input divided by vertical output (X/X), the transmissibility values are below one for the head indicating that the input signal was mitigated. However, for lateral input and lateral output (Y/Y), the head had the highest transmissibility with the peak value almost double the peak value of the pelvis and scapula.

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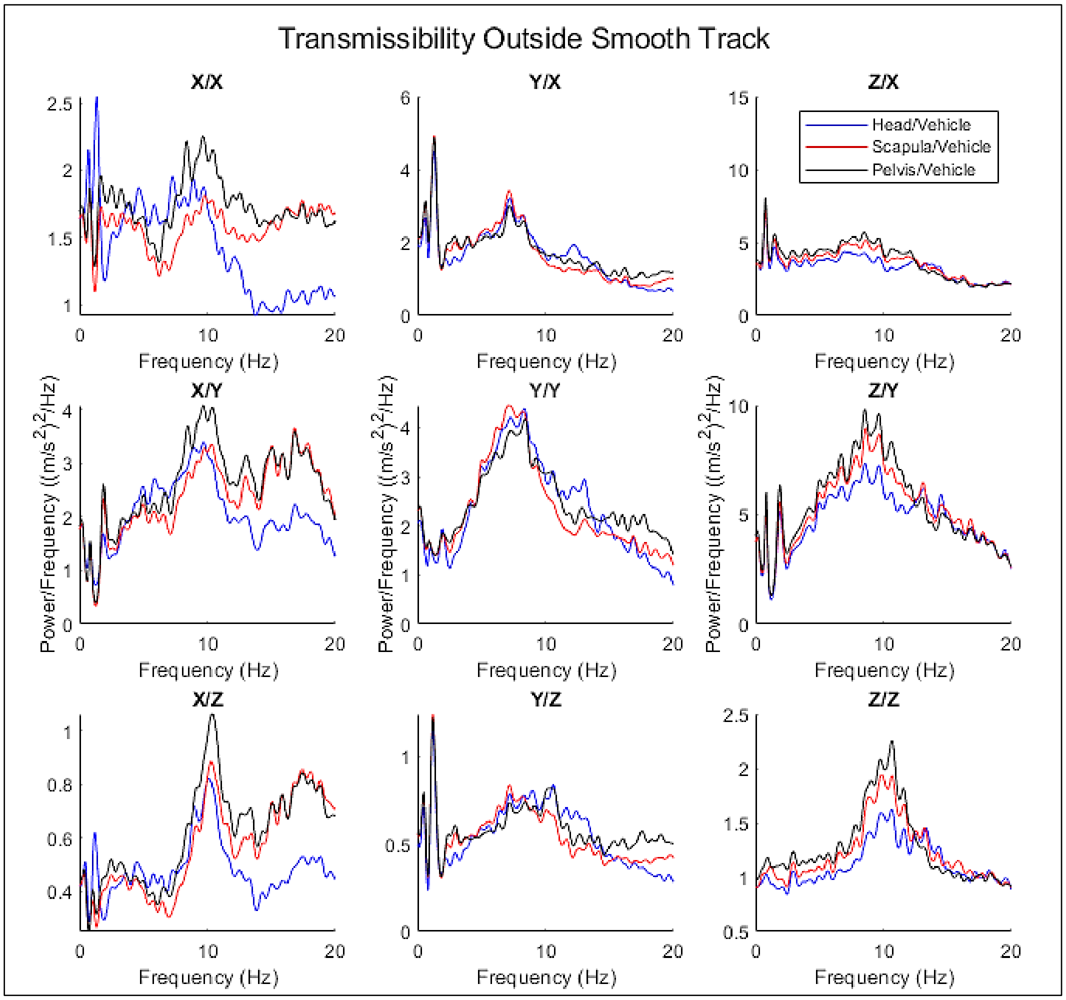

Figure 24. Directional transmissibility of the outside smooth section.

When comparing the Inside Smooth track transmissibility (Figure 24) to the outside smooth track transmissibility, there is less mitigation in X/X direction, but there is also less amplification in the Y/Y and Y/Z directions. Similar to the outside smooth track, there is a drop in transmissibility in the X/X direction for the head/vehicle after 10 Hz indicating that the output signal was mitigated.

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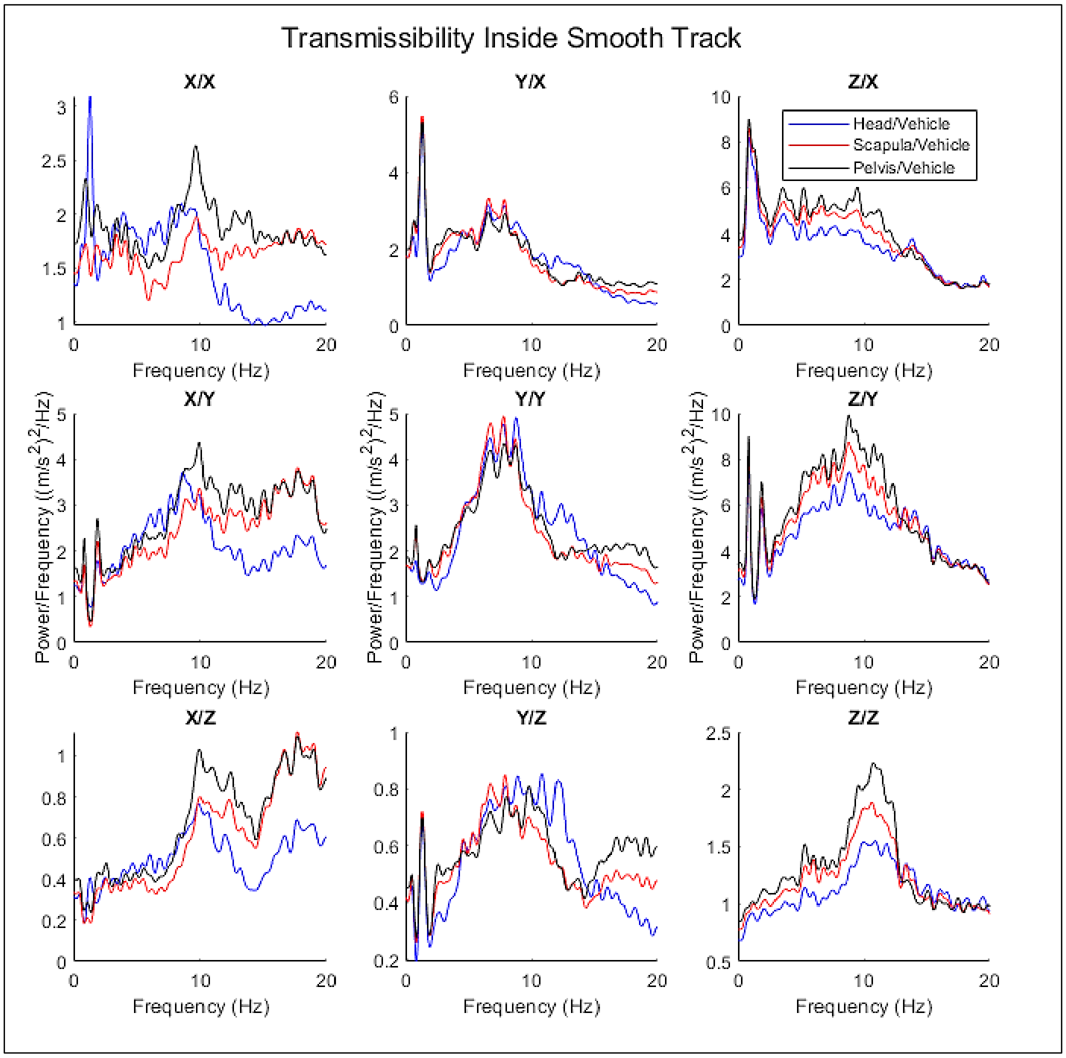

Figure 25. Transmissibility of the inside smooth section.

Discussion

The entire test track was resurfaced between the animal study FY13-100 and human study 2016-012. Testing for animal study FY17-077 took place after the human study. The average RMS acceleration response to the outside bumpy track versus the inside bumpy track during the FY13-100 study indicated the outside bumpy track was slightly rougher than the inside bumpy track. After the track resurfacing, this trend was flipped. Both human study 2016-012 and animal study FY17-077 showed the same characteristic of the outside bumpy track being less rough than the inside bumpy track. This carried through the half-straddle segments in study FY17-077, since the half-straddle involved two of the tires driving on the inside or outside bumpy track and the other set of tires on the smooth track. Study FY13-100 involved a full straddle segment, where the tires on one side of the vehicle were on the inside bumpy track and the other set of tires were on the outside bumpy track segment. The full straddle was closer in total sum acceleration magnitude to the inside and outside bumpy tracks, while the half-straddle segments were lower in magnitude than the bumpy segments for both the animal and human studies.

The smooth track segments are not in perfect synchrony in terms of magnitude for the animal studies, but repeated driving passes from the previous animal and human studies are thought to account for the lower acceleration magnitudes seen in study FY17-077 for the smooth segments. During the human study, faster speeds were driven on the smooth tracks, making a direct comparison between acceleration magnitude not advisable. The sum accelerations for the two animal studies are in relatively good agreement across the common track segments tested. Both groups exhibited similar small increases in magnitude for the sum RMS acceleration at the sternum as compared to the head, and at the pelvis compared to the sternum, across all track segments. The human subjects data showed a similar trend, though the magnitude of the transmitted vibration is larger than all equivalent animal data.

The power spectral density data was not a direct one-to-one comparison between the human study or either animal study but there are similar patterns of energy peaks present in the vertical direction of the animal spine board data as seen in the human head and sternum data across the gravel track segment. Significant energy is present in the 2 to 3 Hz range, which correlates directly with the suspension response of the ground vehicle. The energy peaks seen around 6 Hz and 8 to 10 Hz correspond to the human whole body resonance frequency. The presence of these peaks in the animal data (if somewhat muted in FY17-077) are encouraging for the use of the animal model in place of humans.

The transmissibility data from the human study and animal study FY17-077 had the same input and output locations but examined somewhat different track segments. There are still commonalities to be seen in the data patterns such as exacerbation of the energy in the frequency ranges that were identified in the PSDs previously. The transmissibility for study FY13-100 was calculated between the spine board and the on-the-body sensors. Because the body tends to couple to the spine board and move in unison, there is often little information that can be gleaned from this analysis. Transmissibility values around 1.0 and lower are expected as frequencies increase.

The eventual goal of the comparison between the human and animal datasets would be the construction of a model that could be extrapolated to address injured humans using the combination of healthy human, healthy animal, and injured animal data. An example of a two-dimensional (2D) supine-human model being transported on a litter and spine board is presented below. This model predicts human response to vertical whole-body vibration. The model was developed previously by researchers at University of Iowa and was modified to accommodate subjects with different masses. The schematic drawing of the 2D supine human model is shown in Figure 25. Table 7 and Table 8 demonstrate the parameters of this 2D model for the supine human and the litter plus underlying spine board transport system.

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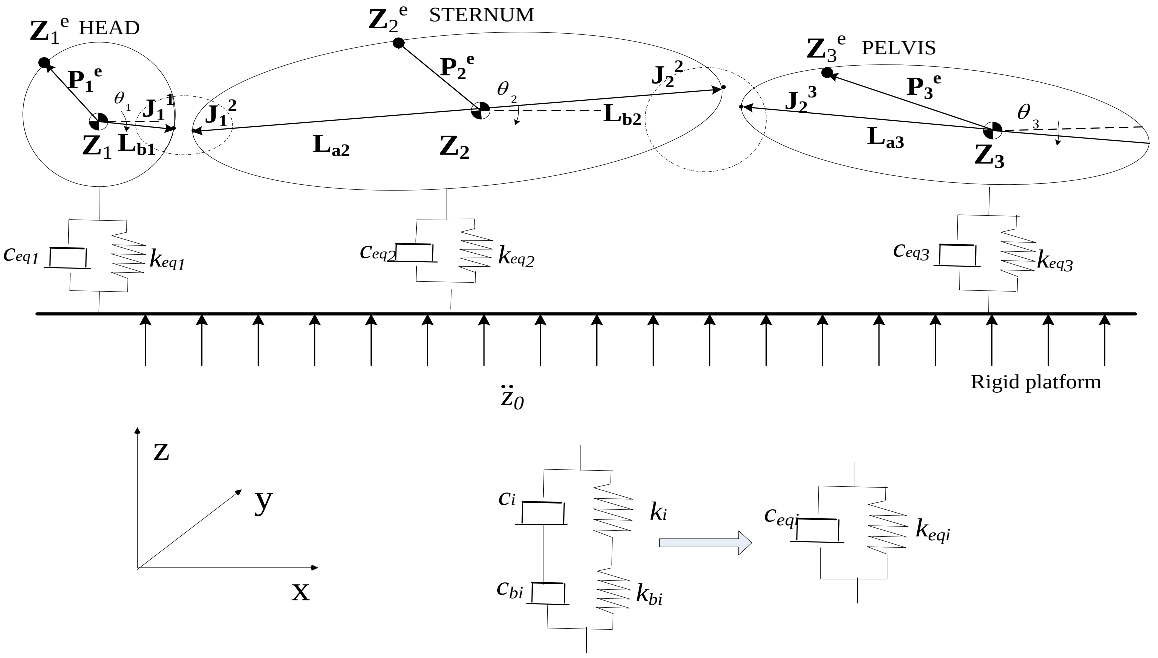

Figure 26. Schematic drawing of the supine human model.

Table 7. Supine Human Model Spring and Damper Coefficients for 3DOF

	Head	**Torso**	**Pelvis**	**Rotational Joint 1**	**Translate Joint 1**	**Rotational Joint 2**	**Translate Joint 2**
Spring	55448.23	207185.39	242609.46	3132.58	7578.2373	540962.6422	10195.0095
Damper	172.94467	3449.5632	2155.1538	0.001058910	147.39050	48681.06650	183.7761
Spring coefficient unit*: N/m* (translate) and *N·m/rad* (rotational) Damper coefficient unit: *N·s/m* (translate) and *N·m·s/rad* (rotational)							

Note. N = newton(s), *m* = meter(s), *rad* = radian(s), *s* = second(s)

Table 8. Litter-Board Spring and Damper Coefficients

	k_{b1}	k_{b2}	k_{b3}	c_{b1}	c_{b2}	c_{b3}
Coefficients	61269.92	44843.74	62264.61	126.77	361.24	645.83
Spring coefficient unit: *N/m* (translate) Damper coefficient unit: *N·s/m* (translate)						

The parameters of this model are based on the height of 1.82 m and weight of 81 kg for the subject. When the model is applied on subjects with different masses and heights, a scaling process is used. A biomechanical system can be described by its physical model by the mass matrix (M), damping matrix (C), and stiffness matrix (K). The equation of motion of this system without external force can be given in a matrix form, as shown in Eq. 2.

$$\mathbf{M}\ddot{\mathbf{u}}(t) + \mathbf{C}\dot{\mathbf{u}}(t) + \mathbf{K}\mathbf{u}(t) = \mathbf{0} \quad (2)$$

If Eq. 2 is multiplied by a scalar *α*, then,

$$\alpha\mathbf{M}\ddot{\mathbf{u}}(t) + \alpha\mathbf{C}\dot{\mathbf{u}}(t) + \alpha\mathbf{K}\mathbf{u}(t) = \mathbf{0} \quad (3)$$

This new system keeps the frequency characters, so if the mass of a specific subject is known, then the scaling parameter *α* can be calculated as shown in Eq. 4.

$$\alpha = m_s / m_a \quad (4)$$

where m_s and m_a are the mass of the specific subject and the average model, respectively.

It is clear from the construction of the model that the mass and spring/damper coefficients of the biological system must be defined in order for the model to be robust. The method for mass scaling may work for translating the model for the swine, but the coefficients would also need to be defined. Additionally, the translation between these coefficients for the recumbent swine model and the supine human model would need to be defined. Future studies should include collection of data that would permit the calculation of these coefficients, and then exercising of the model behavior against the empirical data sets to verify robustness. If the model behaves similarly to the supine human model, then scaling between the models to permit human response from the animal data should be possible.

Limitations

The major limitations of the comparisons presented in this study are the imperfect equivalence between the ground vehicle’s transport excitations presented to the human and animal subjects, and the different methods used to analyze the data from the three studies. The authors did not have access to all raw data sets which did not permit re-analysis of the data.

Conclusion

The biodynamic response of the swine exhibits similar patterns to that of the healthy human biodynamic response to the same ground ambulance excitations. Changes to the roughness of the terrain show similar shifts in transmitted acceleration and energy across similar frequency bands. What is not directly equivalent is the magnitude of the transmitted vibration energy. As the example 2D model of the human shows, this biodynamic response is dependent on the mass and spring/damper coefficients of the human or equivalent subject, and a scaling process must be used for humans of different anthropometry. Given these considerations, it is reasonable to conclude the swine could be an acceptable model for the biodynamic response of humans subjected to ground transport, if appropriate scaling factors can be defined and applied.

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Appendix A. Acronyms and Abbreviations

Acronym/Abbreviation	**Meaning**
2D	Two-dimensional
3D	Three-dimensional
6DOF	6 degree-of-freedom
ACURO	Animal Care and Use Review Office
DAQ	Data acquisition system
deg	Degree
DoD	Department of Defense
DTIC	Defense Technical Information Center
EDO	Exempt Determination Official
HMMWV	High Mobility Multipurpose Vehicle
HR	Half-round
HS	Hemorrhagic shock
Hz	Hertz
IB	Inside bumpy
IRB	Institutional Review Board
IS	Inside smooth
IST	Inside half-straddle
IT	Inside bumpy
kg	Kilogram
LBRI	Lovelace Biomedical Research Institute
m	Meter
MDO	Multi-domain operations
MEDEVAC	Medical evacuation
mph	Miles per hour
mV	MilliVolt
OB	Outside bumpy
OS	Outside smooth
OST	Outside half-straddle
OT	Outside bumpy
PSD	Power spectral density
RMS	Root mean square
s	Second
SCI	Spinal cord injury
ST	Straddle
TBI	Traumatic brain injury

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