SUBJECTIVE AND ASSOCIATED OBJECTIVE RESPONSE TO REPEATED MECHANICAL SHOCKS IN SEATED HUMANS

by

Alan Vitomir Vukusic

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NAME: Alan Vitomir Vukusic

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EXAMINING COMMITTEE:

Chair: Dr. John Dickinson

Dr. James B. Morrison
Senior Supervisor

Dr. Parveen Bawa

Dr. Dan Weeks

Dr. Kevin Hamilton

Dr. Murray Hodgson
Occupational Hygiene Program
University of British Columbia

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ABSTRACT

The purpose of the present study was to describe subjective response to shock exposures containing realistic ranges of parameters of motion including shock amplitude, frequency, axis, direction and duration of exposure. The subsequent objectives were to correlate subjective response with the associated biomechanical response (transmission of acceleration) and to assess computational and biodynamic methods of evaluating exposure to motion such as the Vibration Dose Value (VDV) and the Dynamic Response Index (DRI). Two main types of experiments were used: one which examined subjective rating of the severity of single shocks of different amplitudes, axes and directions over a range of waveforms (frequency); and another that examined subjective rating of comfort, predicted tolerance, tiredness and severity of exposures to repeated shocks. The experiments involved exposing 54 seated males to motion signatures delivered by a simulator (±x, +y, and ±z axes; 0.5 g to 4 g; 2 to 20 Hz waveforms; and 5.5 minute to 7 hour duration). Results demonstrated that the subjective rating of severity of single shocks were closely correlated with the associated biomechanical response for all axes (positive direction: $r^2=0.918$ to $r^2=0.958$; negative direction: $r^2=0.872$ to $r^2=0.954$). Subjective rating of severity were poorly correlated with outputs of biodynamic models and filters, except for the Fairley-Griffin and DRI (8.4Hz) models for the positive z axis ($r^2=0.985$ and $r^2=0.959$, respectively). Exposure to repeated shocks demonstrated that subjective rating of comfort, tiredness and severity had a significant time-dependence for long term exposures of up to 4 hours ($p<0.05$). Both short term (15 to 30 minutes) and long term (overnight) rest intervals significantly improved rating of comfort, tiredness and severity ($p<0.05$). Subjective ratings of exposure to repeated shocks did not support the time- or amplitude-dependency of the VDV. The study shows a need to develop a new dose model which has a frequency response, amplitude- and time-dependency designed to enable the prediction of the human response to mechanical shocks.

QUOTATION

'Whooo-eeee, I tellllllllllll you...' *(with Southern drawl)*

-Bobby Dillard

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DISCLAIMER

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INTRODUCTION

In occupational and military environments involving heavy machinery and off-road vehicles the type of motion experienced often includes exposure to vibration and repeated mechanical shocks (i.e., high amplitude, transient acceleration waveforms superimposed on random vibration). This type of motion may be associated with various health concerns such as disorders and pain in the back, cardiovascular, respiratory, and gastro-intestinal areas (Magid *et al.*, 1960; Guinard, 1972, 1974, and 1985; Weaver, 1979; Sandover, 1986; and Barnes 1987).

Although previous studies have characterized the human response to vibration, very few have considered the effects of exposure to mechanical shocks. It has been suggested that the existing literature, current methods of evaluation and standards concerning the assessment of repeated mechanical shocks are inadequate for evaluating effects on health and safety (Village *et al.*, 1995). The development of accurate methods to evaluate exposure to motion, and effective standards to limit exposure to mechanical shocks will benefit the health of people exposed to such motion (ISO 2631, 1994).

Subjective response is one parameter which may be used to evaluate the effects of exposure to vibration and mechanical shocks. It is considered to be a valuable measure because it may reflect symptoms of stresses on the body that would not be identified by objective measures. Such symptoms include pain originating from internal organs, headaches, and localized superficial tissue pain. Additionally, subjective response can be obtained easily and is inexpensive when compared to objective measures (Sandover, 1986). Previously, subjective discomfort has been widely used as an index for assessing the effect of exposure to vibration (Griffin, 1990). However, the effect of exposure to mechanical shocks on subjective response has not been thoroughly investigated. Additionally, the relations between subjective response and the associated physical responses, such as biomechanical transmission of acceleration, have not been established. Furthermore, it has also been suggested that the existing computational methods and biodynamic models for evaluating the health effects of exposure to motion are not applicable for evaluating the effects of exposure to mechanical shocks (Village *et al.*, 1995).

The development of accurate methods of evaluation and effective guidelines to limit human exposure to motion are dependent on gaining a clear understanding of the effects of mechanical shocks. Thus, the present study will contribute an understanding of the relation between subjective response to mechanical shocks and the associated biomechanical response, and the ability of computational methods and biodynamic models to evaluate the effects of exposure to mechanical shocks.

BACKGROUND

The various types of exposure to motion can be considered to range along a continuum, becoming increasingly severe and complex from one end to the other. At the least severe end of the continuum, motion can be described as single axis, sinusoidal, low amplitude vibration. Progressing along the continuum, motion may contain higher amplitude waveforms, may occur in more than one axis, and may contain random or multi-sinusoidal waveforms. Further yet, high amplitude transient waveforms may be occasionally superimposed on the vibration. Exposure to mechanical shocks may be characterized as frequent, high amplitude shocks superimposed on background vibration. The most severe end of the continuum may be characterized by extremely high amplitude, single shocks (Griffin, 1990).

Exposure to motion, in a broad sense, includes a wide range of types of acceleration waveforms. In terms of frequency, exposure to motion may include waveforms of frequencies less than 1 Hz to approximately 1000 Hz. Motion sickness is associated with frequencies of less than 1 Hz and hand-transmitted vibration is associated with frequencies up to 1000 Hz. However, exposure to whole-body vibration (WBV) and mechanical shocks is mainly associated with waveforms frequencies ranging from 1 to 100 Hz. This particular type of exposure to motion will be the topic of concern in this thesis. Thus, in the context of this thesis, exposure to motion will refer to exposure containing mechanical shocks with background random vibration.

Figure 1 demonstrates an example of the types of acceleration waveforms in the z axis which were used to characterize the typical motion experienced in off-road vehicles. Motion measured at the seat of military tactical ground vehicles (TGVs) (Roddan *et al.*, 1995) has been shown to contain shocks with fundamental frequencies between 1 and 60 Hz in the x axis, 0.8 to 56 Hz in the y axis, and 0.5 to 51 Hz in the z axis. In addition, peak acceleration of shocks measured at the seat was shown to be 5.5 g in the +x axis, 5.7 g in the +y axis, and 6.5 g in the +z axis (Roddan *et al.*, 1995).

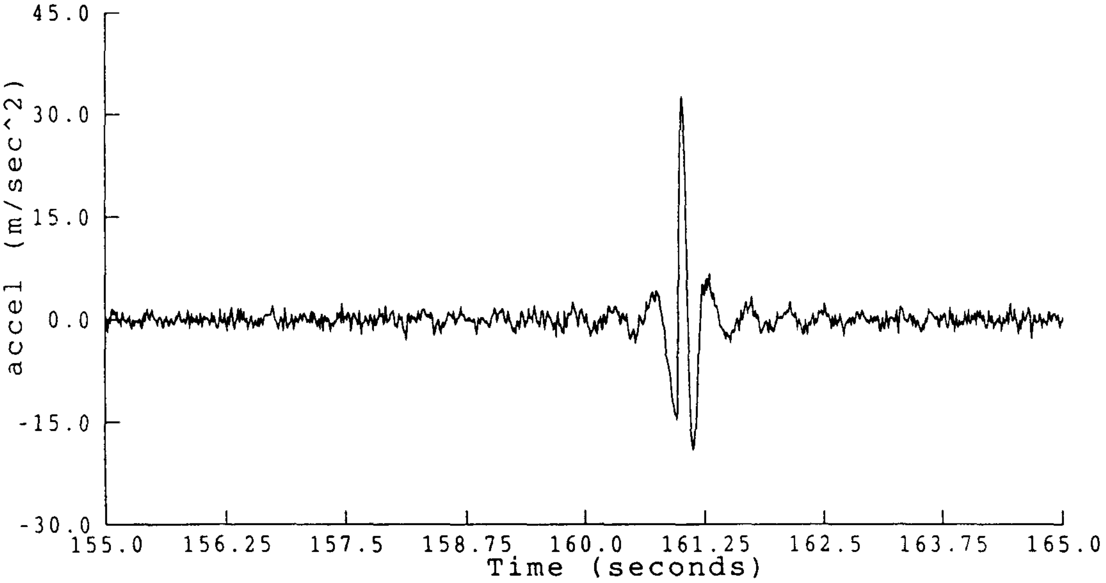


Figure 1 **Acceleration waveforms characteristic of motion experienced in off-road vehicles.**

Subjective Response Scales

Various types of scales have been used to obtain measures of subjective response to motion. Five-point scales with semantic labels for each point were widely used to determine the subjective discomfort of low amplitude vibration. This type of scale was associated with high variability between subjects, due to individual differences in the definition of semantic labels such as 'comfortable' and 'mildly annoying' (Griffin, 1990). In addition, using a five-point scale does not provide much resolution for the subject to decide on an appropriate level of response. Other studies have used subjective response scales expanded to seven points (Cole, 1978) and ten points (Brinkley, 1990). In addition, these studies only assigned semantic labels to the end points of the scales.

Generally, subjective scales are considered to be non-linear closer to the end points of the scale, perhaps due to the reluctance of subjects to provide extreme ratings. Subjective scales are also difficult to calibrate to a physical measure due to the subjective nature of the method. However, the growth of subjective discomfort has been calibrated using psychophysical methods by based on Stevens' Power Law. This suggests that the psychophysical magnitude, ψ, of the stimulus can be related to the physical magnitude of the stimulus, φ, by the equation:

$$\psi = k\varphi^n$$

where the growth in discomfort is determined by the value of the exponent n, which is expected to remain constant for each type of stimulus (Stevens, 1975). The exponent can be determined by the method of magnitude estimation, in which the subject provides a numerical estimate relating two stimuli, or the method of magnitude production, in which the subject adjusts the intensity of one stimulus until it equals a factor of a reference stimulus.

Parameters of Motion

The important parameters involved with exposure to motion are amplitude, axis, direction, frequency and duration. The amplitude of exposure to motion is the value of acceleration (ms^{-2}) in either vibration or shock waveforms. Translational input axes are defined by the basicentric co-ordinate system for expressing amplitudes of vibration in different directions (Griffin, 1990). The origin of the system is in the mid-saggital plane of the subject at the point of contact between the seat and the buttocks. In seated humans the x axis is directed forward in the frontal plane, the y axis is directed to the left side of the person in the transverse plane, and the z axis is directed upward in the longitudinal plane. Direction of motion refers to whether the acceleration waveform is input in the positive or negative direction of the respective biomechanical axis. In reference to vibration, frequency (Hz) is the number of cycles of motion per second. In reference to mechanical shocks, the fundamental frequency is the reciprocal of the period of each shock waveform. The number of mechanical shocks occurring in a given time period is defined as the shock rate (shocks · min^{-1}). The duration of exposure to motion refers to the time period of the exposure.

Relation of Subjective Response to Parameters of Motion

The subjective response to vibration and mechanical shock is a complex phenomenon, in terms of discomfort, tolerance, fatigue and pain. The many variables associated with the motion, the exposed person, the activities being performed during exposure, and the environmental conditions all exert influences on the magnitude of a subjective response. The interplay of these many variables tends to cause difficulty in using subjective response to evaluate accurately the severity of exposure to vibration and mechanical shocks. However, it has been demonstrated that subjective response is correlated with pain and health effects as a result of exposure to motion (Magid *et al.*, 1960). It then follows that subjective response can be considered as an indicator of potential or imminent damage to the human body, and should not be discounted in the development of evaluation methods and guidelines for exposure to motion.

The debate then dwells on the influence of the variables associated with subjective response to vibration and mechanical shocks. Of particular value is understanding the influence of variables of motion such as shock amplitude, frequency, axis, direction and duration of exposure on subjective response. Waveform frequency has been shown to affect the time which vibration may be tolerated at various amplitudes. For example, Magid *et al.* (1960) demonstrated that seated humans were most sensitive to high amplitude, sinusoidal vibration between the frequencies of 4 to 8 Hz (Figure 2).

The influence of these variables determines the relations we can define to assess the effects of exposure to motion. Thus, subjective response can be used to develop methods to evaluate the severity of exposure to motion, and provide support for the establishment of guidelines which limit exposure to potentially hazardous environments.

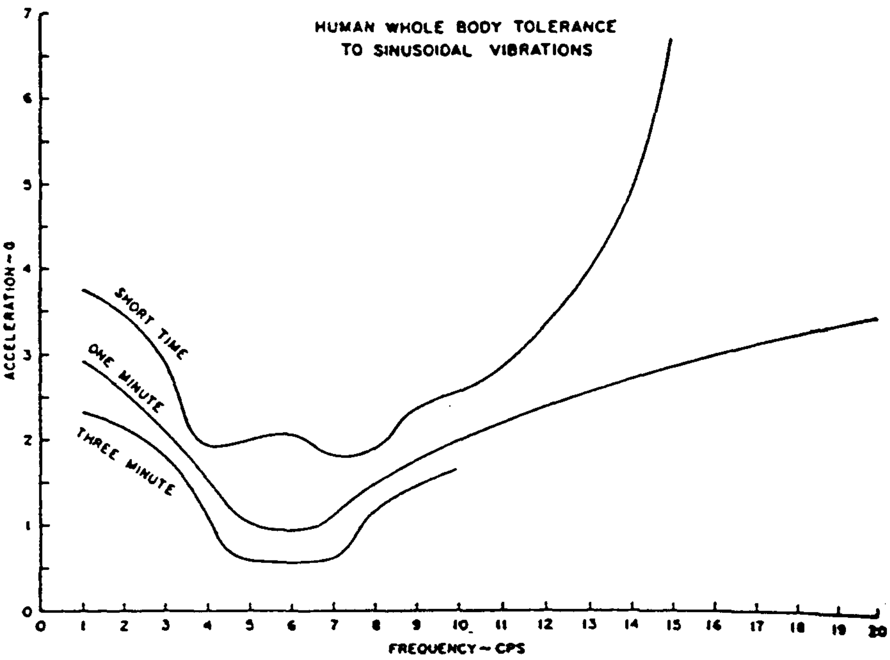


Figure 2 **Tolerance to high amplitude sinusoidal vibration, as a function of vibration frequency (Magid *et al.*, 1960)**

Effects of Duration of Exposure

Miwa (1968) completed one of the first studies to suggest that discomfort resulting from exposure to motion was a function of duration. The 'vibration greatness', a subjective value quantifying the difference between a pulsed sinusoidal vibration and a reference continuous sinusoidal vibration, was determined for various motions. The purpose of the study was to determine the 'vibration greatness' of various waveforms in order to provide data for the evaluation of pulsed vibration (Miwa, 1968). The pulsed sinusoidal vibration was varied in duration and frequency from 0.005 to 6.0 seconds, and from 2 to 300 Hz, respectively. It was found that 'vibration greatness' increased as a function of duration of the pulses up to a 'critical time' of 2.0 seconds for motion with frequencies between 2 to 60 Hz. A 'critical time' of 0.8 seconds was obtained for 100 to 200 Hz motions. Beyond the 'critical time', no further increase in 'vibration greatness' was observed. These pulsed sinusoidal motions were tested through a number of conditions in which the rest time between pulses was varied (0.5 to 5.0 seconds), as well as the intensity levels. It was suggested that the relation of 'vibration greatness' and duration for pulsed sinusoidal vibration can be simply characterized as a straight line with a 7 dB/decade slope, regardless of the fundamental frequency or intensity levels (Miwa, 1968). Although this supports the existence of a relation between pulse duration and subjective response, it is limited in application to only very short duration exposures.

Griffin and Whitham (1980) completed a study which involved determining the effect of the duration of pulsed vibration on human discomfort. By varying the duration of exposures through a range of frequencies and magnitudes of acceleration, data were collected to support the development of the root-mean-quad (r.m.q.) measure for predicting the discomfort of motion containing 'bumps', indicated by the equation:

$$\text{r.m.q.} = \left[T^{-1} \int_0^T a^4(t)\,dt \right]^{1/4}$$

where T is the period of measurement, and a is the frequency weighted acceleration. The first two experiments involved exposures up to 4.0 and 32 seconds, respectively. In contrast to earlier studies (Miwa, 1968), no short finite integration time, or 'critical time', was found to exist within these durations (Griffin and Whitham, 1980). In addition, regression lines were formulated for discomfort ratings as a function of duration, demonstrating a range in the slope of the function from 0.29 to 0.45 for the different frequencies. This indicates that for a constant vibration level the ability of two different frequencies of motion to cause the same discomfort is dependent on duration of the exposure. A third experiment used five exposures with equal values for duration, frequency and average acceleration, although varying in their configuration of peak acceleration amplitude and number of pulses. Regardless of the constant root mean square (r.m.s.) acceleration level of the five different motions, the pulsed motions with the highest peak values caused the greatest discomfort (Griffin and Whitham, 1980). In addition, by characterizing the relation between subjective discomfort and number of pulses for short duration exposures, an exponent of 4 was determined for the integration of acceleration with respect to time. It was reasoned from the results of the first experiment that the rate of increase in discomfort with duration is dependent on frequency. Hence, if the slopes obtained in the first experiment (0.29 to 0.45) apply to exposures of longer duration, then the shapes of equivalent contour curves for frequency depend on the duration of exposure. Overall, these results indicated that the degree of discomfort experienced by motion is dependent on the duration of the exposure (Griffin and Whitham, 1980).

Kjellberg and Wikstrom (1985) investigated the effect of the duration of transient vibration to determine an appropriate evaluation method for exposure to mechanical shocks. In operating environments, subjective response is dependent on both the mean amplitude of the motion and the presence of high amplitude transient waveforms (Kjellberg and Wikstrom, 1985). The duration of a transient waveform influences the perception of the impulse, and thus affects the strength of discomfort perceived by the exposed person. This occurs because the duration of the transient waveform influences the resulting displacement and velocity, which in turn affect perception of discomfort.

It is important to understand the effect of duration, in the form of a 'critical time', and the rate of growth of subjective discomfort. One of the specific objectives of the study by Kjellberg and Wikstrom (1985) was to examine how discomfort due to vibration increased as a function of duration from zero to a few minutes. In order to examine the effect, three experiments were designed to expose seated subjects to z axis vibration of varying durations. The first experiment exposed subjects to 31.5 Hz motion for durations of 0.1 to 4.0 seconds, at an acceleration level of 1.1 or 2.3 ms^{-2} in the z axis. A second experiment contained the same vibration characteristics, but extended the duration to 128 seconds. These two experiments demonstrated that subjective response increased with duration up to approximately 3 to 4 seconds, defining a 'critical time' after which discomfort still increased, but at a much lower rate. The third experiment attempted to examine the effect of frequency throughout a duration of 117 seconds by using two motions (equal overall strength) with two different frequencies (6.3 Hz, and 31.5 Hz), and two different amplitudes (1.1 and 2.3 ms^{-2}). The 31.5 Hz motion exhibited increasing discomfort with duration and demonstrated a 'critical time'. The discomfort with 6.3 Hz motion showed a slower growth rate than with 31.5 Hz motion, and demonstrated no 'critical time'. The results indicated that frequency had an effect on the influence of duration on subjective discomfort.

Another finding was that the regression coefficient was below 0.5, suggesting that the r.m.s. method of averaging exposure acceleration underestimates the influence of shocks (Kjellberg and Wikstrom, 1985). These conclusions support the idea that discomfort increases with increasing exposure time. However, the rate of increase of discomfort and the presence of a 'critical time' are dependent on amplitude and frequency.

Howarth and Griffin (1991) examined subjective reaction to vertical mechanical shocks of various waveforms. Two experiments were designed to assess discomfort from exposure to mechanical shocks in the z axis . The first experiment tested the influence of frequency and duration on the growth of discomfort with increasing single shock amplitude. The experiment used 1, 4 and 16 Hz motion, with vibration dose values (VDV) of 0.6 to 4.0 $ms^{-1.75}$, through a range of durations from 0.1 to 4.0 seconds. For a definition of the VDV, refer to the section entitled 'British Standards Institution document 6841'. To obtain subjective discomfort, the method of magnitude estimation was used. The relation between the median magnitude estimation and VDV was determined, which was described by the equation:

$$\psi = k\varphi^n$$

where ψ is the median magnitude estimate, φ is the vibration dose value, and exponent n describes the rate of growth of subjective magnitude with increasing objective magnitude. This function can be used to describe the relation between objective and subjective magnitude (Howarth and Griffin, 1991). A change in the value of the exponent as a function of duration of exposure would indicate that the rate of growth of discomfort with duration of exposure is dependent on the magnitude of the exposure (Howarth and Griffin, 1991). However, the results indicated that there was no significant effect of duration on the value of the exponent n. This suggested that a single method of weighting the effect of duration may be appropriate in the evaluation of shocks, regardless of magnitude (Howarth and Griffin, 1991).

Summary of the Effect of Duration of Exposure

It has been well demonstrated that subjective response is dependent on duration for short exposures (Miwa, 1968; Griffin and Whitham, 1980; Kjellberg and Wikstrom, 1985). Miwa showed a time dependency up to 2.0 seconds, after which the discomfort ceased to increase. Griffin and Whitham (1980), however, demonstrated a time dependency up to 30 seconds without indication of a 'critical time'. This finding was supported by Kjellberg and Wikstrom (1985) with durations of 117 seconds.

In terms of applying the findings of these studies to the evaluation of the effects of mechanical shocks, there are limitations concerning the methods employed. The effect of duration needs to be tested throughout a more realistic range of exposure times. A range of durations of exposure that is commonly experienced in operational environments would give an indication of the short term (several minutes) and long term (several hours) dependence of subjective discomfort on duration of exposure. Each of these periods would exert effects on the exposed person, thus requiring knowledge of the short term influence of duration on the evaluation of acceleration waveforms. In relation to the effect of mechanical shocks, each shock, or period of time containing a shock, can be considered to exert an effect on subjective discomfort. Duration, in the form of the time in which the shock is delivered, as well as the time over which the shock is evaluated, has been demonstrated to be an important variable. However, over a long duration exposure, the effects of these smaller periods must be summated. It has been suggested that there are existing recovery processes occurring during exposure which influence the long duration effects of mechanical shocks (Roddan *et al.*, 1995). Although data which have been obtained in relatively short duration experiments are valuable in describing the short term human response to a shock or sub-period of exposure to motion, more experimentation is required to describe the long term response. Data from these experiments would contribute to the development of a relation for the prediction of the effects of long term exposures. In addition, the levels of amplitude which were used in previous studies were relatively low compared to the shocks commonly experienced in operational environments. Therefore, there is uncertainty in extending the application of their data to long term operational conditions involving high amplitude, repetitive shocks.

Research directives need to be formulated to comprehensively assess the influence of duration on the effects of repeated mechanical shocks. This would include exposure to high amplitude shocks, in the three axes, throughout a full range of frequencies and duration of exposure which are representative of operational environments.

Effects of Frequency of Exposure Waveform

The frequency content of motion waveforms is an important variable affecting the human response to motion. The shape of the acceleration waveform determines the degree to which the forces exerted by motion are transmitted to the body (Griffin, 1990). Similarly, the resulting effects in the body are determined by the frequency composition of the input waveform.

Much of the early investigation on subjective response to vibration focused on the effect of frequency. Relevant literature includes vast range of equal contour curves which provide the equivalent perceived comfort level across a frequency range. Contours have been developed for many conditions and involve many variables which affect the comfort response.

In the z axis, for seated subjects, equivalent contours for subjective comfort over a range of frequencies from 0.01 to 100 Hz have been compiled from various studies. Overall, it seems apparent that comfort is most affected between approximately 5 to 6 Hz (Griffin, 1990). This implies that with respect to comfort, a whole-body resonance exists in the z axis for the seated human body. Sensitivity decreases as vibration moves into higher frequencies. Very low frequencies (< 1 Hz) are also associated with increased discomfort, specifically with motion sickness. Studies concerning the subjective response of seated humans to vibration in the x axis indicate that people are more sensitive at frequencies less than 4 Hz. Above this level, it appears that subjective response decreases linearly with frequency (Griffin, 1990). In the y axis, a number of studies indicate that the intensity of subjective response decreases in a linear fashion with frequency above 2 Hz (Griffin, 1990). Similar to the x axis studies, the most severe subjective response was found to be at the low frequency range, below 2 Hz.

Problems exist in the acceptance of these frequency response phenomena for use in evaluating exposure to mechanical shock. There is a great deal of variation between the subjective response contours obtained from the various studies. This can be attributed partially to the differences in experimental methods. The contours were obtained at different amplitudes of vibration, with different seating geometries and various footrest and backrest conditions. In addition, different psychophysical methods were used, the subject groups had different characteristics, and the experiments used vibration stimuli of varying quality (Griffin, 1990). In the light of such uncertainty, caution should be exercised in using such data for the development of evaluation methods and standards. However, such information offers an indication of the relative discomfort experienced in the biodynamic axes at various frequencies. In addition, it provides a basis for further research to define a more accurate frequency response.

The application of these findings for evaluating the effects of repeated mechanical shocks should be regarded even more tentatively. Although resonance is implied at the frequencies which reflect maximum sensitivity, the amplitudes at which discomfort was tested were relatively low (0.1 to 10.0 ms^{-2} for z and y axis; 0.05 to 30.0 ms^{-2} for x axis). Mechanical shocks commonly experienced in operational conditions often reach levels of up to 50 ms^{-2} (Wikstrom *et al.*, 1991). To imply that the same relation exists for the response to mechanical shocks, it must be assumed that a linear relation exists between subjective discomfort and the amplitude of experienced motion at various frequencies.

Subjective responses to motion have been presented in the form of tolerance to motion of varying frequencies. A series of relatively short term experiments were conducted to define the subjective tolerance to sinusoidal WBV at different frequencies (Magid *et al.*, 1960). The experiments tested the maximum amplitude of acceleration that could be tolerated during three different exposure periods: short duration, one minute, and three minutes. The subjects were exposed to motion in the z axis in the frequency range of 1 to 20 Hz. Tolerance limit was defined to the subjects by the investigators as the point at which the subject feels that bodily harm will occur. The results demonstrated that subjective tolerance varied with frequency with maximum sensitivity occurring in the range of 4 to 8 Hz. Sensitivity decreased with increasing and decreasing frequencies outside that range (Magid *et al.*, 1960) (Figure 2).

In addition, perceptions of pain and discomfort were reported in the form of the criteria for terminating the exposure, i.e., reaching tolerance. These perceived tolerance criteria symptoms were tabulated for each frequency, and indicated several dominant sensations.

Chest and abdominal pain was significant at 3 to 9 Hz., dyspnea from 1 to 4 Hz., and a general discomfort at all frequencies. It was noted that sensations were classified in relation to frequency, reflecting that resonance of parts of the body play a role in determining subjective response. From these results, it was suggested that subjective response may be utilized in defining mechanical and physiological effects occurring from vibration (Magid *et al.*, 1960).

These results are encouraging for use in the evaluation of repeated mechanical shocks. The amplitudes tolerated were between 20 to 70 ms^{-2}. These levels of mechanical shocks are closer to the level experienced in operational conditions, and therefore more applicable. In light of the relation between sensation and frequency, the subjective response can be considered valuable in predicting health effects of exposure to motion. However, the experimental range of frequencies over which subjective tolerance was defined was limited. Furthermore, there is only one data point above 10 Hz and the study has relied on interpolation of the data from 10 to 20 Hz. In addition, the seating conditions were specific to the environment in which this experiment was performed. A modified jet seat was used, involving the use of a backrest, lap and shoulder harnesses, and the subject was permitted to grip handholds on the chair for bracing purposes. Posture has a strong influence on the response to motion (Griffin, 1990). By permitting the subjects to grip the armrests of the seat, the viscoelastic (spring and damper) characteristics of the upper body are modified. The combination of these factors would undoubtedly change the mechanical responses of the body, and subsequently alter the subjective response. Thus, with respect to evaluating the effects of mechanical shocks, the results of Magid *et al.*, (1960) describing the frequency response should be considered tentatively. However, the method employed by Magid *et al.*, (1960) could be developed further to determine an accurate and comprehensive frequency response to mechanical shocks.

A study by Howarth and Griffin (1991) examined subjective reaction to vertical mechanical shocks of various waveforms. The relation between the median magnitude estimation and VDV was determined and used to describe the relation between subjective and objective magnitude (Howarth and Griffin, 1991). The results indicated that frequency weightings used for the assessment of subjective response to mechanical shock were independent of shock amplitude. Therefore, it was suggested that a single frequency weighting could be employed for all amplitudes of shock (Howarth and Griffin, 1991).

The limitations of these findings exist in the experimental conditions which were employed. Firstly, only three frequencies were actually tested (1, 4, and 16 Hz). The few frequencies tested seem inadequate to confirm that the existing frequency weightings accurately assess the severity of shocks, regardless of shock amplitude. In addition, the experiments were carried out using relatively low amplitude shocks (maximum VDV 4.0 $ms^{-1.75}$) and using very short duration exposures (0.1 to 4.0 seconds).

Summary of the Effects of Frequency of Exposure Waveform

It has been well demonstrated that the subjective response to motion is highly dependent on the frequency of the waveform (Magid, 1960; Griffin, 1990). A combined review of studies examining subjective response to relatively low amplitude vibration indicated that the maximum sensitivity is observed between 5 to 6 Hz, with progressively decreasing sensitivity with higher and lower frequencies (Griffin, 1990).

An encouraging finding from the experiments of Magid *et al.* (1960) was that physical sensations and pain were associated with certain frequencies. This supports the use of subjective response in the evaluation of mechanical shocks. The relation between subjective response and objective evaluation of shocks was supported by the findings of Howarth and Griffin (1991). They concluded that a single frequency weighting could be used for shocks of all amplitudes.

It is apparent from these findings that the subjective response to frequency is well described and justifies the frequency weightings employed to evaluate vibration. However, further research is required before the knowledge can be applied confidently to the evaluation of repeated mechanical shocks. It is suggested that the frequency response should be determined for shocks of relatively high amplitude, and over a comprehensive range of frequencies which are indicative of those experienced in operational conditions. This would define a frequency response specific to exposure to mechanical shocks. In addition , to provide support for the use of subjective response in procedures for the evaluation exposure to mechanical shock, the associated objective measures of the human response (e.g., biomechanical and physiological) should be determined simultaneously.

Evaluation Methods and Biodynamic Models for Exposure to Motion

There are several existing methods of evaluating the effects of exposure to motion: the British Standards Institution document BS 6841 (1987); the Air Standardization Coordinating Committee (ASCC) Methodology for Repeated Shocks (ASCC, 1982); and the International Organization for Standardization document ISO 2631 (1985). These three methods were originally developed for specific purposes and applications. However, attempts have been made to extend the application of these methods to the evaluation of repeated mechanical shocks.

Additionally, several biodynamic models exist which attempt to characterize the human biodynamic response to acceleration input at the seat. The Dynamic Response Index (DRI) (ASCC, 1982) is applicable to shocks in the z axis. However, other versions of the DRI have been formulated which may be applicable to motion in the x and y axes (Payne, 1984). The Fairley-Griffin model is another model which predicts the human biomechanical response in the z axis (Fairley and Griffin, 1989).

British Standards Institution Document 6841

The BS 6841 (1987) deals specifically with WBV. However, in an appendix the BS 6841 recommends the use of the vibration dose value (VDV) when an exposure includes mechanical shocks.

The VDV involves integration of the frequency-weighted acceleration, with respect to time (Griffin, 1984), represented by the following equation:

$$\mathrm{VDV}=\left[\int_0^T a^4(t)dt\right]^{1/4}$$

where *a,* is the frequency weighted acceleration. The VDV of a shock is proportional to the amplitude of the shock and the fourth root of the shock duration (or number of shocks within the duration). Thus, by increasing the amplitude of shocks present in the exposure by a factor of two, the VDV is increased by a factor of two. However, to increase VDV by a factor of two, when both shock amplitude and rate are constant, the duration of exposure must be increased by a factor of 16. The VDV incorporates the influence of acceleration waveform frequency and input axis through the use of a set of frequency weighting curves. The VDV can be accumulated over a single duration of exposure or several exposures to provide a daily dose value. It has been claimed that the VDV is applicable for the evaluation of the full continuum of motion from isolated shocks to long duration random vibration (Griffin, 1990).

The literature concerning the evaluation method employed by the BS 6841 (1987) suggests that the VDV is applicable to the evaluation of repeated mechanical shocks. Using the subjective response, it has been demonstrated that an exponent of 4 is appropriate for the evaluation of impulses and shocks (Griffin and Whitham, 1980; Hall, 1987; Wikstrom *et al.,* 1991; and Howarth and Griffin, 1991). The VDV has also been shown to give accurate evaluations of shock and impulse acceleration independent of the duration of exposure (Hoddinott, 1986; Hall, 1987; Wikstrom *et al.*, 1991; Howarth and Griffin, 1991).

These results support the use of the VDV to evaluate repeated mechanical shocks. However, the experimental conditions under which the relation was tested were limited. Firstly, acceleration amplitudes used to examine the VDV were low when compared to the levels commonly experienced from mechanical shocks in operational environments (Hoddinott, 1986; Hall, 1987; Wikstrom *et al.*, 1991; and Howarth and Griffin 1991). Secondly, although the VDV was effective in assessing the subjective response to short duration exposures, the ability of the VDV to evaluate long duration exposures has not been investigated. The effects of suggested biological recovery processes occurring during long duration exposures have not been evaluated (Roddan *et al.*, 1995). In addition, the influence of fatigue processes has not been considered.

ASCC Ride Comfort Methodology

The ASCC methodology of assessing repeated shocks is based on the assumption that discomfort is proportional to the peak mechanical load (or stress) in the human body (Payne, 1992). The method also assumes that physical injury occurs at a critical load (or stress). Objective measurements of mechanical impedance and apparent mass induced by various types of vibration suggest that the human body behaves as a single degree of freedom, lumped parameter system (Payne, 1992). The DRI is a simple linear model originally developed to simulate the severity of vertical shocks and potential for spinal injury resulting from aircraft ejection (Payne, 1992 and 1994). It is composed of a mass, spring, and damper system, which relates the peak deflection of the spring to a mechanical stress (Figure 3).

The DRI is described by the equation:

$$\mathrm{DRI} = \omega^2\delta / g$$

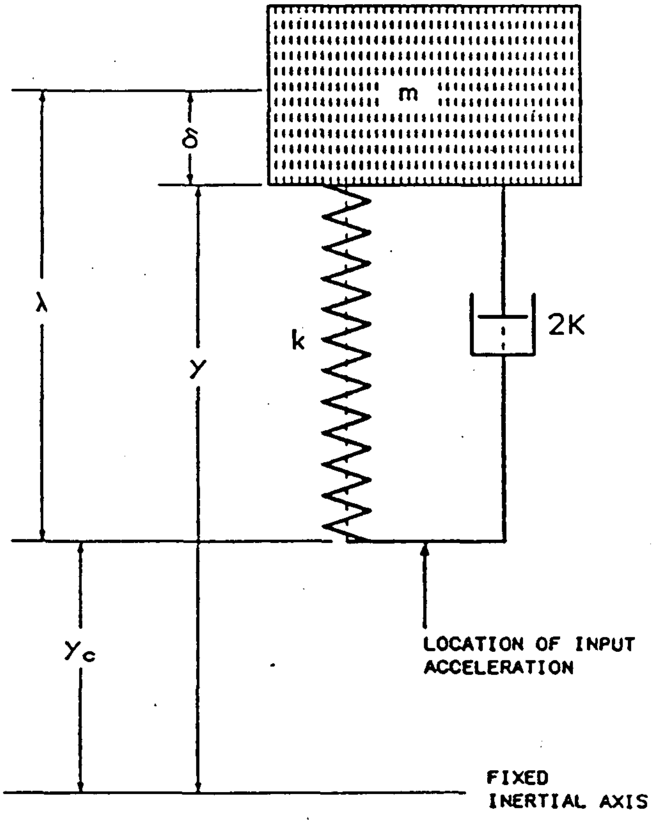
where, ω is the undamped natural frequency of the system, δ is the spring (compressive) deflection, g is the gravitational force on the mass.

Since the DRI has the ability to predict injury from single vertical shocks, it was reasoned that it could be used in ride comfort methodology for assessing the discomfort level from repetitive shocks (Payne, 1994). To be useful in the evaluation of repeated mechanical shocks, the ASCC methodology employs the assumption that fatigue-induced failure of biological material is a result of cyclic exposure to peak stresses (Sandover, 1986). Thus, for a certain magnitude of stress (or strain reflected by spring deflection of the model), material fatigue failure will occur after a specific number of cycles.

This is described by the equation:

$$N = [\sigma_s/\sigma_p]^a$$

where, σ_s is the static failure stress, σ_p is the peak cyclic stress, N is the number of cycles to material fatigue failure, and a is the fatigue exponent.



Where:

m = mass

k = spring stiffness

2K = damping constant

δ = spring (compressive) deflection

Figure 3 **DRI linear biodynamic model based on a mass, spring, and damper system.**

A dose function can then be described with a set of contour curves, outlining a maximum allowable cumulative DRI for a certain number of cycles, or shocks, based on injury data. These contour curves describe various levels of exposure limits (i.e., severe discomfort, 5% injury rate, etc.).

There is compelling incentive to employ the DRI for such evaluation based on the fact that the DRI was developed from objective measures in response to shock acceleration producing injury (Payne, 1992). In addition, it has been suggested that the model is more relevant to evaluating the human response to shock, as it was developed using high acceleration amplitude data (Payne, 1992).

However, the ability of the ASCC (using the DRI) to accurately evaluate subjective response to repeated mechanical shocks is unsupported by existing research. Payne (1992) suggested that the DRI limits agree with subjective response data from previous experiments performed with sinusoidal vibration. Payne *et al.*, (1994) also demonstrated the DRI was able to accurately evaluate subjective response to single shocks (using previously obtained data of Cole (1978) and Brinkley (1990)). Questionable analysis methods were used to determine correlations between the DRI and subjective response. In addition, limitations of experimental methods employed by the original experimenters existed, such as seating conditions (e.g., subjects were allowed to grip armrests and were restrained by a harness system). Also a limited range of shock amplitudes, shock frequencies, and shock input directions were used. Hence, the data is inadequate to support the use of the DRI to assess the subjective effects of repeated mechanical shocks.

International Organisation for Standardisation Document 2631

In an attempt to set standards which limited exposure to vibration, the International Standards Organization document (ISO 2631) was published in 1974, with revisions in 1978 and 1985. The ISO 2631 was formulated based on the results of early investigations on subjective response (subjective tolerance and discomfort) to sinusoidal WBV. It provided limits for exposure to WBV, in relation to the effects on comfort, performance and health (Griffin, 1990).

Although useful to assessing passenger comfort involving steady-state WBV, the ISO 2631 contains certain limitations. One concern is the complex time dependency for exposure limits. There is no documentation of its rationale or origin (Griffin, 1990). The ISO time dependency allows extremely high exposure levels for short durations. However, for 24 hour exposures the acceleration limit is well below motion experienced without harm on any transportation system (Griffin, 1988). Another limitation is the use of the r.m.s. averaging procedure, which is dependent on the duration of the integration period. The measurement of acceleration must be performed during a period of exposure which is indicative of the typical exposure. This meets with increasing difficulty when non-stationary exposures, or exposures with high amplitude transients are to be assessed. The r.m.s. method of evaluation has been found to underestimate the influence of high amplitude pulses or shocks, indicating that an exponent of 2 is not appropriate for motion containing mechanical shocks (Griffin and Whitham, 1980; Hoddinott, 1986; Hall, 1987). This is recognized by the ISO 2631 which states that the vibration limits it provides should be regarded very tentatively for vibration having crest factors greater than 6 (Howarth and Griffin, 1991), where the crest factor is defined as:

$$\text{Crest Factor} = \frac{\text{peak acceleration}}{\text{r.m.s. acceleration}}$$

In review of these limitations, it is apparent that the ISO 2631 is not an appropriate method of evaluation of repeated mechanical shocks.

Biodynamic Models

The DRI applicable to motion in the z axis was originally developed to have a natural frequency of 8.4 Hz and a critical damping ratio of 0.224. The DRI has since been revised and now has a natural frequency of 11.9 Hz and a critical damping ratio of 0.35. In addition to the DRI for the z axis, versions have been developed for the x and y axes (Payne, 1984). The DRI for the x axis has a natural frequency of 10 Hz and a critical damping ratio of 0.15, whereas the DRI for the y axis has a natural frequency of 7.2 Hz and a critical damping ratio of 0.15. These versions were developed from data obtained in experiments concerning aircraft seating and restraint systems (Brinkley, 1981).

The Fairley-Griffin model was developed from experiments which exposed 60 seated subjects (24 male, 24 female and 12 children) to 1.0 ms^{-2} sinusoidal vibration across a frequency range of 0.25 to 20 Hz. The apparent mass was determined to characterize the frequency response of the upper body. Apparent mass was determined from the force and acceleration at the seat-person interface, expressed as:

$$\text{Apparent Mass} = \frac{\text{force at the seat-person interface}}{\text{acceleration at the seat-person interface}}$$

The results demonstrated a major resonance of the upper body at 5 Hz (Figure 4). From these data, a linear lumped-parameter model was developed including a natural frequency of 5 Hz and a critical damping ratio of 0.475 (Fairley and Griffin, 1989).

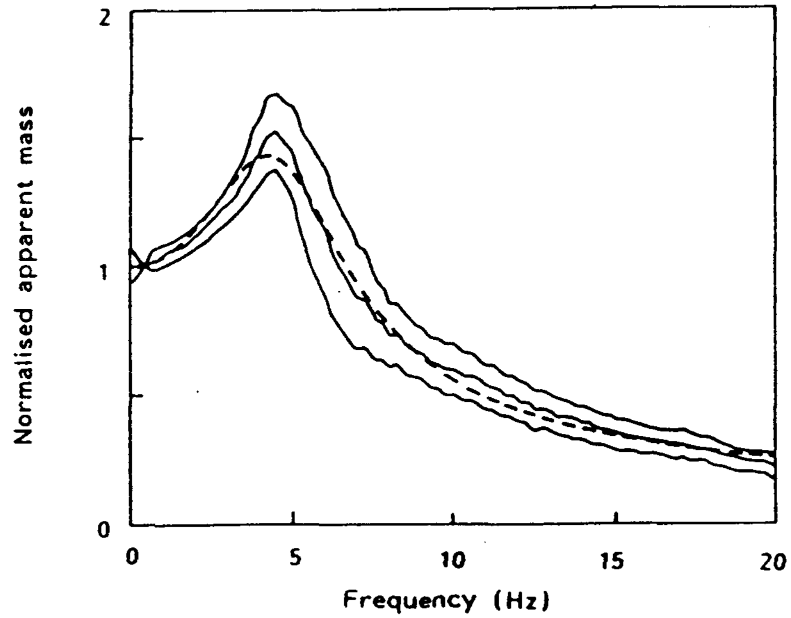


Figure 4 **Apparent mass as a function of vibration frequency (Fairley and Griffin, 1989).**

Although the model has been successful at predicting the human biodynamic response to low amplitude sinusoidal vibration, it may not be applicable to evaluating high amplitude mechanical shocks. In addition, the model does not account for the effects of factors which affect the biodynamic response such as posture, seat backrests, or muscle tension.

Limitations and Implications of the Existing Literature

It is apparent that limitations exist regarding the understanding of subjective response to repeated mechanical shocks. Previously, subjective response to motion has been examined using inadequate levels and ranges of parameters of motion (i.e., shock amplitude, shock frequency, shock input axis and duration of exposure). In addition, the associated objective response has been inadequately described in relation to subjective response.

Research directives should be focused on determining an improved relation of subjective response to repeated mechanical shock, and the associated objective response. Results may then be used to evaluate existing methods of quantifying the effects of repeated mechanical shock exposure, and to determine whether modifications to theoretical relations contained in their frequency weightings and accumulated dose theory are necessary.

STATEMENT OF THE RESEARCH PROBLEM

Objectives

The overall objective of the present study was to determine subjective response to mechanical shocks. This involved examining subjective response to exposure to mechanical shocks containing realistic ranges of parameters of motion including shock amplitude, frequency, axis, direction and duration of exposure. The specific objectives of the experiments included:

- Determining subjective severity of high amplitude single shocks, in all biomechanical axes and directions, over a comprehensive range of individual shock frequencies.
- Establishing the correlation between subjective response to individual mechanical shocks and the output of existing biodynamic models and filters (BS 6841 frequency weighting filters; Dynamic Response Index model; and Fairley-Griffin model).
- Establishing the correlation between subjective response to mechanical shocks and the resultant acceleration measured at the spine.
- Determining the effect of shock axis, direction, amplitude and rate on subjective response to repeated mechanical shocks.
- Determining the effect of rest intervals on subjective response to repeated mechanical shocks over a long duration.
- Determining the time dependency (hourly, daily and weekly) of subjective response to repeated mechanical shocks.
- Examining the relation between the VDV and subjective response to long-term mechanical shock exposure.

Hypotheses

The hypotheses tested were:

- The subjective response to mechanical shock is non-linear with respect to the amplitude and frequency of the shock waveform.
- The subjective response to mechanical shocks, as a function of frequency and amplitude, is representative of the associated biomechanical response.
- Rest intervals during exposure to mechanical shocks will cause recovery in the indices of subjective response.
- The time dependencies of existing dose functions do not accurately represent the subjective response to exposures of mechanical shocks.

Significance of the Study

It is intended that the results of the present study will contribute to the development of more accurate methods of evaluating exposure to mechanical shocks. The International Organisation for Standardisation is moving toward developing a new methodology for evaluating exposure to mechanical shocks. Determining the effect of shock frequency will contribute to improved parameters for predictive models (natural frequency, damping coefficient). An improved description of the influence of the axis of input shock will be valuable in extending current models for evaluation to exposures containing shocks in all three axes. The influence of rest intervals during long term exposures will help assess the effects of recovery processes. The effect of rest intervals is not addressed by current methods, and may be incorporated into a model for evaluating the dose of exposure. The effect of the duration of exposure on subjective response will help to assess computational methods for calculating exposure dosage. The study will provide information concerning the influence of shock amplitude, particularly whether the response to mechanical shocks is linear or non-linear with increasing amplitude across the range of tested shock frequencies. Another contribution of the present study will be to determine whether subjective response is highly correlated with associated biomechanical responses (transmission of acceleration). In addition to testing the ability of existing evaluation methods and biodynamic models to assess mechanical shock exposures, the study will contribute to the development of an accurate dose-response model to limit exposure.

METHODOLOGY

The study was subject to review by the following committees: Ethics Review Committee, Simon Fraser University; Scientific Review Committee, United States Army Aeromedical Research Laboratory; Human Use Review Committee, United States Army Aeromedical Research Laboratory; and Human Subjects Research Review Board, Office of the Surgeon General of the United States.

Subjects

The subject pool consisted of 54 volunteers from the US Army assigned to Fort Rucker, AL. All subjects were fit, and between the ages of 19 and 40 years old. Subjects were fully informed of all possible risks and outcomes prior to their participation in the experiments. The subjects all had previous experience with exposure to motion (e.g., military vehicles and aircraft).

Exposure to Motion

A Multi Axis Ride Simulator (MARS, Schenk Pegassus, Detroit) was used to produce the exposures. The MARS has a frequency range from 2 to 40 Hz and a maximum displacement range of ± 3.5 inches. It incorporates hydraulically driven actuators in each axis which control the amplitude and frequency output during operation. The vibration frequency and acceleration amplitude are determined from a pre-recorded synthesized input signal. The output acceleration signal at the MARS is corrected for the table by means of a correction matrix and an iterative process in which the input signal and output signals are compared for quality of fit. The desired acceleration signatures were developed and then input to the MARS in the form of command signals for displacement. The output acceleration was measured at the motion platform and corrected by iteration to produce an acceptable fit. Control signals were then stored in the DEC-PDP11 computer system at the MARS facility.

A solid metal seat was securely mounted on the MARS platform and a bean-bag taped on top of the seatpan. The seat did not have a backrest, since it was determined from communication with US Army Aeromedical Research Laboratory (USAARL) personnel that most drivers and occupants of

TGVs do not utilize a backrest. The seat was adjusted so that the subject's feet rested comfortably on the MARS platform with the knees and hips at approximately 90°, while the subject sat in an upright posture. The bean-bag was moldable to provide a seat-person interface which equally distributed the weight of the subject. This provided a relatively comfortable seat, without altering the input acceleration signal with a cushion. The bean-bag was taped firmly to the metal seatpan in order to minimize lateral shear effects between the seat and the bean-bag.

Motion Signatures

A motion signature is a continuous signal containing a series of acceleration waveforms (shocks) at discrete time intervals delivered by the MARS. The motion signatures input to the table were based on real motion data from TGVs analyzed in a previous study (Roddan *et al.*, 1995). Due to the limitations of the MARS, shock amplitude was limited to 4 g. Shocks of 0.5 and 1 g were generated with waveform frequencies between 2 and 20 Hz. However, also due to MARS limitations, 2, 3 and 4 g shocks had frequencies between 4 and 20 Hz. Figures 5a and 5b demonstrate examples of the type of motion signature used in the experiments, and the accompanying spectral density for each signal. The spectral density plots represent the frequency content of the shocks (damped sinusoidal waveforms) alone without any background vibration. Although the spectral density plots clearly show that the maximum energy is located at the nominal frequency of the motion signatures, the frequency resolution of the plots is limited by the finite duration of the shock waveforms. Thus the frequency resolution for the 20 Hz shock (T=50 ms) is lower than for the 4 Hz shock (T=250 ms).

Control records of up to 327 seconds were generated and reproduced on the MARS system. The digital control sequence for each axis was prepared using a number of programs developed on the GEDAP (Generalized Data Acquisition/Analysis Programs) software system. Generation of the desired motion signatures required development of control signals for the MARS that incorporated the background vibration with the superimposed shock waveforms. For experiments of longer duration, short motion signatures (300 seconds) were sequentially repeated to provide a relatively continuous exposure to motion.

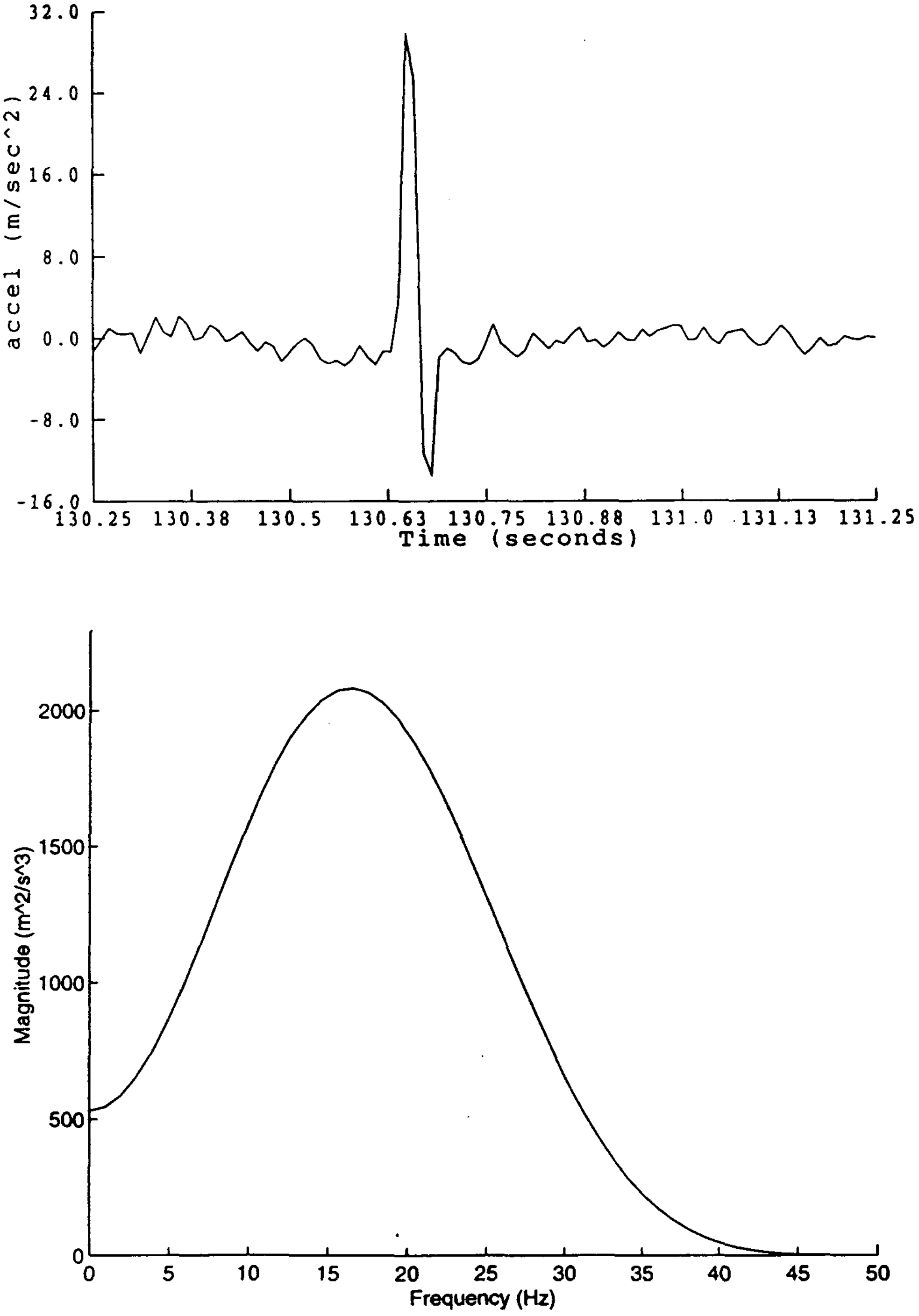


Figure 5a One-second segment from a motion signature including a 4 g, 20 Hz shock waveform, and the accompanying spectral density.

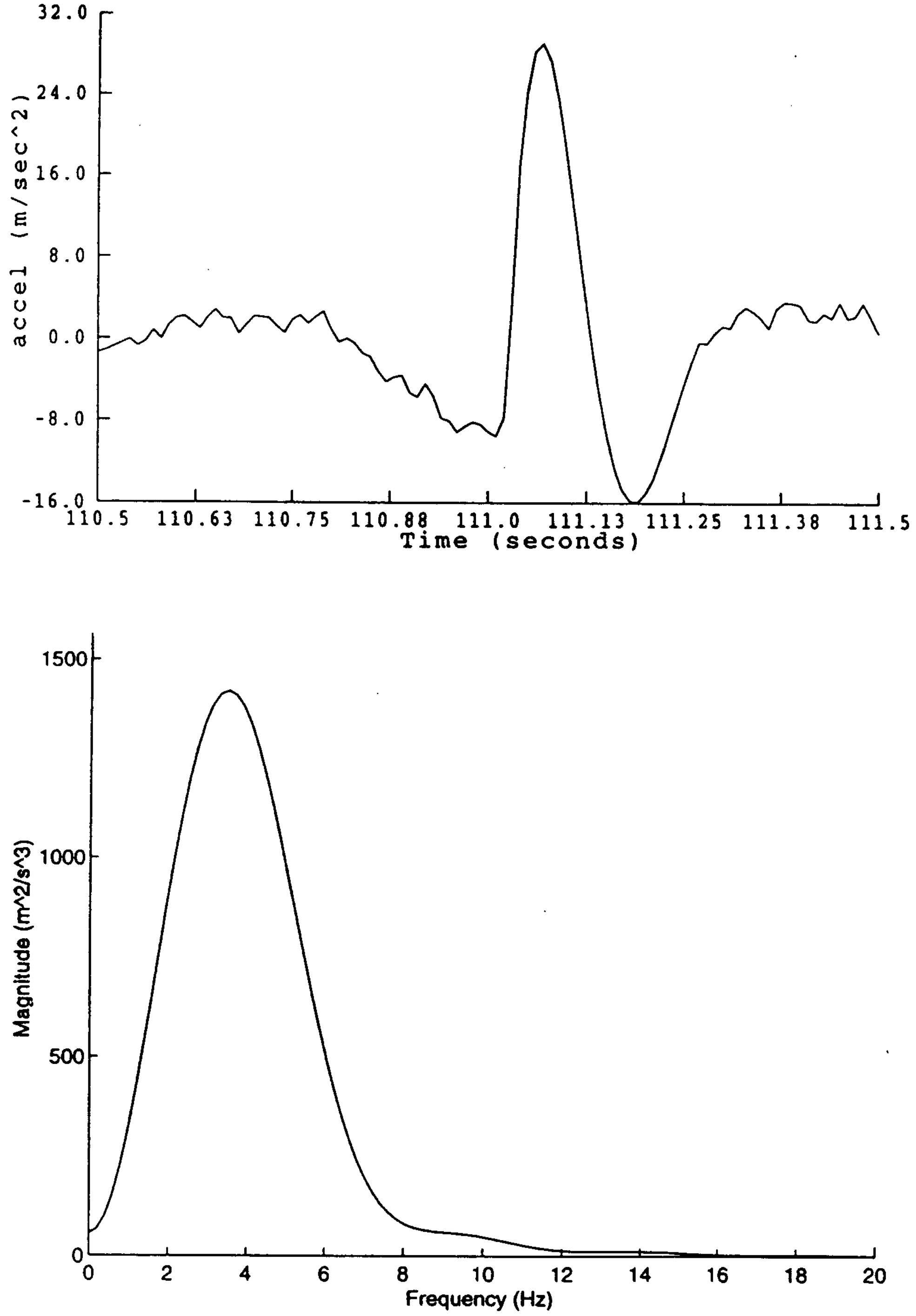


Figure 5b One-second segment from a motion signature including a 4 g, 4 Hz shock waveform, and the accompanying spectral density.

Overview of Experimental Design

The experiments in the present study were designed to examine both the human response to single mechanical shocks, and the response to repeated shock exposures. The short term experiments were designed to evaluate the human response to mechanical shocks over a comprehensive range of shock frequencies, acceleration amplitudes and in each biodynamic axis and direction. Short term experiments consisted of only one series of experiments (ST1). The response curves generated from these experiments may be used to characterize frequency weighting curves.

The long term (LT) experiments were a series of five different experiments (LT1 to LT5) designed to evaluate the response to long duration repeated mechanical shock exposures of different axes, amplitudes, duration and direction. The LT experiments also involved examining fatigue and recovery effects as well as the ability of the VDV to assess long duration exposures. These findings may contribute to the development of a dose-response model for evaluating exposure to mechanical shocks.

Design of Experiments

Short Term Experiment 1

Motion signatures were prepared with individual shocks having a range of amplitudes from 0.5 to 4 g and frequencies from 2 to 20 Hz in the +x, -x, +y, +z and -z directions. Each signature was 327 seconds in duration and contained shocks of the type listed in Table 1, presented in random order (maximum of 34 shocks per signature).

The responses to positive and negative shocks were expected to differ in the x and z axes, due to the asymmetrical nature of the musculoskeletal system in those directions. Hence shock signatures were presented separately in both positive and negative directions for the x and z axes. As the body is symmetrical about the saggital plane (lateral movement), y axis shocks were presented in a single direction.

Table 1 **Shock Characteristics in Experiment ST1.**

Amplitude (g)	Frequency (Hz)							
0.5	2	4	5	6	8	11	15	20
1	2	4	5	6	8	11	15	20
2		4	5	6	8	11	15	20
3		4	5	6	8	11	15	20
4		4	5	6	8	11	15	20

Each of the types of shock shown in Table 1 was presented twice for each shock direction. To present this number of shocks, 3 separate shock signatures of approximately 5.5 minutes were designed to complete the shock pattern in one axis and in one direction. The 3 signatures were presented to the subjects in each of the five directions, resulting in a total of fifteen shock signatures. The shock amplitudes contained in each signature were organized according to Table 2. The order of presentation of shock frequencies was random within each signature. The interval between shocks ranged from 7 to 13 seconds.

Table 2 **Summary of shock signatures for experiment ST1.**

Shock Amplitudes	Axes	Duration of each Signature (minutes)	Number of Signatures*
0.5 and 1 g shocks	+x,-x, +y,+z,-z	5.5	5
2 g and 3 g shocks	+x,-x, +y,+z,-z	5.5	5
4 g shocks	+x,-x, +y,+z,-z	5.5	5

A 20 second warm-up period containing 2 shocks was included in each signature. These data were not included in the analysis. Each subject experienced a maximum of 7 signatures per day (1 axis, positive and negative directions, plus the swept sinusoid). Signatures were separated by a 2.5 minute rest period. Including rest periods, the total time a subject was seated on the MARS was approximately 60 minutes, with an exposure of 35 minutes per day. Each subject completed 3 sessions (one for each axis) on separate days, with a minimum of 48 hours between each session.

Eleven subjects participated in this protocol of whom ten completed the experiment. The subject who did not complete the experiment did not want to be exposed to all of the shock amplitudes and therefore was excused from the protocol.

Long Term Experiment 1

In the development of a health hazard assessment index for shock and vibration, it is necessary to develop a model to predict the cumulative dose of repeated shocks that may result in injury or chronic health effects. However, it is not ethical to expose subjects to a high enough dose to cause physical damage. In this experiment each subject was exposed to a short duration shock signature and asked to predict the amount of time that this type of motion could be tolerated in an operational environment. Comparisons were made between signatures having equivalent VDV, but containing shocks of different amplitudes, and delivered in different directions.

In all LT experiments, a single shock frequency (6 Hz) was selected in order to limit the number of variables in the experiments (i.e., shock frequency was kept constant). The frequency of 6 Hz was selected as an intermediate value between the peak response frequency observed in preliminary studies (4 Hz), and the natural frequencies of the Fairley-Griffin (5 Hz) and DRI (8.4 Hz) models (Fairley and Griffin, 1989; ASCC, 1982).

Five shock signatures were prepared to provide a VDV of 15 or 30 $ms^{-1.75}$, in the z axis. Identical shock signatures were then presented in each axis and direction. For each signature, the amplitude, shock rate and VDV are listed in Table 3. Note that for comparative purposes, identical shock amplitudes were presented in each direction. The VDV given in Table 3 is the true VDV for the z axis. As the frequency weighting function of the x and y axes is different than the z axis, the true value of the VDV as described in the BS 6841 for the x and y axes would be lower than reported.

Table 3 Motion signatures for Experiment LT1. Each signature was repeated in +x, -x, +y, +z, -z, and combined x, y, z directions.*

Amplitude* (g)	Direction	Rate (shocks min^{-1})	Time (min)	VDV ($ms^{-1.75}$)
1	+x, -x, +y, +z, -z	128	3.75	14.5
2	+x, -x, +y, +z, -z	8	3.75	14.4
2	+x, -x, +y, +z, -z	128	3.75	29.1
2	combined x,y,z	128	3.75	29.1
4	+x, -x, +y, +z, -z	8	3.75	28.9
Daily Total			18.75	38.6

* A shock frequency of 6 Hz was used in all signatures.

Each subject participated in experiment LT1 on five separate days with a minimum of 48 hours rest between experiment days. On each experiment day the subject was exposed to five shock signatures separated by a ten minute rest. Of these five signatures, four presented shocks in a single direction (+x, -x, +y, +z, or -z), with a different direction being presented on individual days. The fifth signature was a combined x, y, z signature which was presented on each day to provide a consistent frame of reference.

Ten subjects participated in this experiment. To allow a rest period between signatures, two or more subjects rotated through the protocol simultaneously. During the final minute of each exposure, subjects were asked to estimate the maximum time the specific motion signature could be tolerated, and to rate their subjective comfort and the severity of the shocks.

Long Term Experiment 2

Experiment LT2 was designed as an extension of LT1 as part of the walk-up design for LT3 and LT4, and to examine the effect of longer duration exposures (120 minutes) with different axes, directions, shock rates and amplitudes (Table 4).

Each subject was asked to report his subjective responses (predicted tolerance time and subjective comfort, tiredness and severity) to the motion at regular time intervals throughout the 120 minute exposure. See the section entitled 'Procedures' for details.

Table 4 **Motion signatures for Experiment LT2.***

Amplitude (g)	Direction	Rate (shocks·min^{-1})	Duration (min)	VDV (ms$^{-1.75}$)
2 g	+y	32	120	48.3
2 g	-z	32	120	48.3
2 g	combined x,y,z	32	120	48.3
4 g	- x	2	120	48.3
4 g	+z	2	120	49.5

*A shock frequency of 6 Hz was used in all signatures.

Six subjects participated in experiment LT2. The total daily exposure time for each subject was 120 minutes. To complete all motion signatures, each subject completed a 120 minute session on five different occasions, separated by a minimum recovery period of 48 hours.

Long Term Experiment 3

Sustained operations in tactical ground vehicles may require soldiers to be exposed to a motion environment for prolonged periods of time. In order to simulate a vehicle ride representative of operational field conditions, a motion signature was created containing shocks in the positive and negative directions of all three axes (Table 5). The motion signature consisted of 2 g shocks delivered in the ±x, ±y, and ±z directions and 4 g shocks delivered in the +z direction. All shocks had a fundamental frequency of 6 Hz. During each five minute period, subjects were exposed to 128 shocks of 2 g amplitude (randomly distributed as 32 ±x, 32 ±y and 64 ±z) and 2 shocks of 4 g in the +z direction.

A total of 10 subjects participated in this protocol. Each subject was exposed to seven hours of motion in a single eight hour session which included three rest intervals.

The exposure consisted of 4 motion periods of 105 minutes. The motion periods were separated by a 15 minute rest interval at mid-morning, a 30 minute rest interval at approximately noon and a 15 minute rest interval at mid-afternoon. The rest intervals allowed the subject a reasonable opportunity for washroom, food and beverage breaks. The subject was exposed to a VDV of: 29 at 15 minutes; 41 at 60 minutes; 48 at 120 minutes; 57 at 240 minutes; and 66 at 420 minutes of exposure.

Table 5 Motion signature for Experiment LT3.*

Amplitude (g)*	Direction	Time (min)	VDV ($ms^{-1.75}$)
2 g	±x,±y,±z	420	66.1
4 g	+z		

*A shock frequency of 6 Hz was used in all signatures.

Each subject was instrumented with accelerometers. See the section entitled 'Procedures' for details. During the experiment, data were collected for 5 minutes every 30 minutes, resulting in 15 collections over 7 hours.

Subjects were asked to report their subjective responses to the effect of the exposure at 3.75, 15, 30, 60, 90, 120, 150, 180, 210, 240, 270, 300, 330, 360, 390 and 410 minutes. Each subject rated the severity of the shocks, their level of discomfort, their predicted tolerance time and their subjective tiredness.

Long Term Experiment 4

Subjects were exposed to four hours of motion each day on five consecutive days. In order to simulate operational field conditions, subjects were exposed to the same shock signature as in LT3, consisting of 2 g and 4 g shocks at 6 Hz in a combined x,y,z signature (Table 6). This resulted in a VDV of: 29 at 15 minutes; 41 at 60 minutes; 48 at 120 minutes; and 57 at 240 minutes. On each day, the exposure consisted of 2 motion periods of 120 minutes. The motion periods were separated by a 15 minute rest interval to allow the subject a washroom and beverage break. A total of 8 subjects participated in this protocol.

Table 6 Motion signature for Experiment LT4.*

Amplitude (g)*	Direction	Time (min)	VDV ($ms^{-1.75}$)
2 g	±x,±y,±z	240	57.4
4 g	+z		

*A shock frequency of 6 Hz was used in all signatures.

Each subject was instrumented with accelerometers and subjective responses to the effects of the exposure were obtained at 3.75, 15, 30, 60, 90, 120, 150, 180, 210, and 240 minutes.

Long Term Experiment 5

Operations in a TGV expose soldiers to an intermittent motion environment. A rest interval may allow soldiers to recover from the previous exposure to motion. In this event, then rest intervals could be an important component of operational procedures, whether they are naturally occurring or deliberately imposed. To investigate this type of exposure pattern, subjects were exposed to a series of 3.75 minute shock signatures, totaling one hour per day, with or without a rest interval between each 3.75 minute signature. A total of 10 subjects participated in this protocol.

Each subject was exposed to two motion conditions having the same maximum VDV (Table 7). The motion signature contained the same shock pattern as experiments LT1 and LT2 with 2 g shocks combined in x, y, z directions at a rate of 128 shocks min^{-1}. In one condition, a 3.75 minute shock signature with a VDV of 29 was followed by 7.5 minutes of rest. This was repeated over 16 cycles for a total exposure time of 60 minutes distributed over a three hour period. The other motion condition consisted of the same 3.75 minute shock signature repeated 16 times without rest periods This resulted in a continuous exposure of 60 minutes.

In both conditions the subject rated the severity of the shocks, their level of discomfort, their predicted tolerance time and their subjective tiredness after each 3.75 minutes exposure The VDV of each condition was 58. Subjects completed each exposure on separate days, with a minimum of 48 hours between exposures.

Table 7 Motion signatures for Experiment LT5.*

Amplitude (g)	Axis	Rate (shocks· min^{-1})	Time (min)	VDV ($\text{ms}^{-1.75}$)
2 g	combined x,y,z	128	60	58.2
2 g	combined x,y,z	128	16 cycles of: 3.75 motion 7.5 rest	58.2

*A shock frequency of 6 Hz was used in all signatures.

Procedures

Measurement Scale for Subjective Response Rating

Subjective response to motion was rated through as series of questions asked at specific measurement intervals in each experiment. A seven-point scale was used for determining the subjective response rating of comfort, tiredness and severity to shock exposures. Subjects rated the exposures from 1 to 7 (e.g., 1=barely perceptible; 7=extremely severe). A seven-point scale was used to obtain subjective rating for several reasons: the middle point provided a reference point for the subjects; seven points provided sufficient scale resolution; and ratings were easily obtained (did not require a reference stimulus and thus compatible with the protocol). In experiment ST1, to expand the accuracy of ratings of single shocks which were relatively close in frequency, a scale with gradations of 0.1 of a unit was presented visually to the subjects. For rating exposures to repeated shocks, a sample scale with gradations of 1.0 units was presented. Predicted tolerance ratings were obtained using an unrestrained time scale, and ratings were measured in hours of exposure. Appendix A includes subjective data forms which contain the subjective response semantic scales, the format of the questions and the measurement time intervals for short term and LT experiments.

Acceleration

Acceleration was measured at the seat, and at the skin over the spinous processes of the lumbar and thoracic vertebrae. Seat acceleration was measured in the x, y and z axes with three uniaxial accelerometers (EGAX, Entran Devices, ± 25 g) mounted in a triaxial accelerometer block within a molded epoxy seatpad, which was secured to the seat. Acceleration was measured with uniaxial accelerometers (EGAX, Entran Devices, ± 10 g or ± 25 g) at the skin above the spinous processes of vertebrae T1, T2 and T3 in the x, y and z axes, respectively, and similarly at vertebrae L2, L3 and L4. The accelerometers were attached to the skin with a small square of two-sided adhesive tape. The acceleration signals were amplified (200X or 500X) and filtered (lowpass 220 Hz) by a signal conditioning unit (Terrascience) and recorded on a VAX 400 computer system

Subject Training

The subjects were given a 15 minute orientation exposure several days before their experimental trials to allow them to become familiar with the subjective questions. A sample rating scale (marked to the nearest 0.1 units) was placed in the visual field of the subject, at a distance of approximately 1.5 m forward. The subjective response scales and questions were explained to each subject. During the orientation exposure, the subjects responded to each question on several occasions. This enabled the subjects to practice the subjective response questions, to provide a frame of reference for the response scale in reference to exposure to motion, and to bring forth any questions or concerns.

Experimental Procedures

During short term experiments, subjects rated the severity of individual shocks between 1 and 7. Due to the relatively small difference in perception between shocks of the same amplitude at different frequencies, subjective ratings were given the first decimal place (e.g., 2.7). For LT experiments, subjects provided ratings for comfort, predicted tolerance, tiredness and severity of the exposures to mechanical shocks at scheduled measurement intervals. Subjective responses were rated on an integer scale from 1 to 7 in LT experiments. In LT1, subjects provided subjective ratings at the 30 second and 3 minute duration points of each 3.75 minute exposure. In LT2, LT3 and LT4 ratings were obtained at scheduled intervals throughout the exposure. The times at which questions were asked in each experiment are included in Appendix A. Subjective ratings during LT5 experiments were obtained at the 3 minute point of each of the 16 shock exposure signatures which were 3.75 minutes in duration.

Analysis

Short Term Single Shock Experiments

Effect of Shock Characteristics on Severity Rating

Mean and standard deviation of subjective severity rating was generated for each shock type and graphed as a function of shock frequency for each acceleration amplitude, axis and direction (i.e., ±x, +y, and ±z).

Linearity of Subjective Severity to Shock Amplitude

The linearity of subjective severity rating to shock amplitude was assessed by examining the effect of increasing amplitude over the range of tested shock frequencies. Severity rating at each amplitude was normalized and graphed as a function of frequency to compare amplitude effects. The data were normalized by calculating the ratio of severity to mean severity for each amplitude at frequencies between 4 and 20 Hz. A curvilinear regression ($y=mx^a$) was applied to each curve for all amplitudes. The curves were then superimposed on a graph of normalized severity rating as a function of frequency in order to demonstrate differences in the effect of shock frequency for the different tested shock amplitudes. In a linear system, ratings at each amplitude would be expected to become superimposed when normalized in this fashion. To examine the effect of amplitude on subjective severity for the different shock frequencies, severity rating was plotted as a function of increasing shock amplitude for each tested frequency. Linear regression was used to determine the functions for each shock frequency, as well as the correlation coefficient.

Comparison of Subjective Severity with Biodynamic Model Outputs and Transmitted Acceleration

Subjective severity rating was compared with the predicted outputs of the biodynamic models listed in Table 8. The scale for biodynamic model output was normalized to correspond with the subjective severity rating scale in order to directly compare subjective severity and model output.

This was achieved by adjusting the amplitude of each scale according to the ratio of the mean value of the subjective and model output data. The correlations between the subjective severity rating and the model outputs for all amplitudes were determined by linear regression analyses. The same method of normalizing data was used to compare the relation between subjective severity rating and acceleration transmitted to the lumbar (L2, L3, L4) and thoracic (T1, T2, T3) vertebrae.

Table 8 **Existing biodynamic models which were compared to subjective severity rating.**

Model	Axis	Undamped f_n (Hz)	Critical damping ratio	Reference
Fairley-Griffin	z	5	0.475	Fairley and Griffin, 1989
DRI (8.4 Hz)	z	8.4	0.224	ASCC, 1982
DRI (11.9 Hz)	z	11.9	0.35	Payne, 1991
BS 6841 W_b filter	z	NA	NA	BS 6841, 1987
BS 6841 W_d filter	x	NA	NA	BS 6841, 1987
DRI (10 Hz)	x	10	0.15	Payne, 1984
BS 6841 W_d filter	y	NA	NA	BS 6841, 1987
DRI (7.2 Hz)	y	7.2	0.15	Payne, 1984

Long Term Repeated Shock Experiments

Effect of Shock Axis, Direction, Amplitude and Rate on Subjective Response

In the shorter duration repeated shock experiments (LT1: 3.75 minutes), subjective response rating was compared across exposure conditions to determine the relative effect of amplitude, rate, axis and direction of input shocks. The data were first examined with descriptive multiple t-tests to identify factors which could be tested for significance.

These comparisons were performed between subjective response rating to:

- two different shock amplitude/rate combinations producing the same dose level according to the VDV (e.g., 1 g shocks at 128 shocks per minute compared to 2 g shocks at 8 shocks per minute).
- shocks in different axes with similar amplitude and rate conditions (e.g., positive z axis 2 g shocks at 128 per minute and positive x axis 2 g shocks at 128 per minute).
- shocks in the positive and negative direction (e.g., +z axis 4 g shocks at 8 per minute to -z axis 4 g shocks at 8 per minute).

Subsequently, data from the shock rate/ amplitude conditions were collapsed to one data set in order to examine the significance of the effect of shock axis (+x to +z; -x to -z; +y to +z; and +y to +z) and shock direction (+x to -x; and +z to -z). Although multiple comparisons were performed, the maximum familywise error rate was set at $\alpha<0.05$ according to the Bonferroni inequality principle (Howell, 1987). Error levels for individual comparisons were set using the expression,

$$FW \leq c\alpha' = c\,(\alpha/c) = \alpha$$

where, α is the maximum familywise error rate; c is the number of comparisons performed; and α' is the error rate for the individual comparisons.

Effect of Duration of Exposure on Subjective Response

To examine the effect of duration of exposure on subjective rating of comfort, predicted tolerance, tiredness and severity, the mean values of subjective response for each measurement interval were graphed as a function of exposure time for experiments LT2, LT3 and LT4. Subjective response curves were examined for time dependence.

For the LT2 experiments all five of the different shock exposure conditions were collapsed into one data set for significance testing of time dependence. The difference between subjective rating for first and last measurement intervals was assessed by paired t-test.

In experiment LT3, the protocol was designed to limit the permitted exposure time of an individual to 75% of his predicted tolerance rating. Thus, the subjects experienced exposures of varying duration depending on their rating. To examine time-dependent trends in the data, the mean subjective rating was calculated from three subject subsets (n=10, n=6 and n=2), based on the maximum duration of exposure a subset of subjects completed. Using these subject groups, mean values were determined for 2.5 hours of exposure (n=10), 4.5 hours (n=6) and the full 7 hours of exposure (n=2). The subset n=10 was chosen to represent the full sample population; the n=6 subset was chosen to represent the maximum number of subjects remaining after the second rest interval; and n=2 to represent the subjects which completed the experiment.

For the LT4 experiments the data of the 5 days of exposure were collapsed into a single data set to examine the effect of duration of exposure over a daily exposure of 4 hours. A paired t-test was used to test for significance between data of first and last measurement intervals. To examine the effect of duration over the 5 days of exposure the average rating for the daily exposure in Day 1 was compared with those of Day 2, 3, 4 and 5. Although multiple statistical comparisons were performed, the familywise α level was maintained at $p<0.05$ through the Bonferroni inequality principle. For further explanation see the subsection entitled 'The Effect of Shock Axis, Direction, Amplitude and Rate'. The rate of change in subjective rating during a daily exposure was also examined in LT4 experiments. Linear regression was used to determine slopes for the relation of subjective rating of individual subjects with respect to duration of exposure. The slope obtained on Day 1 was compared by multiple t-tests with those of Days 2, 3, 4 and 5 (*FW* α level: $p<0.05$).

Effect of Rest Intervals on Subjective Response

Rest intervals of varying duration (7.5, 15 and 30 minutes; 20 hours) were included in experiments LT3, LT4 and LT5 and assessed for their effect on subjective response. The combinations of exposure and rest interval duration for the experiments are listed in Table 9. Paired t-tests were used to determine the differences between pre- and post-interval subjective response rating in LT3 and LT4. The effect of mid-day (15-minute) and overnight (20-hour) rest intervals in LT4 experiments were examined by collapsing the pre- and post-rest interval data into single data sets. Significance of mid-day and overnight rest intervals was subsequently determined with single paired t-tests. In LT5, the effect of intermittent rest intervals was examined by comparing the mean subjective rating to continuous and intermittent exposure conditions using a paired t-test. Additionally, the rate of change of subjective rating was compared between the continuous and intermittent conditions. Using linear regression, the slopes of subjective rating as a function of duration of exposure were generated for each subject for both conditions. A single paired t-test was used to test for significance between the slopes.

Table 9 Exposure and rest interval combinations examined for experiments LT3, LT4 and LT5.

Experiment	Exposure	Rest Interval Type
LT3	7 hours	two 15-minute and one 30-minute rest intervals per exposure
LT4	4 hours, 5 days	one mid-day (15-minute) interval per exposure and overnight (20 hour) between consecutive days
LT5 (Intermittent condition)	1 hour total (3.75-minute signatures)	sixteen 7.5-minute rest intervals for 1 hour of exposure

Comparison of the VDV and Subjective Response

In LT1 experiments, the change in mean subjective rating from one dose level to another (VDV of 14.5 and 29.1) was compared to expected changes based on the amplitude- and time-dependence of the VDV function. The changes were quantified as ratios of mean subjective rating between the two dose levels for comfort, predicted tolerance and severity. This was done for both low and high amplitude shocks (1 and 2 g comparisons; and 2 and 4 g comparisons). For subjective comfort, a two-fold increase in VDV would be expected to result in a proportional decrease in comfort rating (i.e., ratio for high:low = 0.5). Alternatively, for severity rating a two-fold increase in VDV would expect to result in a two-fold increase in severity (i.e., ratio for high:low = 2.0). In contrast, the expected ratio of predicted tolerance is different because it involves the time dependence of the VDV function. If shock rate and amplitude remain constant the duration of exposure must be increased by a factor of 16 in order to increase the VDV by a factor of two. For further explanation see subsection entitled 'British Standards Institution Document 6841' in the Background section. Ratios for the change in mean subjective rating from one dose level to another, compared to expected changes based on dose level changes are listed in Table 10.

Table 10 Description of comparisons between mean subjective values in LT1 for different dose levels, in relation to expected ratios based on the VDV.

Rating type	Condition comparison	Dose comparison	Expected ratio
Comfort	2g, 128 shocks/min: 1g, 128 shocks/min	high/low	0.5
Severity	2g, 128 shocks/min: 1g, 128 shocks/min	high/low	2.0
Predicted tolerance	1g, 128 shocks/min: 2g, 128 shocks/min	low/high	16

The time dependence of the VDV was compared to that of subjective rating as a function of duration of exposure. This was done using the change in tiredness rating over duration of exposure in experiments LT3, LT4 and LT5. Regression coefficients were generated and compared between subjective rating as a function of duration of exposure (t^1) and as a function of the VDV ($t^{1/4}$).

RESULTS

Short Term Single Shock Experiments

Effect of Shock Characteristics on Severity Rating

Subjective severity rating demonstrated trends in response to different shock characteristics including shock frequency, axis and direction. Each of these characteristics is directly relevant to health hazard concerns. For all single shock conditions, the lowest tested shock frequency resulted in the highest mean severity rating at each shock amplitude. Severity rating decreased in a curvilinear manner with increasing shock frequency. This is illustrated in Figure 6 for positive x axis shocks (See Figures B-1 to B-5 in Appendix B for all axes).

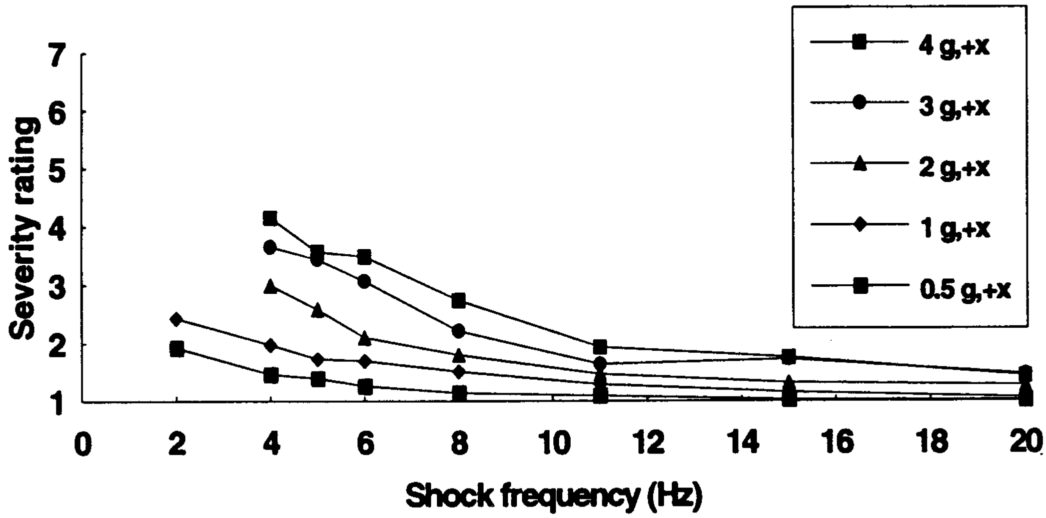


Figure 6 **Subjective severity rating to single shocks in the positive x axis as a function of shock frequency and amplitude.**

There was no significant difference between the severity rating to positive and negative shocks in either the x or z axis as illustrated in Figures 7 and 8. Regression analysis between the subjective rating for positive and negative shocks showed high correlation coefficients for x and z responses (r^2=0.986 and r^2=0.933). Both regression lines were extremely close to the lines of identity ($y=1.004x + 0.064$ and $y=0.968x + 0.0997$, for x and z axes respectively).

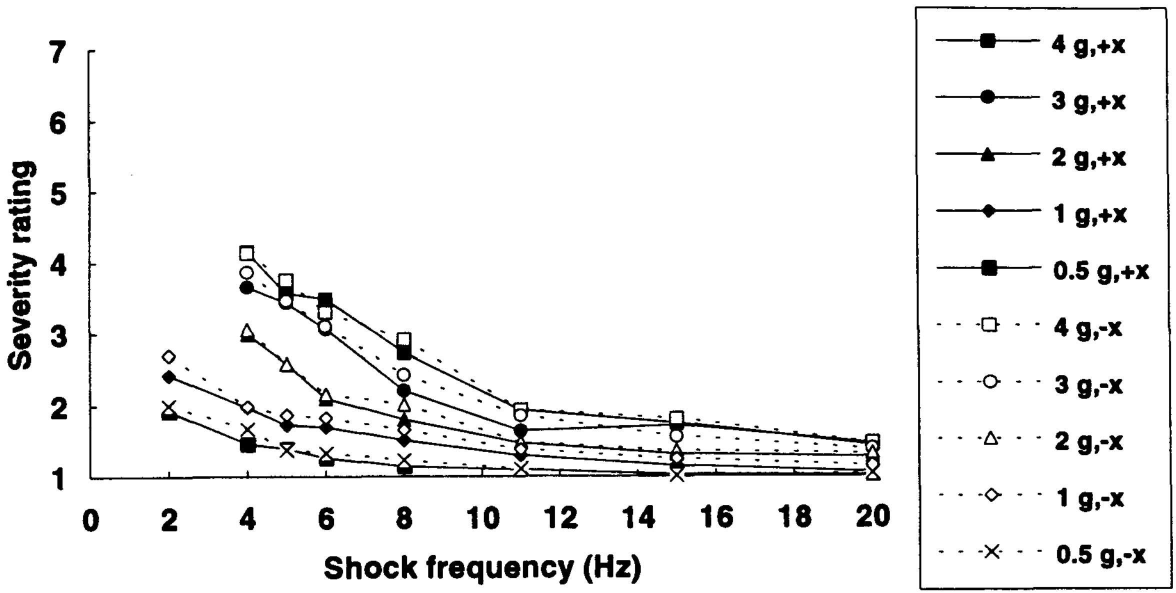


Figure 7 Comparison between subjective severity rating to single shocks in the positive and negative x axis as a function of shock frequency and amplitude.

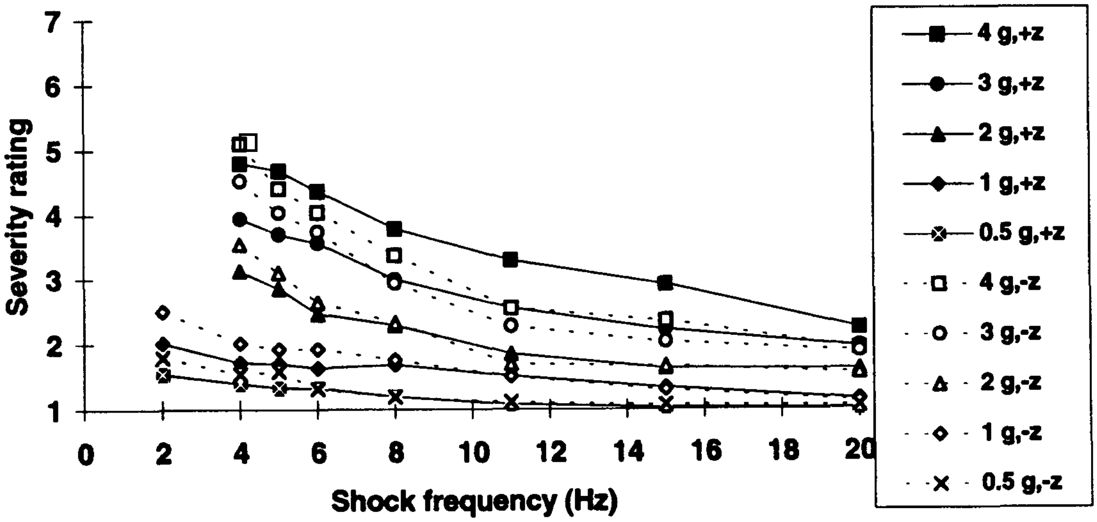


Figure 8 Comparison between subjective severity rating to single shocks in the positive and negative z axis as a function of shock frequency and amplitude.

Linearity of Subjective Severity to Shock Amplitude

Subjective severity rating increased linearly within each shock frequency as a function of shock amplitude for all axes and shock directions. Figure 9 demonstrates this for the severity rating to shocks in the positive x axis (see Figures B-6 to B-10 in Appendix B for all axes).

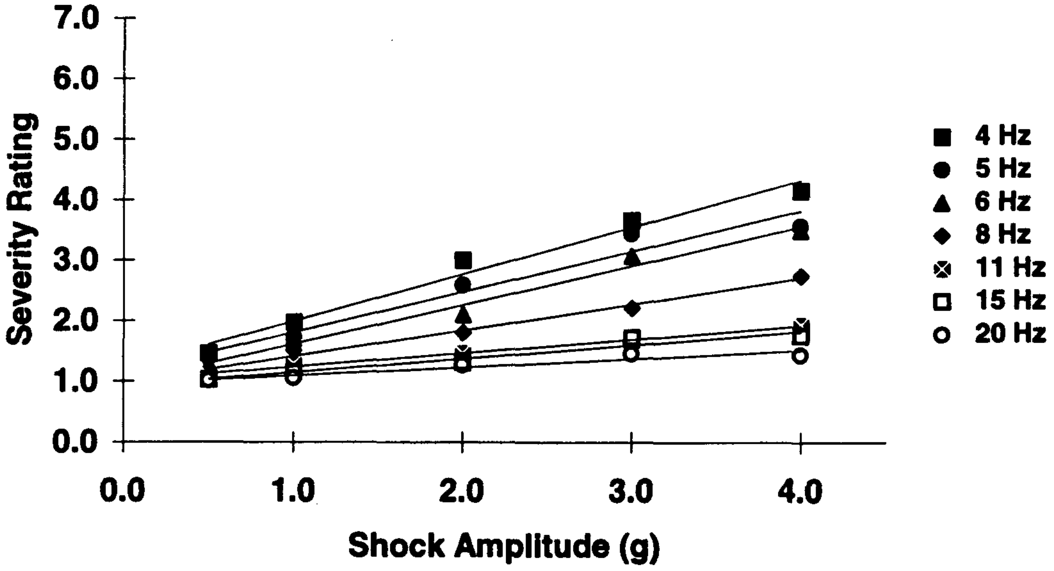


Figure 9 **Severity rating as a function of shock amplitude for different frequency, single shocks in the positive x axis.**

The plots of severity rating as a function of shock amplitude for each tested frequency demonstrated that the effect of shock amplitude on severity rating was linear with respect to amplitude within each shock frequency. However, the rate of increase in severity rating varied across the range of tested shock frequencies. The greatest rate of change was observed with 4 Hz shocks, whereas the least rate of change was observed with 20 Hz shocks (Figure 9). The linear regression equations and coefficients for severity rating as a function of shock amplitude listed in Table 11 also illustrate that severity rating increased linearly for a given shock frequency but demonstrated a change in slope over the range of tested shock frequencies.

Comparing the normalized severity rating in response to each shock amplitude across the tested shock frequencies also demonstrated that subjective severity rating increased linearly with shock amplitude (Figure 10). In a linear system the curves for each amplitude would be expected to be superimposed.

Table 11 **Linear regression equations for subjective severity as a function of shock amplitude for different frequency, single shocks in the positive x axis.**

Shock frequency (Hz)	Regression equation ($y = mx + b$)	Correlation coefficient (r^2, α=0.05)
4	$y = 0.78x + 1.21$	0.977
5	$y = 0.67x + 1.13$	0.955
6	$y = 0.65x + 0.96$	0.982
8	$y = 0.43x + 0.97$	0.987
11	$y = 0.22x + 1.01$	0.984
15	$y = 0.22x + 0.92$	0.946
20	$y = 0.13x + 0.96$	0.904

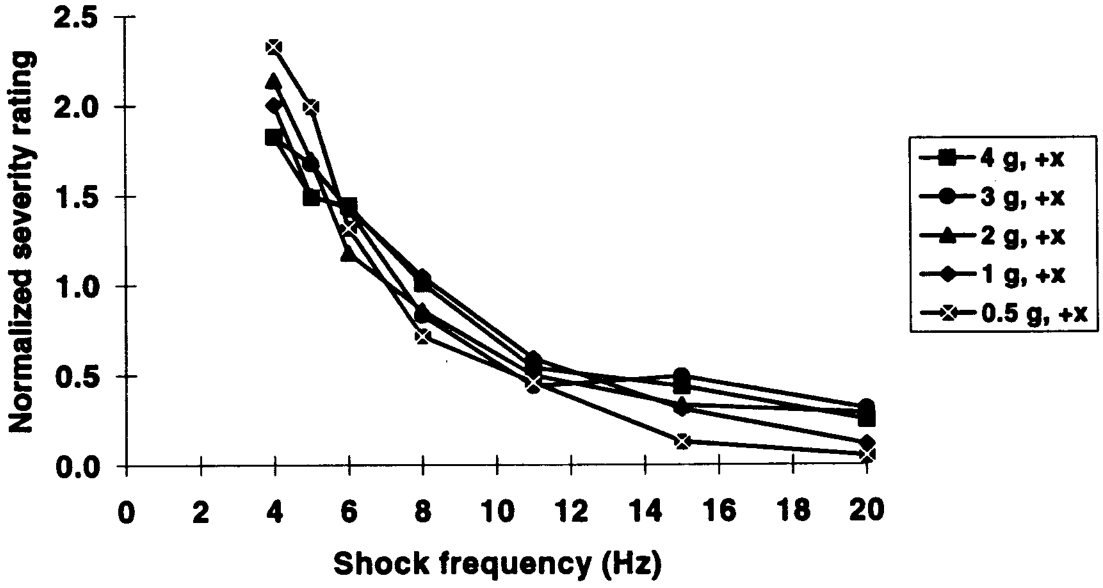


Figure 10 **Comparison of normalized subjective severity rating to single shocks in the positive x axis for different shock amplitudes.**

Comparison of Subjective Severity with Biodynamic Model Outputs

Shocks in the z Axis

Comparison of the subjective severity rating and normalized output acceleration of existing biodynamic models in response to shocks in the positive z axis demonstrated both frequency and amplitude dependent effects. Each of these models underestimated subjective severity at low frequencies and overestimated severity at high frequencies. Figure 11 illustrates the cross-over point from underestimating to overestimating severity was dependent on shock amplitude for all models, ranging from 4 to 15 Hz.

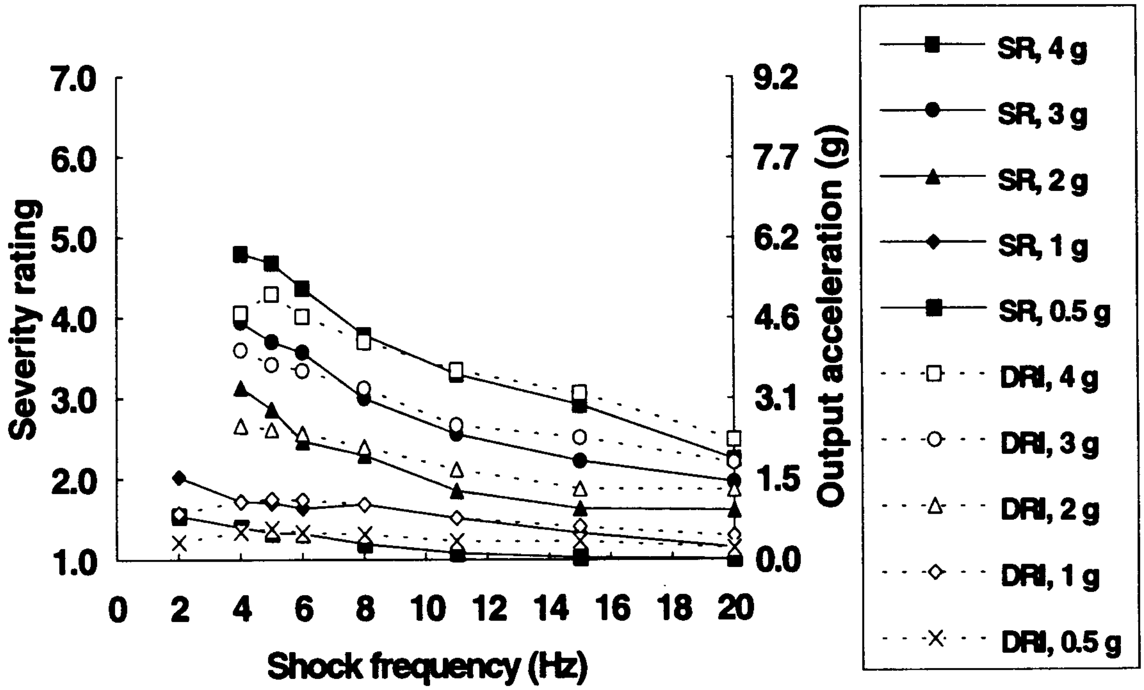


Figure 11 **Comparison between severity rating (SR) and expected output from the DRI model (8.4 Hz) to positive z axis shocks.**

The closeness of fit between severity rating and the existing biodynamic models and filters decreased progressively in the following order: Fairley-Griffin model, DRI model (8.4 Hz version), DRI model (11.9 Hz version) and BS 6841 filter. The trends described for positive z axis shocks were also shown for negative z axis shocks. As shown in Figure 12, the relation between severity rating and the existing biodynamic models was not as good for negative z axis shocks as it was for positive z axis shocks (Figure 12). Correlation coefficients obtained from linear regression analysis for severity rating and biodynamic model outputs are listed in Table 12 (See Figures B-11 to B-18 in Appendix B for all model comparisons).

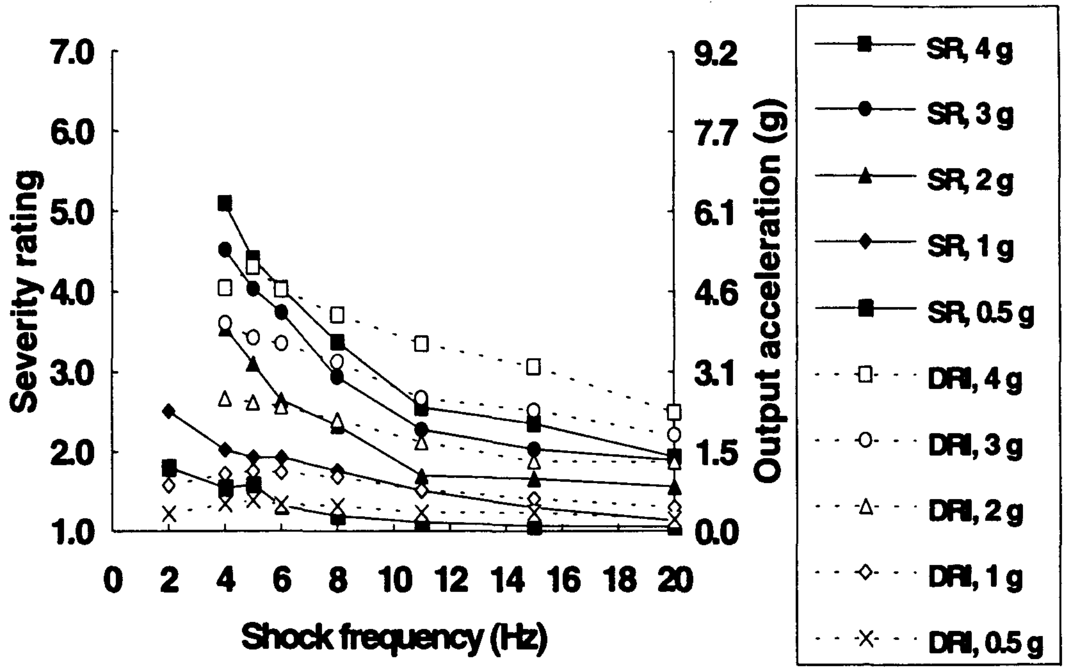


Figure 12 Comparison between severity rating (SR) and expected output from the DRI model (8.4 Hz) to negative z axis shocks.

Table 12 Correlation of subjective severity responses with biodynamic model outputs in response to single shocks in the z axes.

Shock axis	Model or Filter	Positive Direction (r^2, α=0.05)	Negative Direction (r^2, α=0.05)
z	Fairley-Griffin	0.985	0.896
z	DRI (8.4 Hz)	0.959	0.828
z	DRI (11.9 Hz)	0.897	0.712
z	BS 6841 filter	0.760	0.550

Shocks in the x and y Axis

Comparison of subjective severity rating and normalized output acceleration of the BS 6841 frequency weighting filters and biodynamic models in response to x and y axis shocks demonstrated similar trends to those shown above for the z axis. An example of this is demonstrated in Figure 13 for the BS 6841 filter. The closeness of the relation between severity rating and the models was higher for the BS 6841 filter than for the DRI model, for both x and y axes (See Figures B-19 to B-24 in Appendix B for both models in the x and y axes). Linear regression analysis for severity rating and biodynamic model outputs are listed in Table 13.

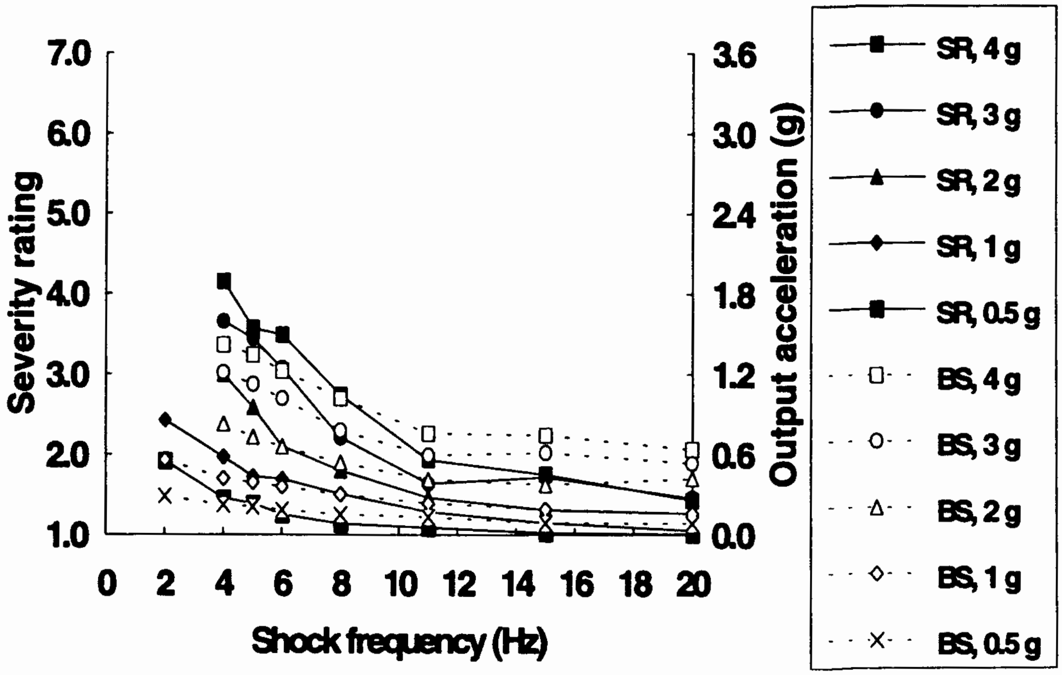


Figure 13 Comparison between severity rating (SR) and expected output from the BS 6841 W_d filter to positive x axis shocks.

Table 13 Correlation of subjective severity responses with biodynamic model outputs in response to single shocks in the x and y axes.

Shock axis	Model or Filter	Positive Direction (r^2, α=0.05)	Negative Direction (r^2, α=0.05)
x	DRI (10 Hz)	0.669	0.637
x	BS 6841 filter	0.878	0.856
y	DRI (7.2)	0.819	NA
y	BS 6841 filter	0.876	NA

Comparison of Subjective Severity with Spinal Transmission

Comparison of the subjective severity rating and normalized spinal transmission measured at the T1 and L2 vertebral levels demonstrated that subjective severity was closely related to spinal transmission in response to both positive and negative x axis shocks (Figure 14). However, a slightly better relation was observed for positive shocks.

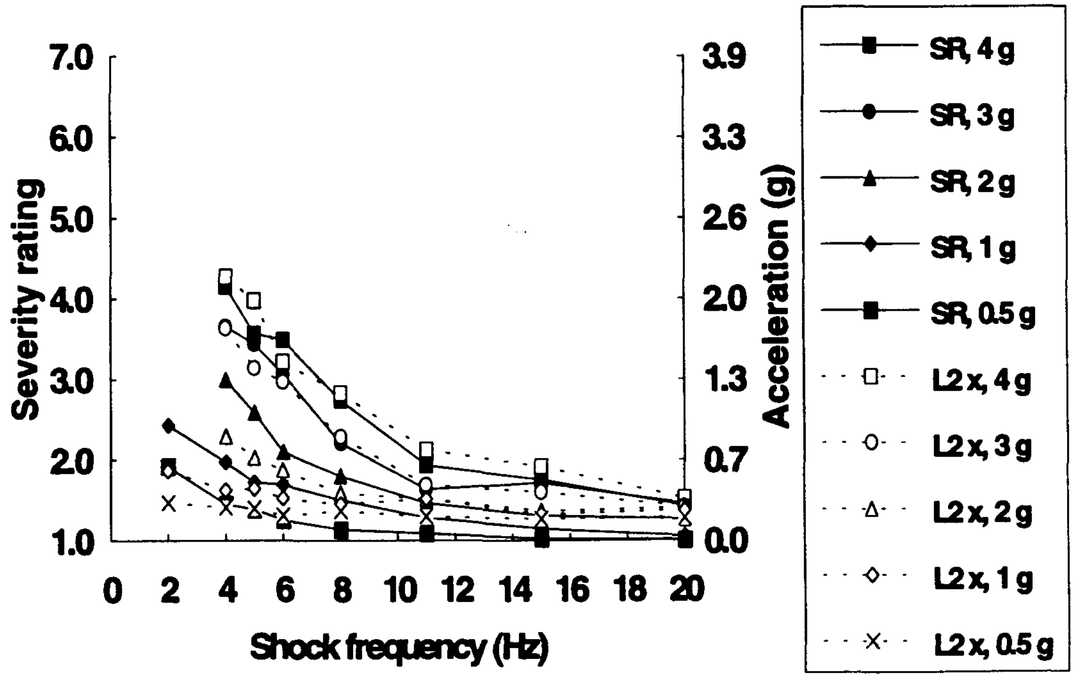


Figure 14 Comparison between severity rating (SR) and acceleration measured at the lumbar spine (L2) in response to positive x axis shocks (L2 x).

Comparisons of the subjective severity rating and normalized spinal transmission also demonstrated a close relation for y axis shocks. Similarly for z axis shocks, there was a close relation between subjective severity and spinal transmission measured at T3 and L4. However, in the z axis, severity rating appeared to underestimate spinal transmission to T3 in response to 2, 3 and 4 g shocks at very low frequencies such as 4 to 6 Hz (Figure 15) (See Figures B-25 to B-34 in Appendix B for comparisons for all axes at both vertebral levels for both positive and negative shocks). The consistent frequency and amplitude effects which were observed in comparisons between subjective severity and the existing biodynamic models were not observed in spinal transmission data. Correlation coefficients obtained from linear regression analysis demonstrated the closeness of these relations (Table 14).

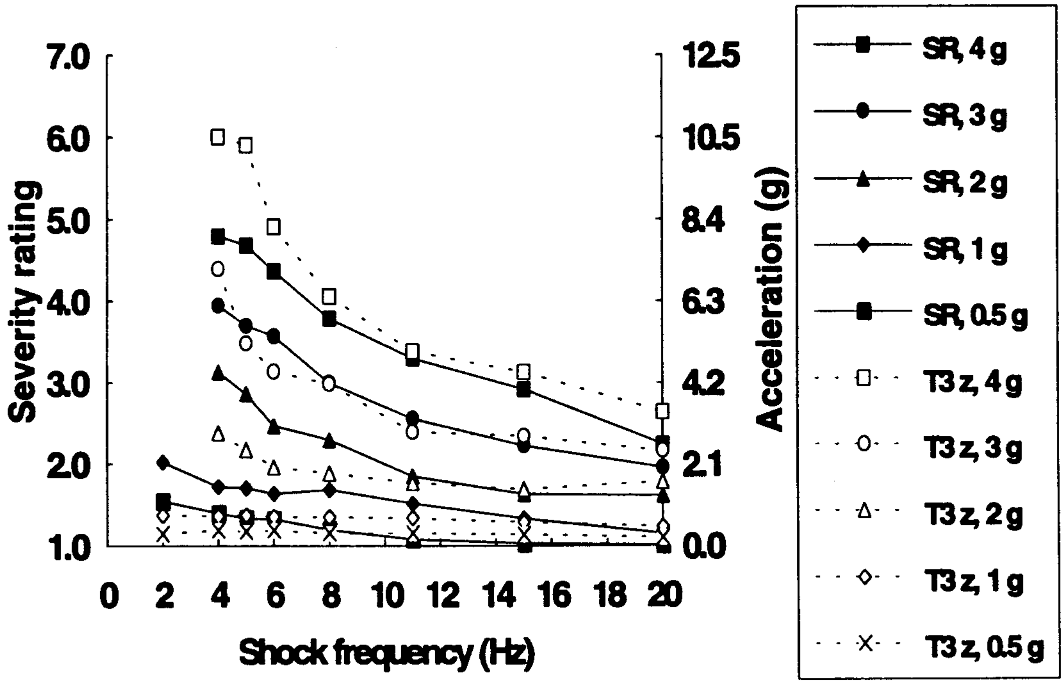


Figure 15 Comparison between severity rating (SR) and acceleration measured at the thoracic spine (T3) in response to positive z axis shocks (T3 z).

Table 14 Correlation of subjective severity rating with spinal transmission to the lumbar and thoracic vertebrae in response to single shocks.

Shock axis	Vertebral Level	Positive Direction (r^2, α=0.05)	Negative Direction (r^2, α=0.05)
x	T1	0.954	0.858
x	L2	0.909	0.872
y	T2	0.958	NA
y	L3	0.940	NA
z	T3	0.918	0.935
z	L4	0.936	0.954

Long Term Repeated Shock Experiments

Effect of Shock Axis, Direction, Amplitude and Rate

The data for subjective response ratings for comfort, predicted tolerance and severity to repeated shock exposures in LT1 are summarized in Tables 15 to 17. Comparison of different axes showed that the x and y axis exposures were not significantly different, whereas motion in the z axis was rated significantly less comfortable, less tolerable and more severe than in the x and y axes. There were no significant differences between positive and negative shock exposures for the x and z axes. These findings were also demonstrated in the shock experiments of ST1. Equal VDV exposures with different shock rate and amplitude were not rated as significantly different.

Table 15 **Subjective comfort rating to LT1 exposures.**

	+y		+x		-x		+z		-z	
Motion signature	*Mean*	*Std Dev*	*Mean*	*Std Dev*	*Mean*	*Std Dev*	*Mean*	*Std Dev*	*Mean*	*Std Dev*
1g, 128 min^{-1}	5.90	0.57	5.40	0.70	5.70	0.67	4.80	1.62	4.60	0.52
2g, 8 min^{-1}	6.10	0.99	5.90	1.10	6.00	0.67	5.30	0.67	4.80	1.03
2g, 128 min^{-1}	4.20	0.92	4.10	0.88	3.90	1.20	2.50	1.08	1.80	0.79
4g, 8 min^{-1}	4.20	1.32	4.20	0.63	3.20	1.32	2.00	0.82	1.70	0.67

Table 16 **Subjective predicted tolerance rating to LT1 exposures.**

	+y		+x		-x		+z		-z	
Motion signature	*Mean*	*Std Dev*	*Mean*	*Std Dev*	*Mean*	*Std Dev*	*Mean*	*Std Dev*	*Mean*	*Std Dev*
1g, 128 min^{-1}	5.70	1.44	5.70	1.69	5.60	1.73	4.53	1.92	4.15	1.25
2g, 8 min^{-1}	6.35	2.33	5.90	2.22	6.40	1.66	5.40	1.85	5.20	2.00
2g, 128 min^{-1}	3.15	0.91	3.35	1.36	3.20	2.14	1.30	0.76	1.20	0.83
4g, 8 min^{-1}	3.20	1.03	4.00	1.78	2.95	1.46	1.33	0.60	0.95	0.50

Table 17 **Subjective severity rating to LT1 exposures.**

	+*y*		+*x*		-*x*		+*z*		-*z*	
Motion signature	*Mean*	*Std Dev*	*Mean*	*Std Dev*	*Mean*	*Std Dev*	*Mean*	*Std Dev*	*Mean*	*Std Dev*
1g, 128 min^{-1}	2.20	0.63	2.70	0.48	2.40	0.84	3.70	1.34	3.30	0.82
2g, 8 min^{-1}	1.70	0.82	2.00	0.94	2.00	0.67	2.70	0.48	2.80	1.03
2g, 128 min^{-1}	4.20	0.63	4.20	0.79	4.40	1.07	5.50	1.27	5.90	0.99
4g, 8 min^{-1}	4.10	1.20	4.50	0.85	4.90	0.99	5.90	0.88	6.00	0.82

Effect of Duration of Exposure on Subjective Response

Subjective ratings demonstrated duration-dependent changes in LT2, including: decreased comfort; decreased predicted tolerance; increased tiredness; and increased severity. A paired t-test demonstrated significant differences between collapsed data of the first and last measurement intervals for subjective rating of comfort, predicted tolerance, tiredness and severity ($p<0.05$) (Figures 16 to 19). The percent changes in subjective rating over the two-hour exposure for the various rating types were: -21% for comfort; -14% for predicted tolerance; +200% for tiredness; and +25% for severity.

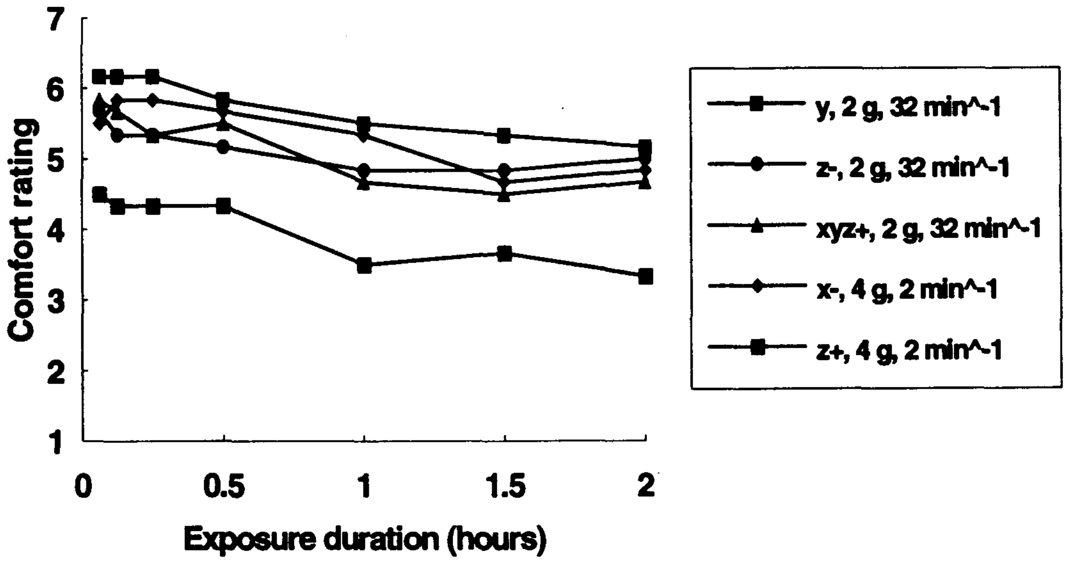


Figure 16 **Subjective comfort rating as a function of duration of exposure for 2 hour repeated shock exposures.**

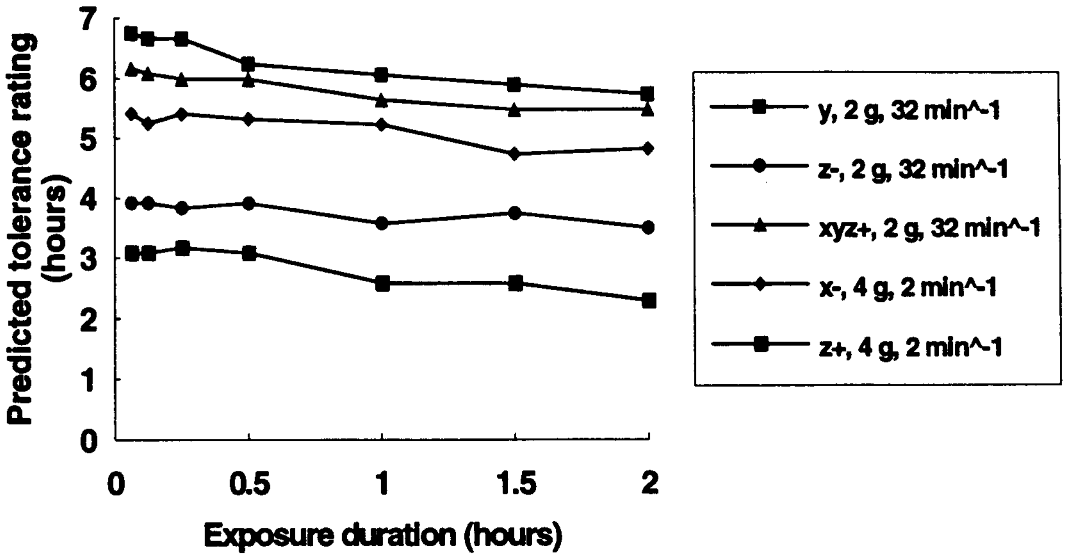


Figure 17 Subjective predicted tolerance rating as a function of duration of exposure for 2 hour repeated shock exposures.

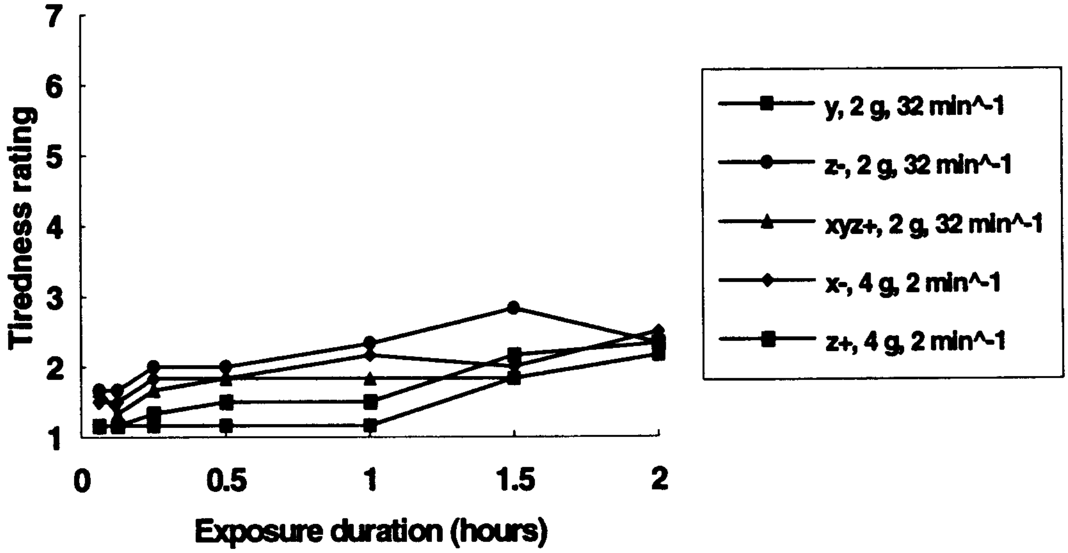


Figure 18 Subjective tiredness rating as a function of duration of exposure for 2 hour repeated shock exposures.

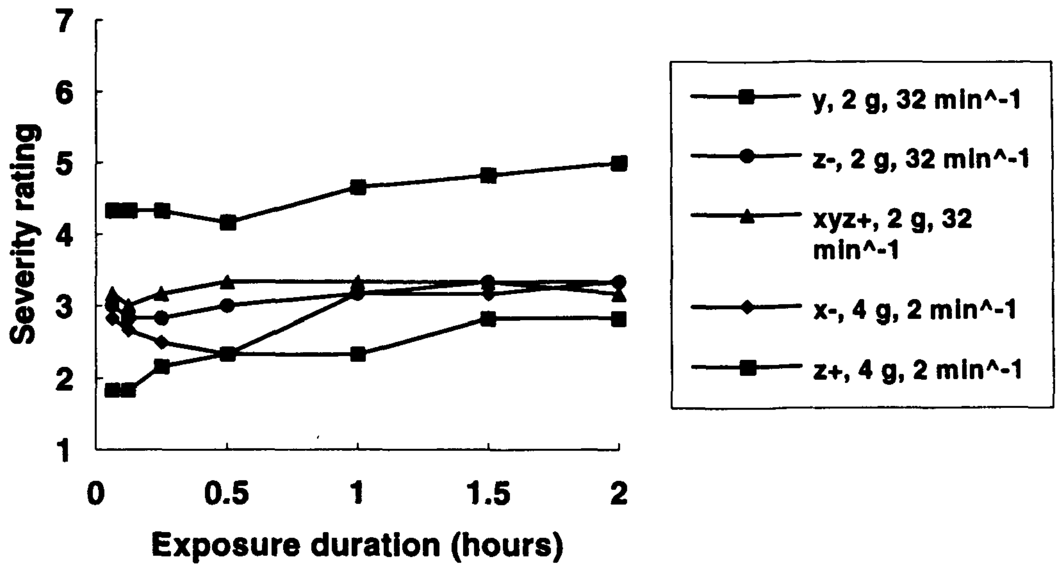


Figure 19 **Subjective severity rating as a function of duration of exposure for 2 hour repeated shock exposures.**

In LT3, subjective comfort for both of the subject subsets (n=6 and n=10) demonstrated a rapid, significant decrease within the first 1.5 hours of exposure (Figure 20). Comfort remained relatively constant beyond 1.5 hours, except for immediately following rest intervals when comfort rating showed significant improvements. Tolerance predictions tended to decrease with increasing duration of exposure for subject subsets n=6 and n=10. However, the decrease in predicted tolerance from the first to last measurement interval was not significant for either subject subset (Figure 21). Subjective tiredness for subsets n=6 and n=10 rapidly increased within the first 0.5 hours of exposure. From 0.5 to 1.5 hours tiredness rating increased significantly, but at a slower rate. There was no significant change in tiredness beyond 1.5 hours of exposure. A trend toward increasing tiredness continued throughout the duration of exposure, but with a gradual decline in rate (Figure 22). Severity rating demonstrated a curvilinear growth with a significant increase within the first 15 minutes of exposure, after which there was no significant change (Figure 23).

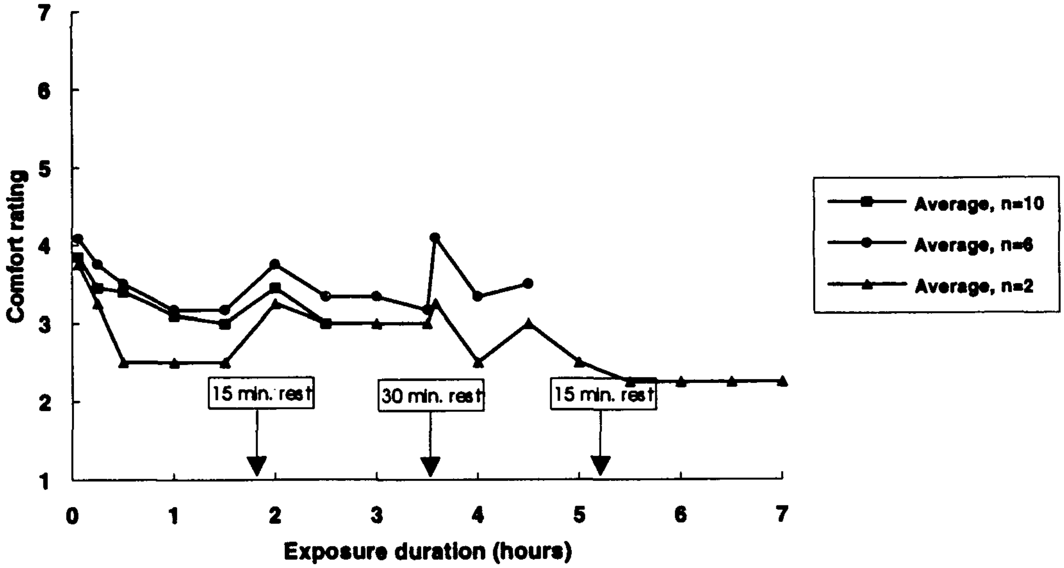


Figure 20 Subjective comfort rating as a function of duration of exposure for a 7 hour repeated shock exposure.

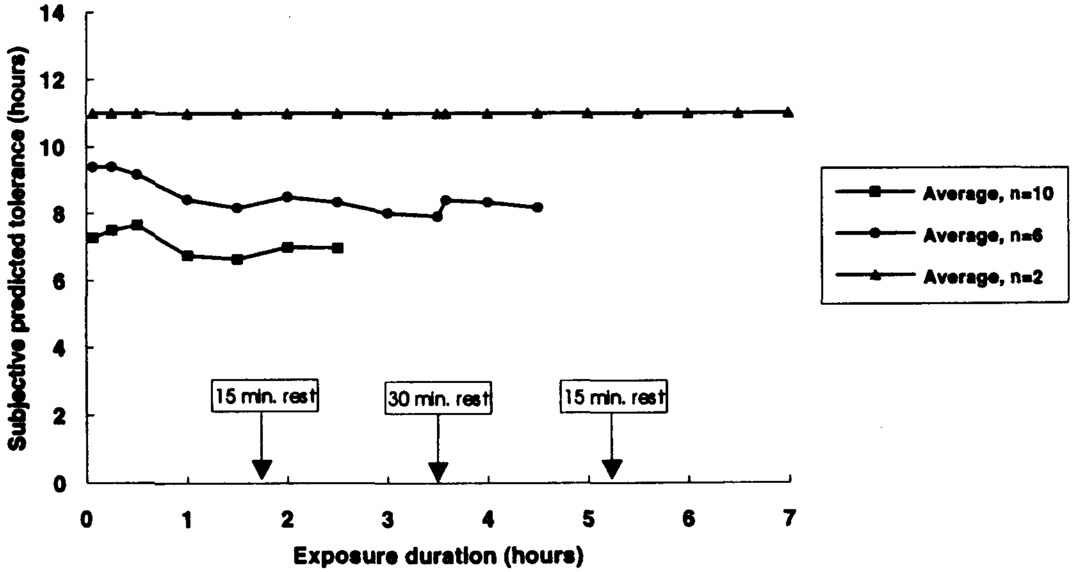


Figure 21 Subjective predicted tolerance rating as a function of duration of exposure for a 7 hour repeated shock exposure.

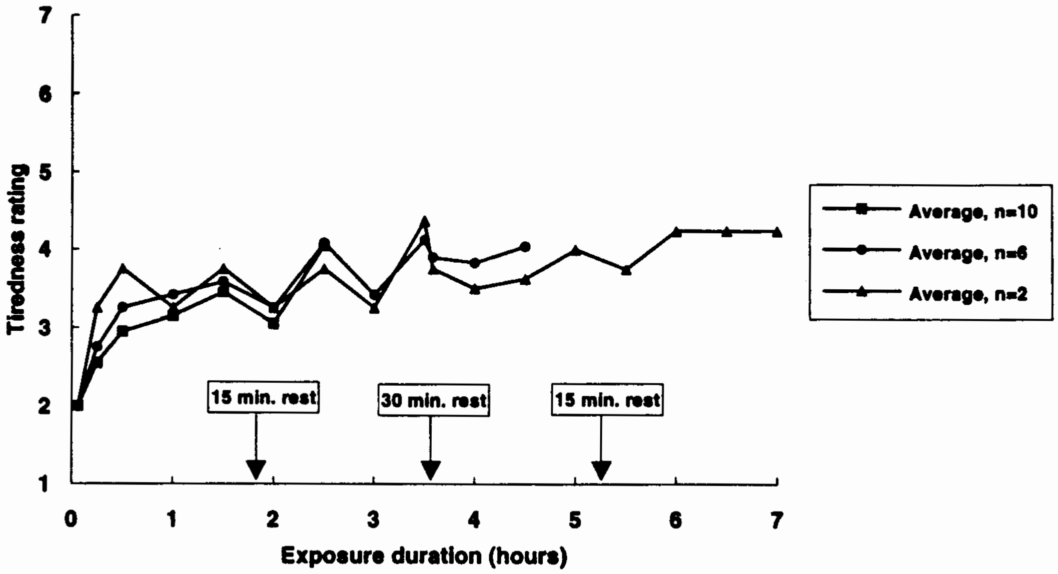


Figure 22 Subjective tiredness rating as a function of duration of exposure for a 7 hour repeated shock exposure.

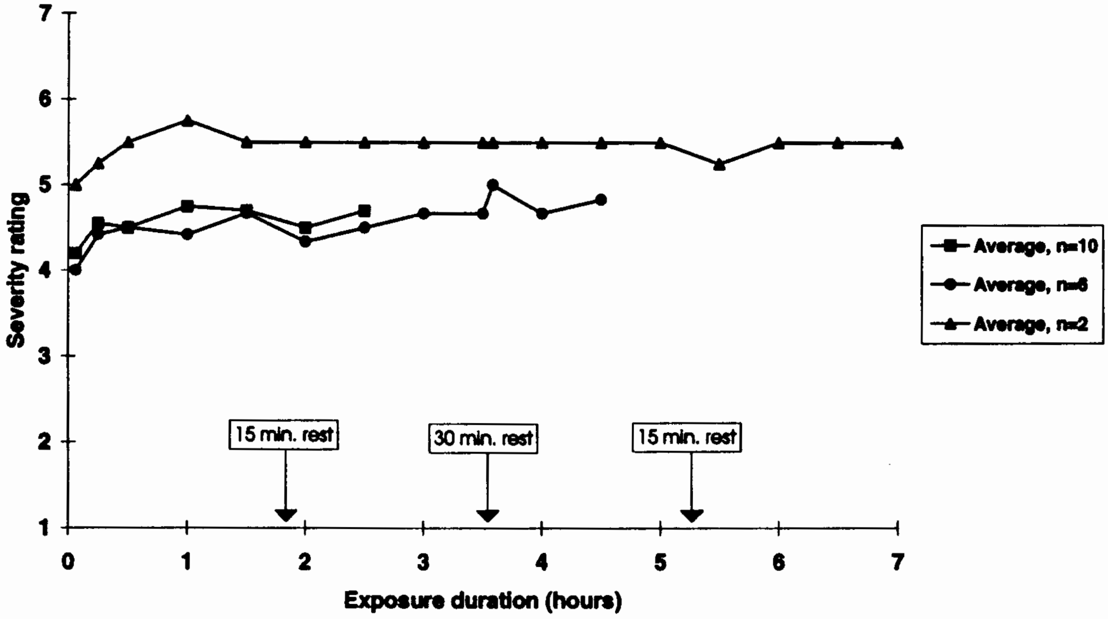


Figure 23 Subjective severity rating as a function of duration of exposure for a 7 hour repeated shock exposure.

In LT4, a significant duration effect was also observed in subjective rating of comfort, tiredness and severity, over the course of the daily exposure. However, predicted tolerance was relatively constant over a single day of exposure, and showed no significant difference between first and last measurement intervals in each day (Figures 24 to 27).

Comparisons of the mean subjective rating for each day in experiment LT4 generally demonstrated no significant changes from Day 1 to successive exposure days. However, from Day 1 to Day 2, rating of predicted tolerance significantly decreased (Figure 27) and severity significantly increased (Figure 26) ($p<0.05$). The rate of change of subjective rating within each exposure day (measured as the slope of the linear regression equation for subjective rating with respect to daily exposure time) did not demonstrate significant change between Day 1 and the successive days with the exception of the change in rate from Day 1 to Day 4 for tiredness rating ($p<0.05$). Although not significant, the daily rate of change of comfort and tiredness rating decreased to a plateau level after Day 1 of exposure (Table 18).

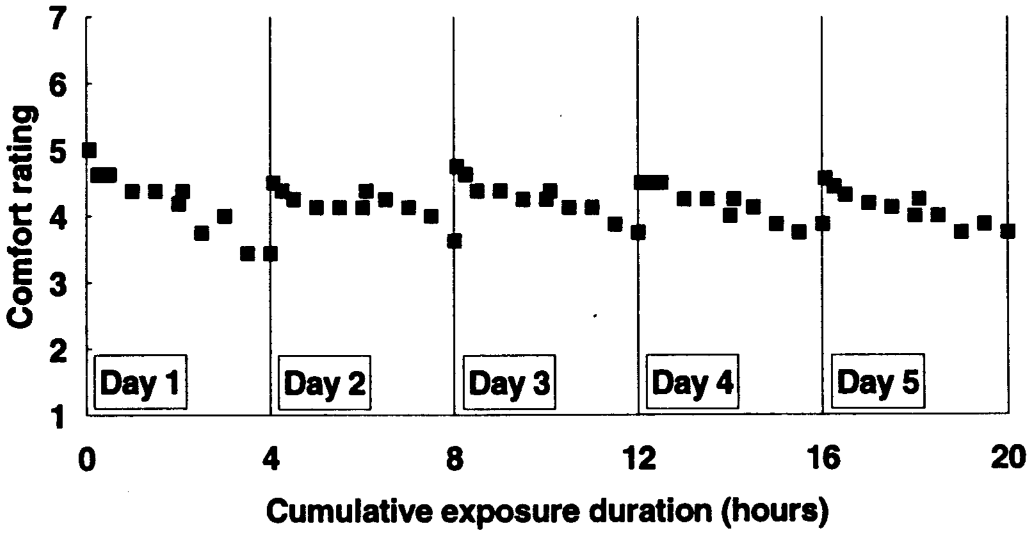


Figure 24 Subjective comfort rating as a function of cumulative duration of exposure for 4 hour repeated shock exposures on five consecutive days.

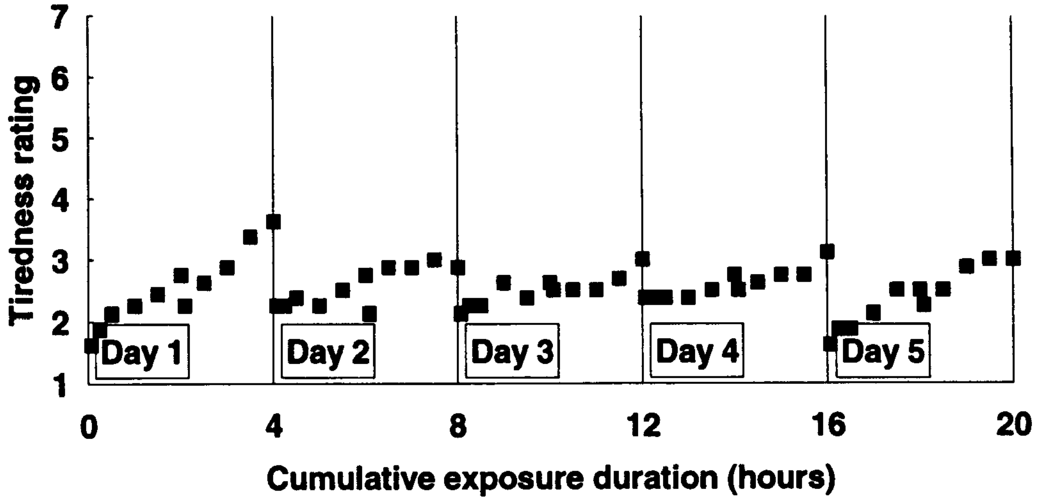


Figure 25 Subjective tiredness rating as a function of cumulative duration of exposure for 4 hour repeated shock exposures on five consecutive days.

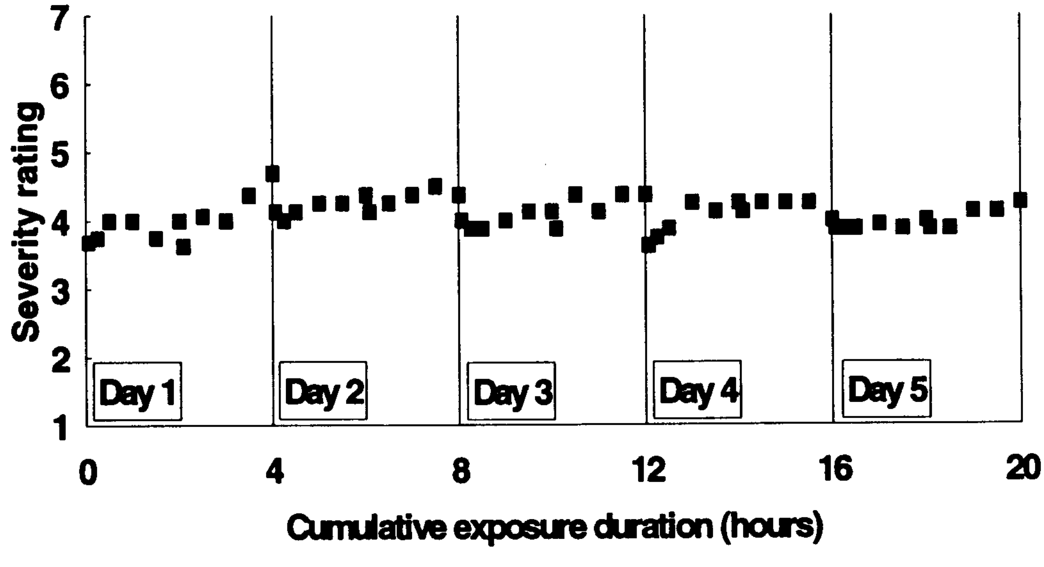


Figure 26 Subjective severity rating as a function of cumulative duration of exposure for 4 hour repeated shock exposures on five consecutive days.

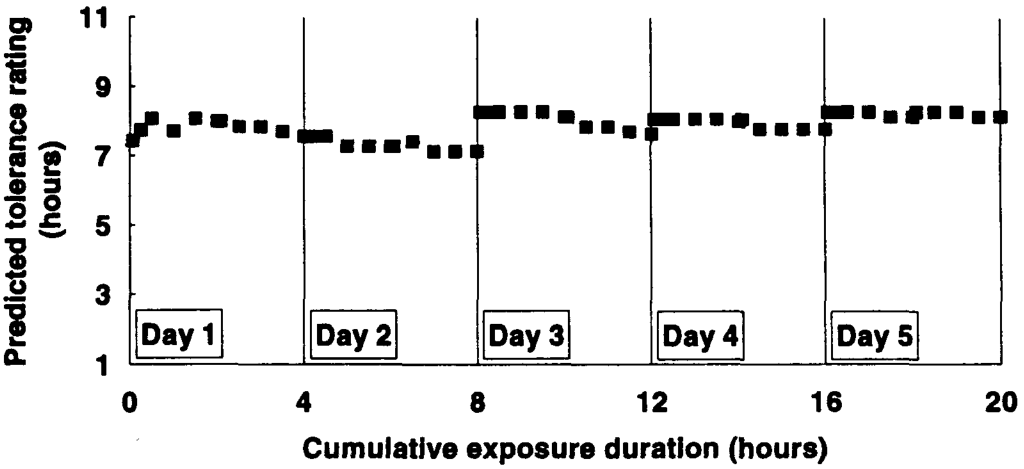


Figure 27 **Subjective predicted tolerance rating as a function of cumulative duration of exposure for 4 hour repeated shock exposures on five consecutive days.**

Table 18 **Linear regression equations of comfort and tiredness rating with exposure time, for each successive day of exposure.**

Exposure Day	Comfort	Tiredness
1	$y= -0.36x + 4.9$	$y = 0.44x + 1.7$
2	$y= -0.14x + 4.4$	$y = 0.20x + 2.2$
3	$y= -0.21x + 4.6$	$y = 0.16x + 2.2$
4	$y= -0.19x + 4.5$	$y = 0.16x + 2.3$
5	$y= -0.19x + 4.5$	$y = 0.34x + 1.7$

Effect of Rest Intervals on Subjective Response

In LT3 experiments, short term rest intervals had a significant effect on comfort rating following the first (15 minute) and second (30 minute) interval ($p<0.05$) (Figure 19). However, short term rest intervals had no significant effect on rating of predicted tolerance, tiredness, or severity (Figures 20 to 22). In LT4, ratings of comfort, tiredness and severity demonstrated significant changes ($p<0.05$) with daily, mid-exposure 15 minute rest intervals (Figures 24 to 26). Comfort and severity rating improved by 7%, whereas tiredness showed a 24% improvement. Predicted tolerance rating did not significantly change following the rest interval (Figure 27). In LT5, comparisons of the slopes of regression equations of continuous and intermittent exposures indicated that intermittent rest intervals had a slight recovery effect (n.s.) on subjective comfort, predicted tolerance, tiredness and severity. However, paired t-tests of the mean values demonstrated that the intermittent condition was significantly more comfortable, less tiring and less severe ($p<0.05$) (Figures 28 to 30). Predicted tolerance did not demonstrate significant differences between the conditions (Figure 31).

In LT4, overnight recovery consistently improved comfort, tiredness and severity ratings ($p<0.05$). This was demonstrated by paired t-test comparison of the last measurement interval of one day and the first interval of the consecutive day of exposure (Figures 24 to 26). Predicted tolerance did not change significantly with overnight rest (Figure 27).

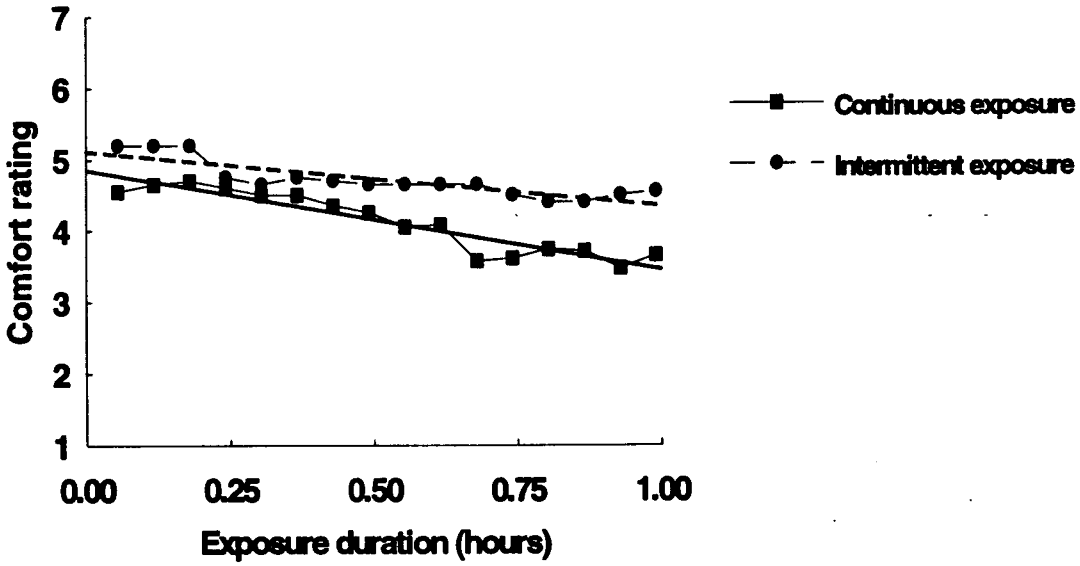


Figure 28 **Comparison between subjective comfort rating to continuous and intermittent shock exposures.**

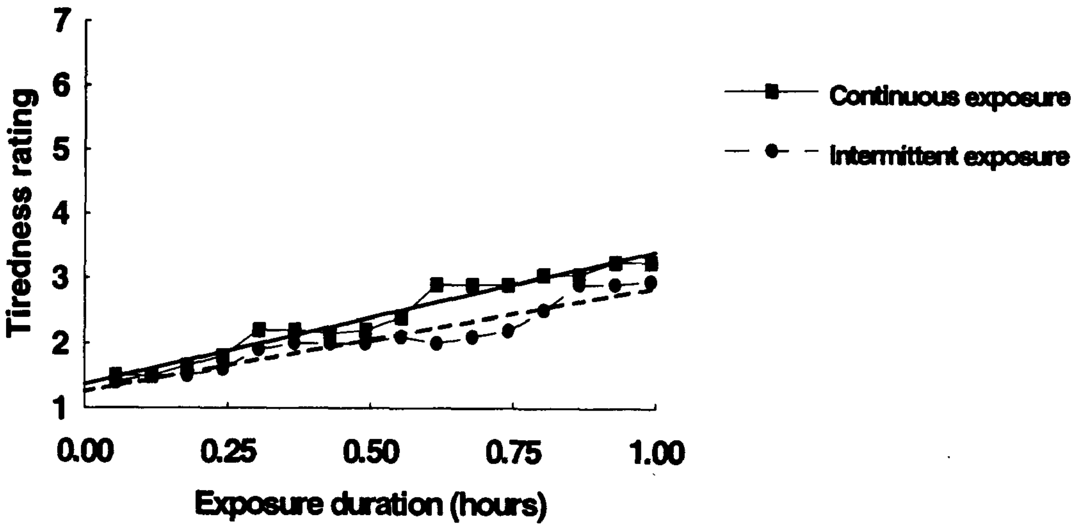


Figure 29 Comparison between subjective tiredness rating to continuous and intermittent shock exposures.

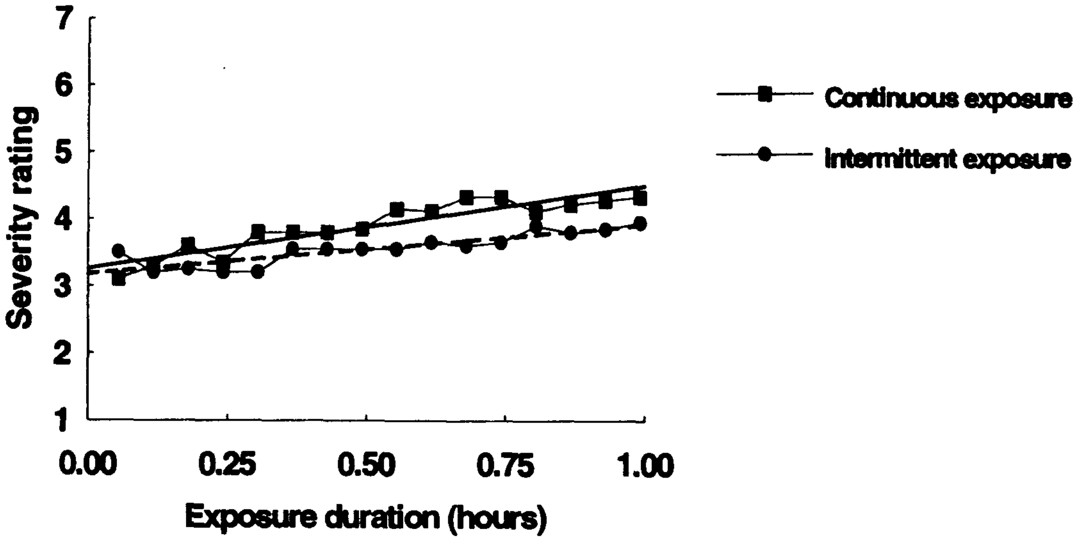


Figure 30 Comparison between subjective severity rating to continuous and intermittent shock exposures.

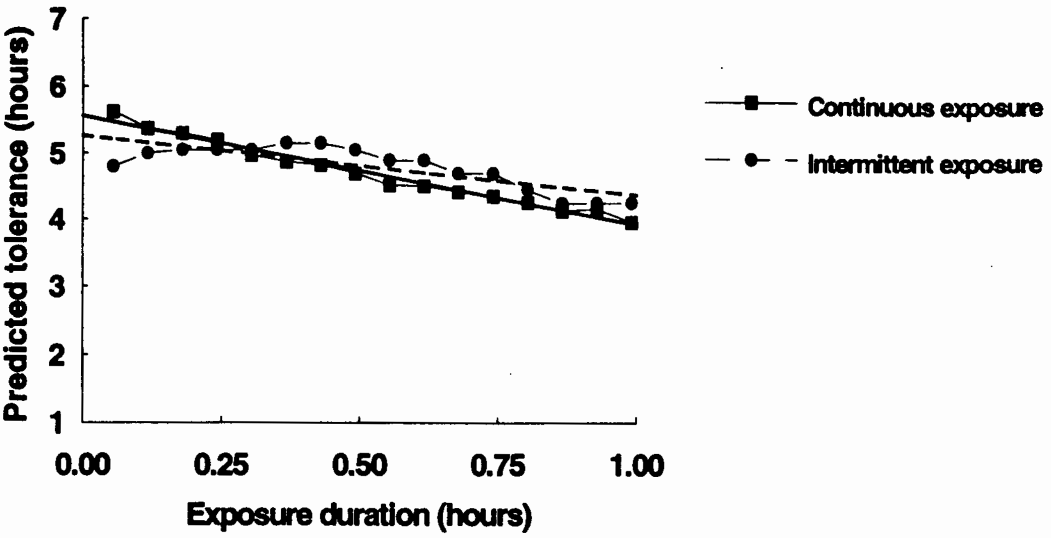


Figure 31 Comparison between subjective predicted tolerance rating to continuous and intermittent shock exposures.

Comparison of the VDV and Subjective Response

In LT1, a comparison of the ratio of the subjective rating obtained at specific dose levels to the expected ratio, based on the VDV, demonstrated several effects. In terms of comfort, the high dose conditions had a greater effect on subjective rating for z axis shocks than that predicted by the VDV, and less effect in the x and y axes (Table 19A). Additionally, comfort values were more affected with the higher amplitude shock conditions in the z axis (i.e., 2g, 8/minute; and 4g, 8/minute). Severity rating increased to a greater extent from low to high dose than predicted by the VDV. However, this was observed only for the higher amplitude shock conditions (i.e., 2g, 8/minute; and 4g, 8/minute) (Table 19B). Following a two-fold decrease in exposure dose, the expected sixteen-fold increase in predicted tolerance was not observed. Instead, predicted tolerance rating only increased by a factor of 1.5 to 5.5, depending on the shock axis (Table 19C). For further explanation see subsection entitled 'British Standards Institution Document 6841' in the Background section.

Comparisons were made between regression of tiredness rating with the time-dependence of the VDV ($t^{1/4}$) and duration of exposure (t^1) in LT3, LT4 and LT5. Regression coefficients demonstrated that subjective tiredness rating in LT4 and LT5 followed a linear function better than the time dependency of the VDV. Figure 32 demonstrates this using LT5 tiredness rating as a function of duration with the superimposed time-dependency of the VDV. In LT3, subjective tiredness rating followed the VDV function better than a linear function (Table 20).

Table 19 **The ratio of subjective rating in Experiment LT1 between two exposures (VDV=14.5 and 29.1 $ms^{-1.75}$) where VDV was doubled by a two-fold increase in amplitude for a given shock rate, for Comfort (A), Severity (B) and Tolerance (C).**

A. Comfort

Condition Ratio (shock amplitude)	Shock Rate (min^{-1})	Expected Ratio	+x	-x	+y	+z	-z
2 g/ 1g	128	0.5	0.71	0.62	0.65	0.40	0.22
4 g/ 2 g	8	0.5	0.65	0.44	0.63	0.23	0.18

B. Severity

Condition Ratio (shock amplitude)	Shock Rate (min^{-1})	Expected Ratio	+x	-x	+y	+z	-z
2 g/ 1g	128	2.0	1.9	2.4	2.7	1.7	2.1
4 g/ 2 g	8	2.0	3.5	3.9	4.4	2.9	2.8

C. Predicted Tolerance

Condition Ratio (shock amplitude)	Shock Rate (min^{-1})	Expected Ratio	+x	-x	+y	+z	-z
1 g/ 2 g	128	16	1.7	1.8	1.8	3.5	3.5
2 g/ 4 g	8	16	1.5	2.2	2.0	4.1	5.5

Table 20 **Coefficients of regressions for subjective tiredness rating with a linear function and with the VDV (non-linear function).**

Experiment	Linear function (t^1) (r^2, α=0.05)	VDV function ($t^{1/4}$) (r^2, α=0.05)
LT3	0.65	0.82
LT4	0.98	0.91
LT5	0.91	0.80

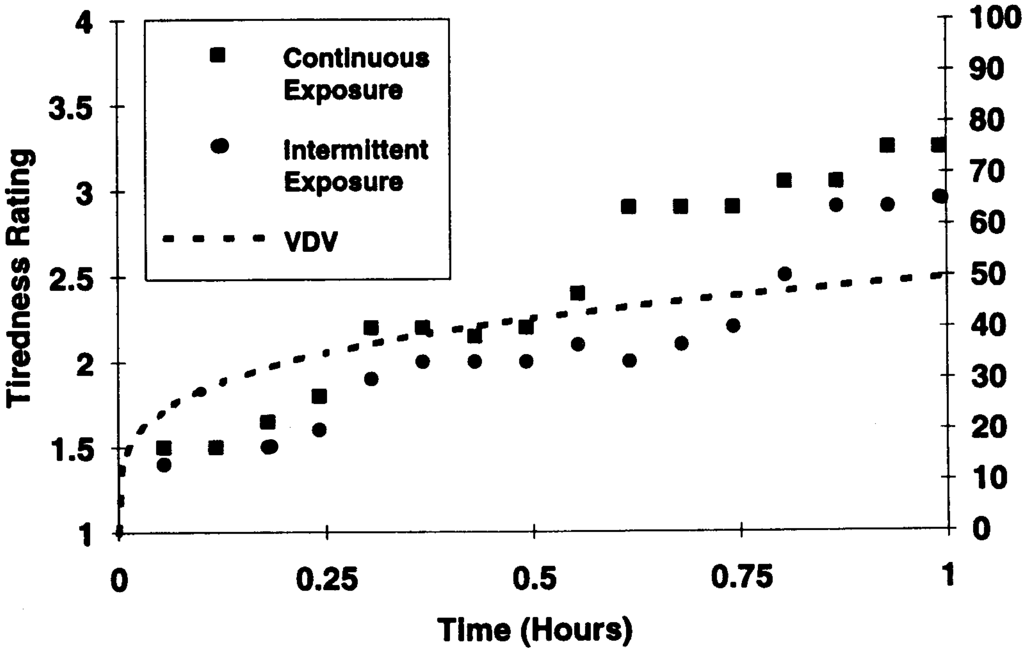


Figure 32 **Comparison of the time-dependency for tiredness rating and the VDV, for LT5 continuous and intermittent exposures.**

DISCUSSION

Short Term Single Shock Experiments

The subjective response to single shocks was examined to determine its relation to shock characteristics, to determine the relation between subjective response and spinal transmission of shocks, and to examine the relation between existing biodynamic models and subjective response.

Effect of Shock Characteristics on Severity Rating

The subjective response to motion has been previously studied for vibration (Magid, 1960; Miwa, 1968; Griffin and Whitham, 1980; and Griffin, 1990), but rarely for mechanical shocks. Studies incorporating mechanical shocks have been limited to low amplitude acceleration and positive z axis shocks (Kjellberg and Wikstrom, 1985; Howarth and Griffin, 1991). The present study expands the existing literature by providing a profile of subjective response to shock exposures which have a more comprehensive range of motion characteristics (i.e., amplitude, axis, direction and frequency).

Based on subjective severity rating, the most severe motion characteristics were z axis shocks at the lowest shock frequency tested (2 or 4 Hz, depending on the amplitude) in both the positive and negative direction. This pattern of relative severity between axes is consistent with studies of equivalent comfort contours collated by Griffin (1990) for low amplitude (0.01 to 1 g) sinusoidal vibration.

Subjective severity rating decreased with increasing shock frequency for all axes, directions and amplitudes. These results are supported by Howarth and Griffin (1991) who showed that discomfort caused by low amplitude (0.4 to 1.4 g) shocks was highest for the lowest tested frequency (1 Hz) and decreased significantly with each increase in test frequency (1, 4 and 16 Hz). Some studies have shown a resonant frequency between 4 to 8 Hz for subjective rating to sinusoidal vibration in the z axis (Magid *et al.*, 1960; and Griffin, 1990). However, this finding was not duplicated in the present study. A maxima in subjective response to shocks could exist at a lower frequency than tested in the present experiments. However, due to the mechanical limitations of the MARS, lower frequency shocks could not be generated. In a simple biodynamic model such as the DRI, transmission of shocks will not produce a maximum response at the resonant frequency as is observed with sinusoidal vibration. This is consistent with test shocks applied to the DRI model in which the maximum response occurs at a shock frequency lower than the resonant frequency. Hence, it was not surprising that a maxima in subjective severity was not observed.

Shocks in the positive and negative direction elicited a similar level of severity rating in the x and z axes. Howarth and Griffin (1991) also found that direction (positive or negative) of low amplitude shocks (i.e., 0.4 to 1.4 g) did not have a significant effect on subjective discomfort. In reference to the evaluation of severity of mechanical shocks, this suggests that negative and positive shocks may be weighted equally with frequency filters, or that one biodynamic model may be applied to shocks in both directions.

Linearity of Subjective Severity to Shock Amplitude

The results of the short term experiments reject the hypothesis that the subjective response to mechanical shock is non-linear with respect to the amplitude. Subjective severity rating increased linearly as a function of shock amplitude for all shock frequencies, axes and directions. These results agree with biomechanical analyses in the present study which demonstrate that transmission of acceleration in the x and y axes measured at the spinous processes of thoracic and lumbar vertebrae increases linearly with shock amplitude. However, transmission of acceleration in the z axis increased non-linearly with shock amplitude. This finding may have resulted from the presence of high frequency components in the biomechanical response to high amplitude, low frequency mechanical shocks in the z axis. It is possible that subjective perception did not reflect the effects of these high frequency components as a non-linear response was not observed with subjective severity rating in the present study. Another possibility is that the subjective rating scale is non-linear. Subjective scales are suggested to be non-linear closer to the end points of the scale. However, several indications in the present study suggested that the scale was linear. The extreme end points of the scale used in the experiments were assigned with semantic labels which were familiar to the sample population. The biomechanical transmission and severity rating data in the x and y axes both demonstrated a linear increase with increasing shock input amplitude. Hence, the close agreement between the transmitted acceleration and severity rating as a function of shock frequency suggests that the subjective scale was linear in the present study.

The results of the short term experiments indicate that the human response to mechanical shocks in the x and y axes can be represented or modelled by simple linear models or frequency weighting filters. The subjective response to z axis shocks was linear, although the biodynamic response was non-linear. These findings indicate that further study of the subjective and biodynamic response to z axis shocks is warranted. This would include determining the effect of the very high frequency components present in the biodynamic response to high amplitude, low frequency mechanical shocks. Overall, the biodynamic data from the present study suggest that the human response to mechanical shocks in the z axis needs to be represented by a non-linear model.

Relation Between Subjective Severity and Spinal Transmission

The results of the short term experiments confirm the hypothesis that the subjective response to mechanical shocks, as a function of frequency and amplitude, is representative of the associated biomechanical response. Subjective severity closely approximated the degree of acceleration transmitted to the thoracic and lumbar vertebral levels in the x, y and z axes. Subjective severity was more closely related to spinal transmission than to any of the existing biodynamic models and filters, with the exception of the Fairley-Griffin (5 Hz) and DRI (8.4 Hz) models in the positive z axis. In terms of evaluating health hazard effects, these findings support the use of subjective severity as a valid method of estimating the relative amplitude of spinal acceleration transmitted to the thoracic and lumbar vertebral levels in response to mechanical shocks.

Long Term Repeated Shock Experiments

The subjective response to repeated mechanical shocks was examined to determine the time- and amplitude-dependency of subjective response, as well as the effect of rest intervals on recovery.

These findings were then compared with the functions and models used in existing methods of evaluating the effects of mechanical shocks.

Testing of Hypotheses

In some instances statistical testing for significance involved the use of multiple t-tests. Interpretation of these findings were treated with caution. Multiple t-tests ($p<0.05$) were used as preliminary statistical methods, and were considered adequate for hypothesis rejection. However, if the tests indicated a significant finding, the data were analyzed again based on the Bonferroni inequality principle to avoid increasing the probability of Type I errors. For further explanation see the section entitled 'The Effect of Shock Axis, Direction, Amplitude and Rate'.

Effect of Shock Axis and Direction

LT1 experiments demonstrated that the direction of shock input (positive and negative) had no significant effect on subjective response to shock exposures in either the x, y or z axis. In the context of subjective response, these results indicate that positive and negative shocks can be weighted equally in any evaluation model. However, z axis shock exposures were rated significantly worse than exposures in the x and y axes. This finding supports the provision of a different weighting for z axis motion, and identical weightings for x and y axis motion.

Effect of Duration of Exposure on Subjective Response

Results of LT2, LT3 and LT4 show that the duration of exposure has a significant effect on comfort, tiredness and severity rating. Similar time dependency has been demonstrated for exposures of short durations (0.5 to 30 seconds) (Miwa, 1968; Griffin and Whitham, 1980; Kjellberg and Wikstrom, 1985). Predicted tolerance demonstrated a significant change with duration in the two-hour (LT2) exposures. Overall, a 14% difference between beginning and end of exposure was demonstrated. For experiments LT3 and LT4, predicted tolerance did not show a significant change as a function of duration of exposure. This suggests that a predicted tolerance rating obtained after a few minutes of exposure can provide a good estimate of exposure tolerance. Although these short term predictions of tolerance were not tested against absolute tolerance, they were shown to be reliable from the beginning to the end of LT repeated shock exposures of 4 to 7 hours in duration.

In the 5 day exposure in LT4, the mean level of subjective rating only demonstrated changes from Day 1 to Day 2 in severity and predicted tolerance. This may be due to physical and psychological reactions resulting from the effects of the first day of exposure. In terms of rate of change within each day of exposure, the only change observed was a decrease in the slope of tiredness from Day 1 to Day 4. However, the general lack of change in subjective rating from day to day suggests that the subjective effect of daily exposure was not cumulative over the course of a five day exposure.

Effect of Rest Intervals on Subjective Response

The results of the LT experiments confirm the hypothesis that rest intervals during exposure to mechanical shocks result in recovery in the indices of subjective response. The short rest intervals significantly improved comfort rating in experiments LT3, LT4 and LT5. Additionally, tiredness and severity rating were significantly improved in experiments LT4 and LT5. In LT4, short rest intervals demonstrated the greatest effect on tiredness rating (up to 24% over a 15 minute rest interval). These findings are supported by anecdotal comments regarding physical status which indicated that short term rest intervals relieved discomfort by allowing the subject to stretch, improve blood circulation, relieve postural discomfort from the seat and provide a mental break from the constant motion.

There was significant overnight recovery in comfort, tiredness and severity rating. The lack of a cumulative effect in mean rating over the five day exposure also supports the concept of overnight recovery. Overnight rest appeared to return the subjects to approximately the same subjective level before each daily exposure. If subjective responses accurately represent the physical well-being of the subject, then overnight rest intervals provided sufficient recovery from daily exposures to mechanical shocks at the exposure level presented in this experiment. However, these findings are not supported by anecdotal comments of physical status after overnight rest which indicated that overnight recovery was not complete. The most common comment involved persistent erector spinae muscle soreness and stiffness. The dichotomy between subjective rating and physical symptoms (pain and soreness) suggests that chronic health effects may accumulate with exposure to repeated mechanical shocks which are not perceived subjectively. Hence, the interpretation and application of subjective rating as a guideline for limiting exposure to mechanical shocks should include a safety margin to avoid chronic health effects such as chronic low-back pain and degeneration of the vertebral column.

These findings support the idea that a short term and long term recovery function should be included in a dose function for the evaluation of exposure to repeated mechanical shocks. The current VDV does not allow for recovery during a day of exposure, and assumes a full recovery overnight, irrespective of the dose magnitude. These findings disagree with the VDV as a method for evaluating exposure to repeated mechanical shocks. A recovery function could be incorporated into a dose function, depending on the time-dependency of the function. In the case of a linear dose function, intermittent rest intervals would modify the growth of the dose function with respect to duration of exposure. Mid day rest intervals would reset the accumulated dose attained by the subject to a lower level, depending on the duration of the rest interval and the overall severity of the exposure. In the case of a non-linear dose function such as the VDV which accumulates via integration of the experienced acceleration, a recovery function could be applied to each discrete exposure time interval. However, further study is required for the development of such recovery functions.

Comparison of Dose Response Functions and Biodynamic Models with Subjective Response

The existing dose response functions, such as the VDV and the ASCC and their respective weighting filters and models, were compared to subjective rating. Generally, the findings of the present study demonstrated that the existing evaluation methods are inadequate for the evaluation of exposure to repeated mechanical shocks.

Subjective rating of comfort and severity in experiment LT1 demonstrated that the amplitude-dependent function of the VDV did not agree with the changes in subjective response with changes in shock amplitude. The VDV was shown to underestimate rating of discomfort at higher dose levels in the z axis and overestimate rating of discomfort in the x and y axes. Severity rating was underestimated by the VDV in all three axes in the higher amplitude shock conditions. These findings suggest that the VDV function is not applicable to the evaluation of mechanical shocks.

The results of the LT experiments confirm the hypothesis that the time-dependency of existing dose functions does not accurately represent the subjective response to exposures of mechanical shocks. It was generally found that the time dependency of subjective tiredness was more closely represented by a linear function as opposed to the non-linear functions of the VDV ($t^{1/4}$) and the ASCC ($t^{1/8}$). This linear time-dependency of subjective response was demonstrated in experiments LT2, LT4 and LT5. However, the time-dependency of subjective response needs to be examined further.

The findings of the present study demonstrate that existing biodynamic models and filters do not accurately represent the subjective severity of single shocks, with the exception of the Fairley-Griffin (5 Hz) and DRI (8.4 Hz) models for +z axis shocks. These findings have implications on the ability of dose response functions to evaluate exposures to mechanical shocks. The VDV relies on frequency weighting filters which were shown to be inadequate in representing the subjective response. The ASCC, which uses the DRI (11.9 Hz) model, would serve as a more useful dose function because it relates to health effects. However, it was also shown to inaccurately represent the human response to mechanical shocks. Based on the subjective severity findings in the present study if severity of the human response is linear with shock amplitude, then the human response can be represented by a simple linear model. However, the findings of the present study indicate that the DRI model parameters need to be modified. This may be accomplished by lowering the natural frequency of the model to approximately 5 Hz, based on the closer representation of severity by the Fairley-Griffin model. In addition, the critical damping coefficient could be adjusted to fit the data more closely. However, the model parameters should be based on both subjective data and objective data.

The ASCC was developed based on injury data, and provides limits which are related to comfort and health effects. In contrast, the VDV has not been related to comfort and health effects and provides only comparative levels of exposure to mechanical shocks. The present study used isolated exposures (i.e., on one day, or in one week) which resulted in no major acute health effects. However, this does not infer that similar levels of exposures could be continued in an occupational setting without the development of chronic health effects. Anecdotal physical status reports indicated that soreness and stiffness persisted for up to 48 hours post-exposure. This is not appropriate for a normal occupational setting and supports that concept that chronic health effects may accumulate with such exposures. Further research is required to develop a dose response function which is able to determine the risk of injury from occupational exposure to mechanical shock. In particular, it is necessary to associate specific dose values with injury or health effect data and to determine the variance in the threshold of injury associated with relevant populations.

CONCLUSIONS

The major conclusions of the present study are:

1. The effect of shock amplitude on subjective severity is linear within each shock frequency.

2. Subjective severity closely approximates transmission of acceleration from the seat to the lumbar and thoracic vertebrae in all three axes.

3. Short term (minutes) and long term (overnight) rest intervals are sufficient to promote recovery in subjective rating of comfort, tiredness and severity and should assist in the development of a recovery function.

4. Existing biodynamic models and filters do not accurately represent the subjective severity of single shocks, with the exception of the Fairley-Griffin and DRI (8.4 Hz) models in the positive z axis.

5. Subjective ratings do not agree with the amplitude- and time-dependency of the VDV dose function.

These findings support the development of a new dose response model for the evaluation of repeated mechanical shocks which has a different frequency response, amplitude- and time-dependency than expressed in the existing VDV and DRI models.

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APPENDIX A

ST1 Subjective Response Data Sheet

Subject: Date: Time: Axis:

Sample Response Scale

1	2	3	4	5	6	7

Barely Perceptible *Extremely severe*

Q1. Compare: Is this shock greater than, equal to, or less than the last shock?

Q2. Rate the severity of this shock. (Barely perceptible = 1 - Extremely severe = 7)

Q3. How do you rate the overall motion? (Very comfortable = 1 - Extremely uncomfortable = 7)

	Exposure Number: Shock Condition (g, axis)						
Shock #	**1:**	**2:**	**3:**	**4:**	**5:**	**6:**	**7:**
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							
11							
12							
13							
14							
15							
16							
17							
18							
19							
20							
21							
22							
23							
24							
25							
26							
27							
28							
29							
30							
31							
32							
Q3 Rating:							

LT1 Subjective Response Data Sheet

Subject:	**Date:**	**Time**
Experiment:	**Shock Axis:**	

Sample Response Scale

1	2	3	4	5	6	7

Not at all comfortable *extremely comfortable*

Q1: Do you feel comfortable? (1 = Not at all comfortable - 7 = Extremely comfortable)

Q2: How long would you be able to tolerate this exposure to motion if you were riding in a vehicle on a cross-country mission? (Unrestrained time scale)

Q3: How severe do you rate the exposure to motion right now? (1 = Extremely severe - 7 = Barely perceptible)

Q4: Rank the 5 exposures that you have had today in order of severity. (1 = least severe - 5 = most severe).

Procedure: (g, axis)	**Time** (min:sec)	**Q1** comfort	**Q2** tolerance	**Q3** severe	**Q4 Rank** Order
#1:	**0:30**				
	3:00				
Rest					
#2:	**0:30**				
	3:00				
Rest					
#3:	**0:30**				
	3:00				
Rest					
#4:	**0:30**				
	3:00				
Rest					
#5:	**0:30**				
	3:00				
End					

LT2 Subjective Questionnaire Data Sheet

Question #:

Q1: Do you feel comfortable? (1 = Not at all comfortable - 7 = Extremely comfortable)
Q2: How long would you be able to tolerate this exposure to motion if you were riding in a vehicle on a cross-country mission? (Unrestrained time scale)
Q3: Do you feel tired? (1 = Not at all tired - 7 = Extremely tired)
Q4: How severe do you rate the exposure to motion right now? (1 = Extremely severe - 7 = Barely perceptible)

Sample Response Scale

1	2	3	4	5	6	7
Not at all comfortable						*extremely comfortable*

Subject: **Date:** **Time:** **Caffeine intake (type, time, amt.):** /
Experiment: **Caffeine intake (type, time, amt.):** /

Exp. Time (min:sec)	**Comfort**	**Tolerate**	**Tired**	**Severe**	***Notes***	**Comments**
Start						
03:45						
07:30						
15:00						
30:00						
35:00						
1:00:00						
1:30:00						
1:35:00						
2:00:00						
END						

Experimental Notes: (Lunch, snacks, etc. for subject - reattachment of sensors - distractions during exp't - etc.)

LT3 Subjective Questionnaire Data Sheet

Question #:

Q1: Do you feel comfortable? (1 = Not at all comfortable - 7 = Extremely comfortable)
Q2: How long would you be able to tolerate this exposure to motion if you were riding in a vehicle on a cross-country mission? (Unrestrained time scale)
Q3: Do you feel tired? (1 = Not at all tired - 7 = Extremely tired)
Q4: How severe do you rate the exposure to motion right now? (1 = Extremely severe - 7 = Barely perceptible)

Sample Response Scale

1	2	3	4	5	6	7
Not at all comfortable						*extremely comfortable*

Subject: **Date:** **Time:** **Caffeine intake (type, time, amt.):**

Experiment: **Caffeine intake (type, time, amt.):** /

/

Exp. Time (min:sec)	Comfort	Tolerate	Tired	Severe	*Notes*	Comments
Start			-			
03:45						
15:00						
30:00						
35:00						
60:00						
1:30:00						
1:45:00						15 minute rest - stop run time
2:00:00						
2:30:00						
2:35:00						
3:00:00						
3:30:00						30 minute rest - stop run time
3:35:00						
4:00:00						
4:05:00						
4:30:00						
5:00:00						
5:15:00						15 minute rest - stop run time
5:30:00						
6:00:00						
6:05:00						
6:30:00						
7:00:00						
END			-			

LT4 Subjective Questionnaire Data Sheet

Question #:

Q1: Do you feel comfortable? (1 = Not at all comfortable - 7 = Extremely comfortable)
Q2: How long would you be able to tolerate this exposure to motion if you were riding in a vehicle on a cross-country mission? (Unrestrained time scale)
Q3: Do you feel tired? (1 = Not at all tired - 7 = Extremely tired)
Q4: How severe do you rate the exposure to motion right now? (1 = Extremely severe - 7 = Barely perceptible)

Sample Response Scale

1	2	3	4	5	6	7
Not at all comfortable						*extremely comfortable*

Subject: **Date:** **Time:** **Caffeine intake (type, time, amt.):**

Experiment: **Caffeine intake (type, time, amt.):**

Exp. Time (min:sec)	Comfort	Tolerate	Tired	Severe	*Notes*	Comments
Start						
03:45						
15:00						
30:00						
35:00						
1:00:00						
1:30:00						
1:35:00						
2:00:00						15 minute rest - stop run time
2:30:00						
2:35:00						
3:00:00						
3:30:00						
3:35:00						
4:00:00						
END						

Experimental Notes: (Lunch, snacks, etc. for subject - reattachment of sensors - distractions during exp't - etc.)

LT5 Subjective Questionnaire Data Sheet

(Part A-60 Minute Exposure)

Question #:

Q1: Do you feel comfortable? (1 = Not at all comfortable - 7 = Extremely comfortable)
Q2: How long would you be able to tolerate this exposure to motion if you were riding in a vehicle on a cross-country mission? (Unrestrained time scale)
Q3: Do you feel tired? (1 = Not at all tired - 7 = Extremely tired)
Q4: How severe do you rate the exposure to motion right now? (1 = Extremely severe - 7 = Barely perceptible)

Sample Response Scale

1	2	3	4	5	6	7
Not at all comfortable						*extremely comfortable*

Subject: **Date:** **Time:** **Caffeine intake (type, time, amt.):**

Experiment: **Caffeine intake (type, time, amt.):**

Exp. Time (min:sec)	Comfort	Tolerate	Tired	Severe	*Notes*	Comments
Start						
03:15						
07:00						
10:45						
14:30						
18:15						
22:00						
25:45						
29:30						
30:00						15 minute rest-stop run time
33:15						
37:00						
40:45						
44:30						
48:15						
52:00						
55:45						
59:30						
END						

LT5 Subjective Questionnaire Data Sheet

(Part B - Intermittent Exposure)

Question #:

Q1: Do you feel comfortable? (1 = Not at all comfortable - 7 = Extremely comfortable)
Q2: How long would you be able to tolerate this exposure to motion if you were riding in a vehicle on a cross-country mission? (Unrestrained time scale)
Q3: Do you feel tired? (1 = Not at all tired - 7 = Extremely tired)
Q4: How severe do you rate the exposure to motion right now? (1 = Extremely severe - 7 = Barely perceptible)

Sample Response Scale

1	2	3	4	5	6	7
Not at all comfortable						*extremely comfortable*

Instructions:
1. Start data collection
2. Subjective Questions given at 3:15 of 3:45 exposure
3. 7:30 of rest
4. Repeat steps 1-4 to Signature 16

Subject: **Date:** **Time:** **Caffeine intake (type, time, amt.):**
Experiment: **Caffeine intake (type, time, amt.):**

Signature #	**Comfort**	**Tolerate**	**Tired**	**Severe**	***Notes***	**Comments**
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						
11						
12						
13						
15						
16						

APPENDIX B

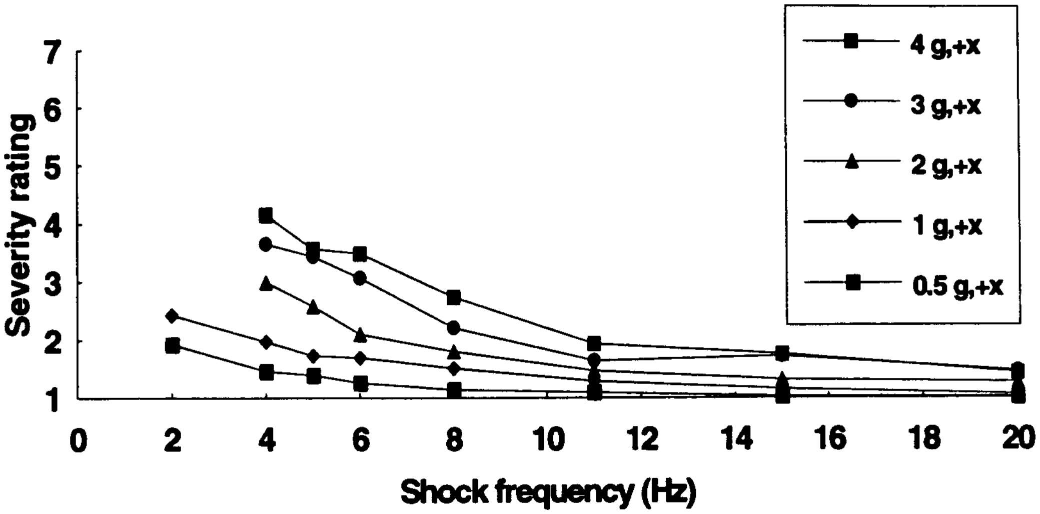

Figure B-1 Subjective severity rating to single shocks in the positive x axis as a function of shock frequency and amplitude.

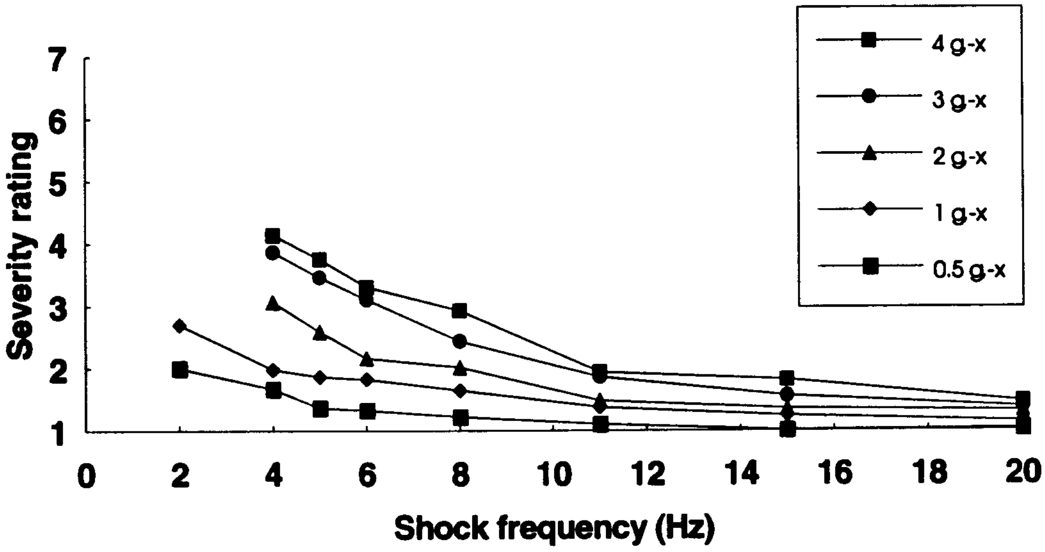

Figure B-2 Subjective severity rating to single shocks in the negative x axis as a function of shock frequency and amplitude.

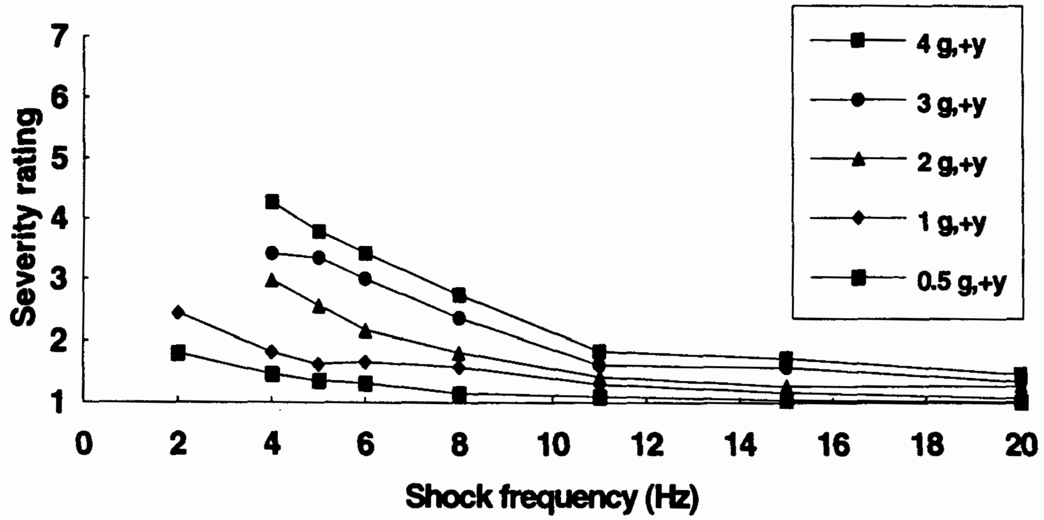

Figure B-3 Subjective severity rating to single shocks in the y axis as a function of shock frequency and amplitude.

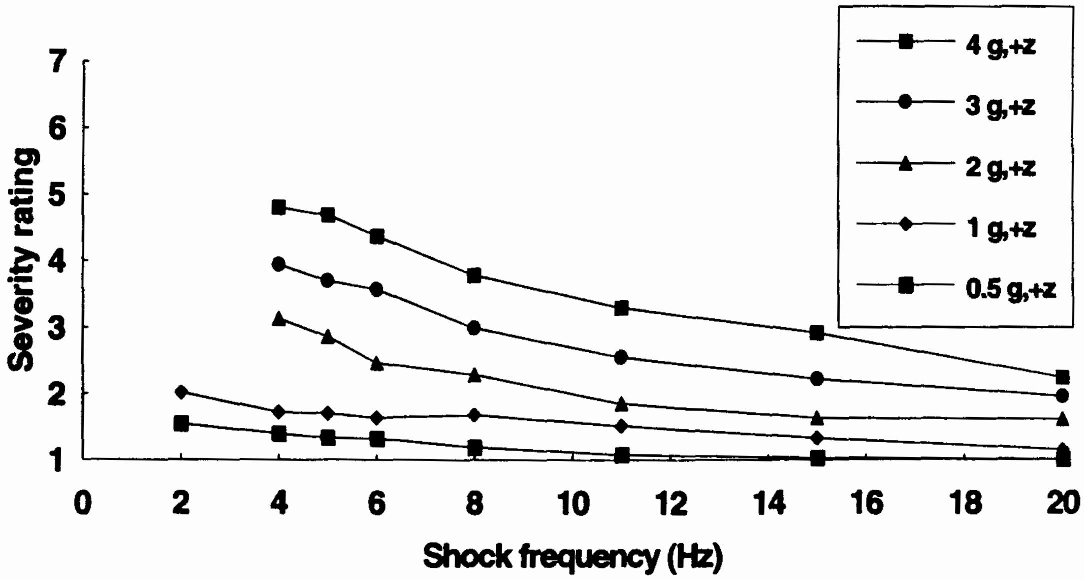

Figure B-4 Subjective severity rating to single shocks in the positive z axis as a function of shock frequency and amplitude.

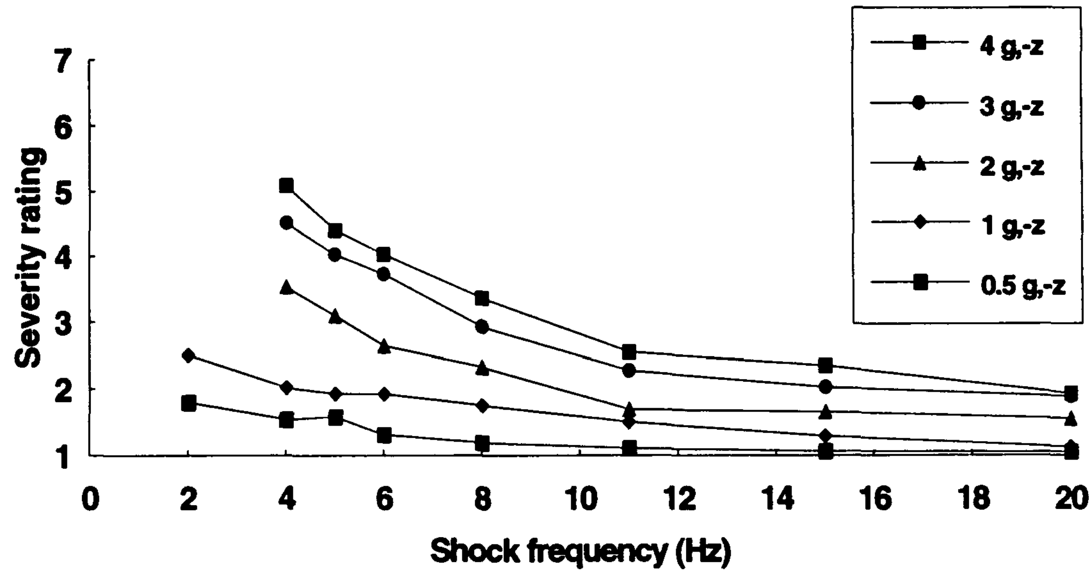

Figure B-5 Subjective severity rating to single shocks in the negative z axis as a function of shock frequency and amplitude.

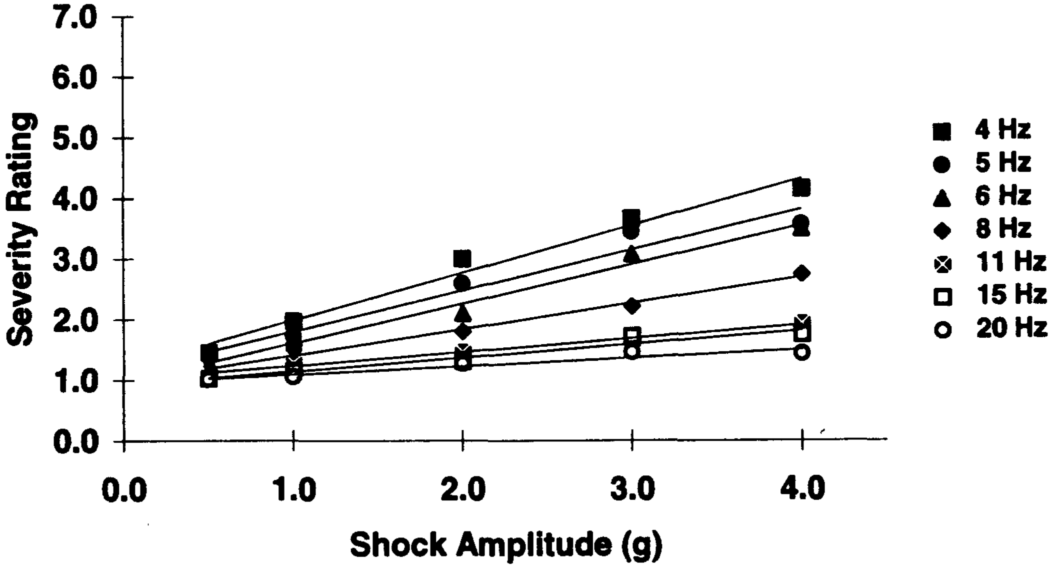

Figure B-6 Severity rating as a function of shock amplitude for different frequency, single shocks in the positive x axis.

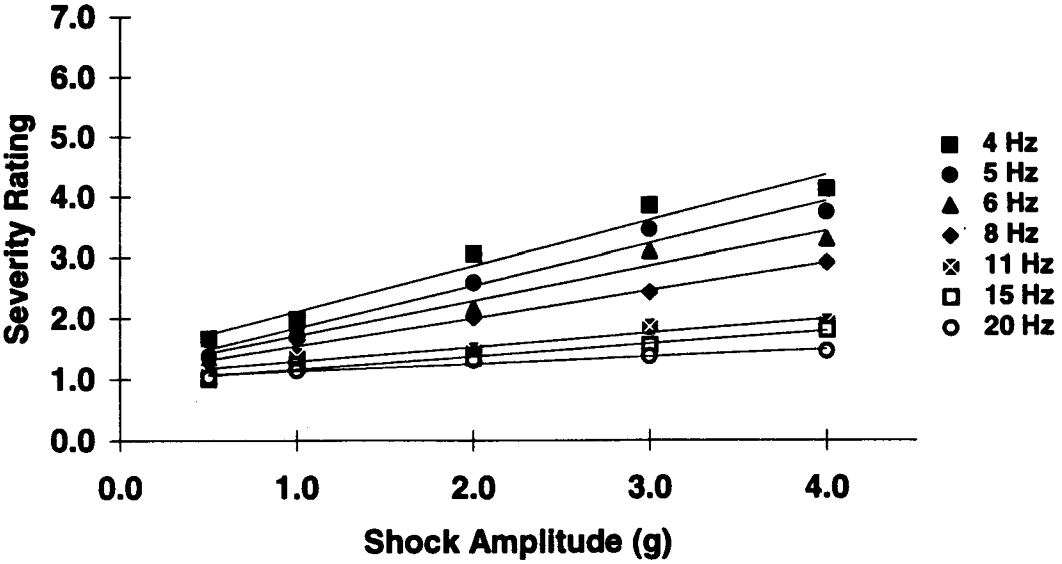

Figure B-7 Severity rating as a function of shock amplitude for different frequency, single shocks in the negative x axis.

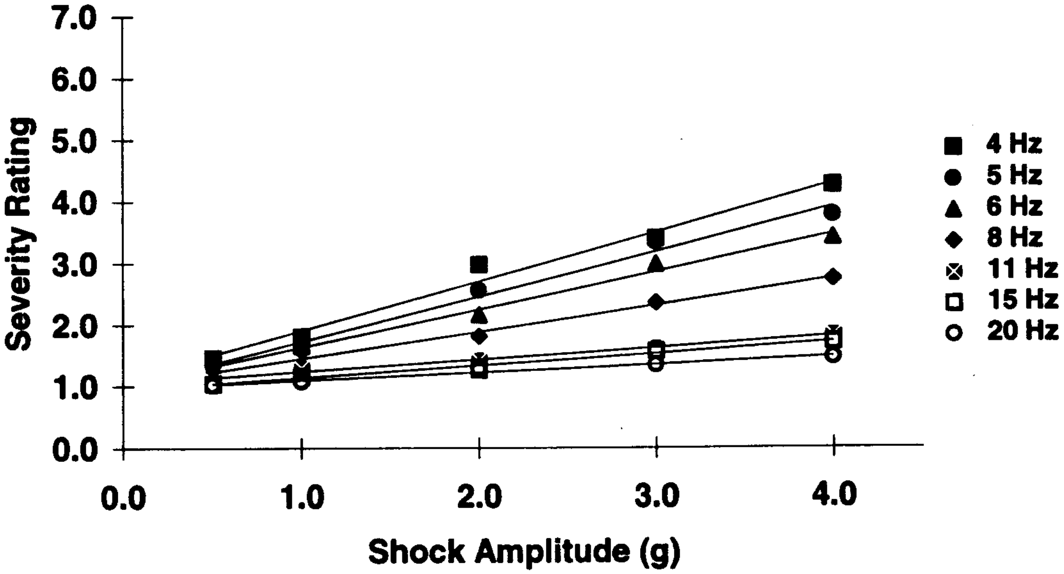

Figure B-8 Severity rating as a function of shock amplitude for different frequency, single shocks in the positive y axis.

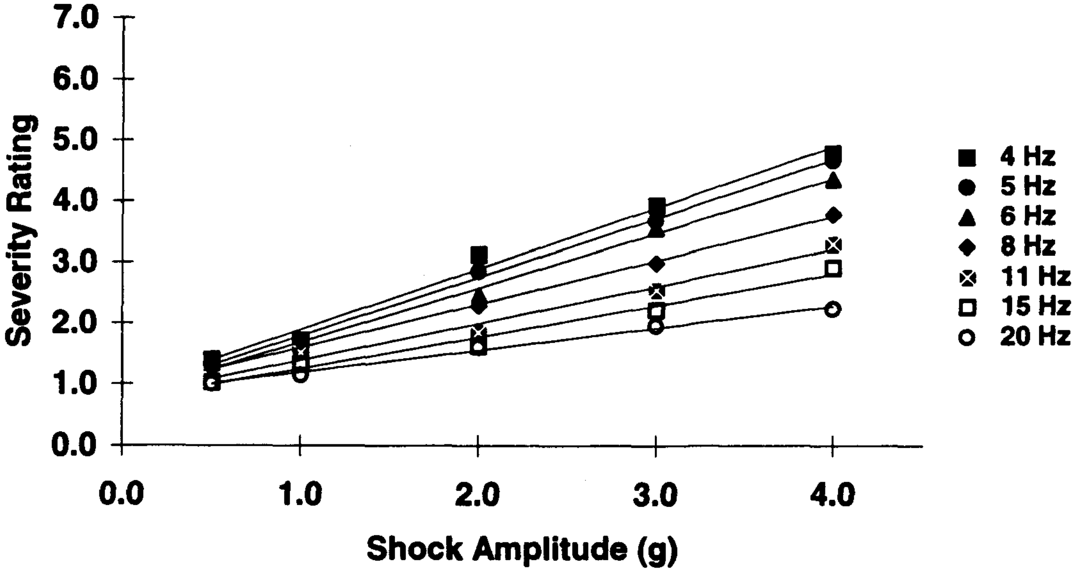

Figure B-9 Severity rating as a function of shock amplitude for different frequency, single shocks in the positive z axis.

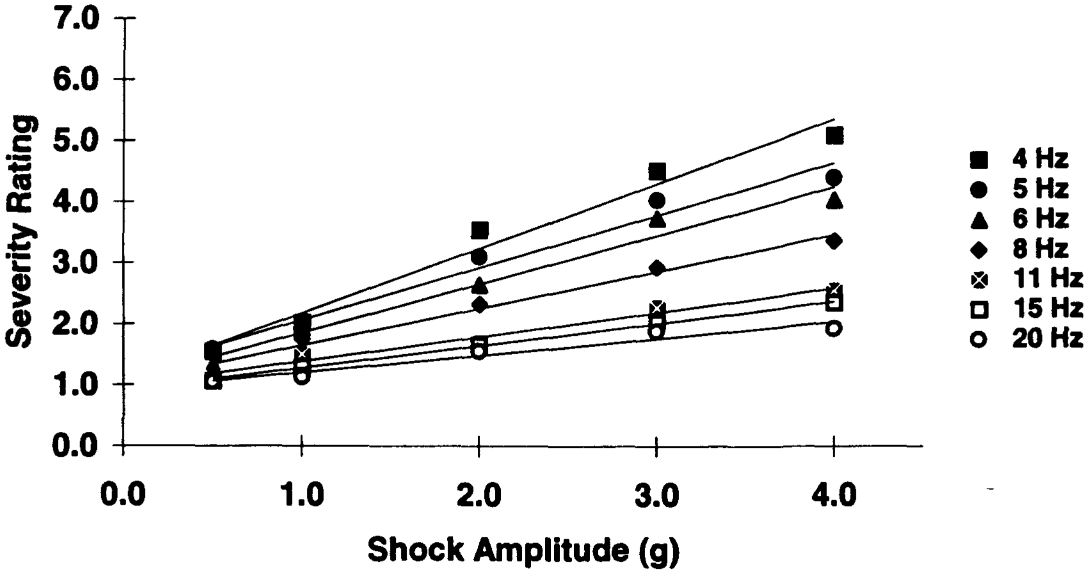

Figure B-10 Severity rating as a function of shock amplitude for different frequency, single shocks in the negative z axis.

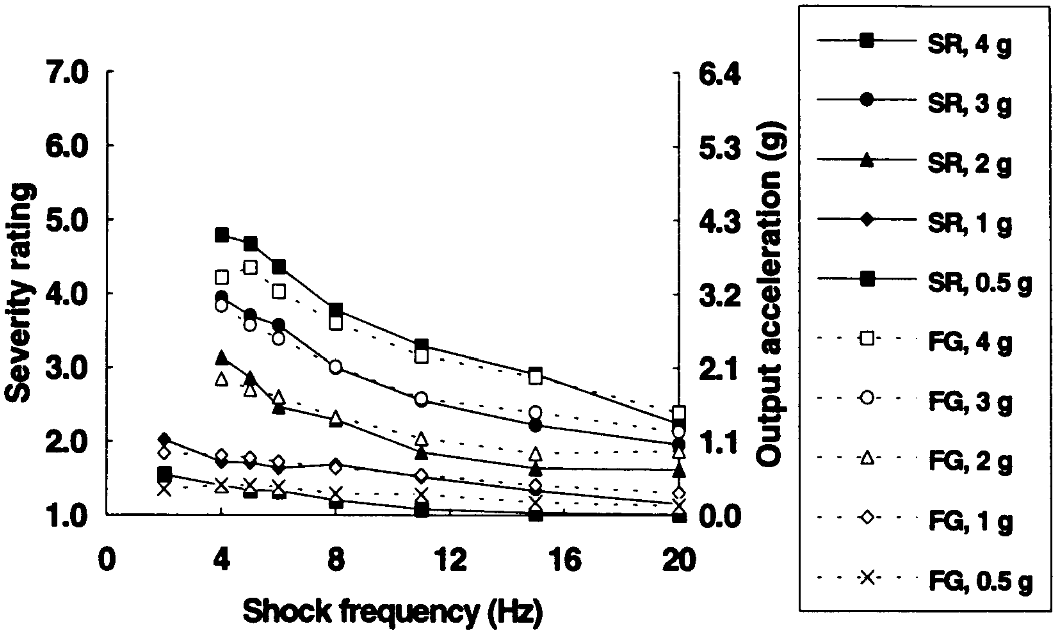

Figure B-11 Comparison between severity rating (SR) and expected output from the Fairley-Griffin (FG) model to positive z axis shocks.

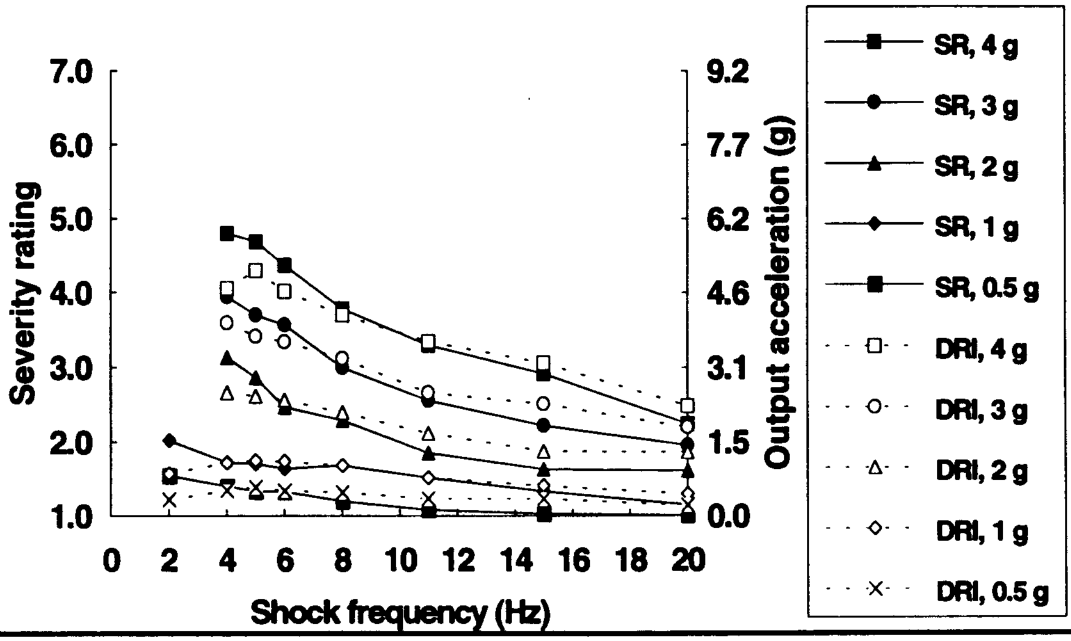

Figure B-12 Comparison between severity rating (SR) and expected output from the DRI model (8.4 Hz) to positive z axis shocks.

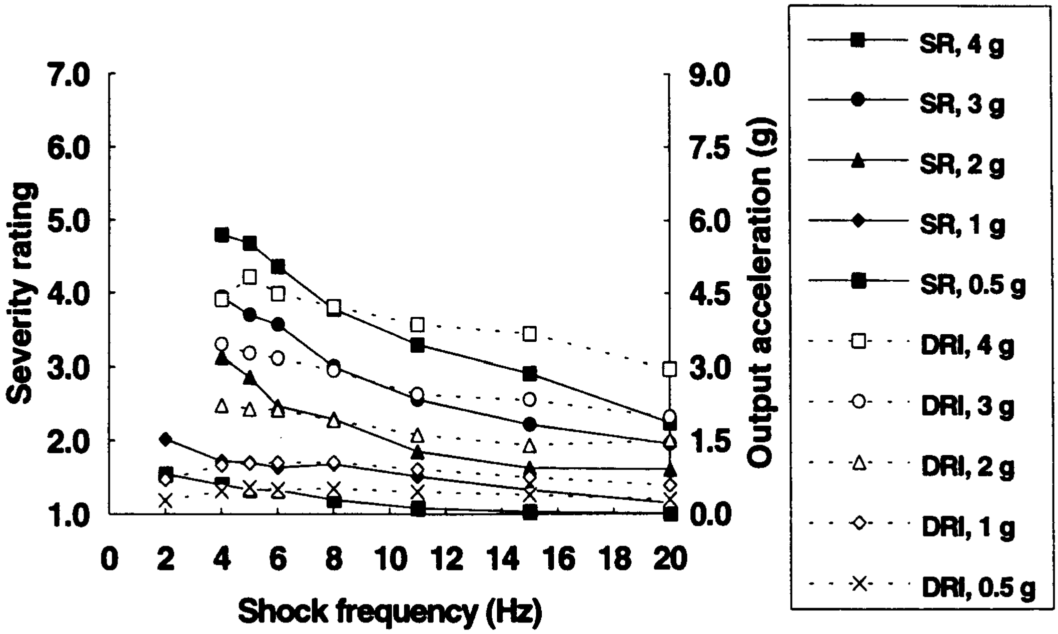

Figure B-13 Comparison between severity rating (SR) and expected output from the DRI model (11.9 Hz) to positive z axis shocks.

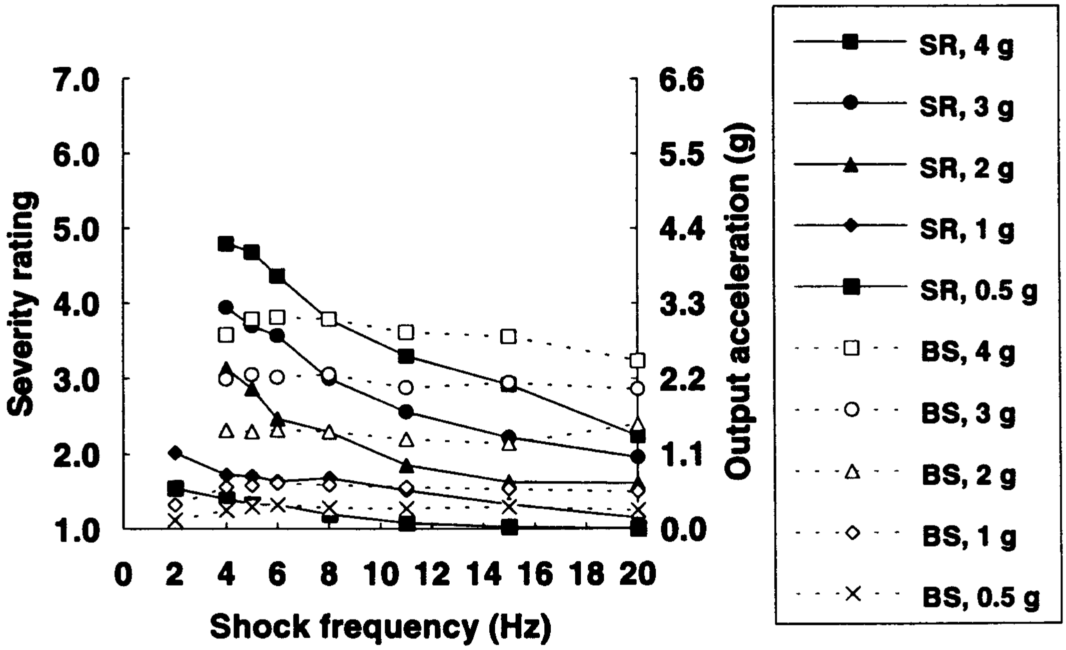

Figure B-14 Comparison between severity rating (SR) and expected output from the BS 6841 W_b filter to positive z axis shocks.

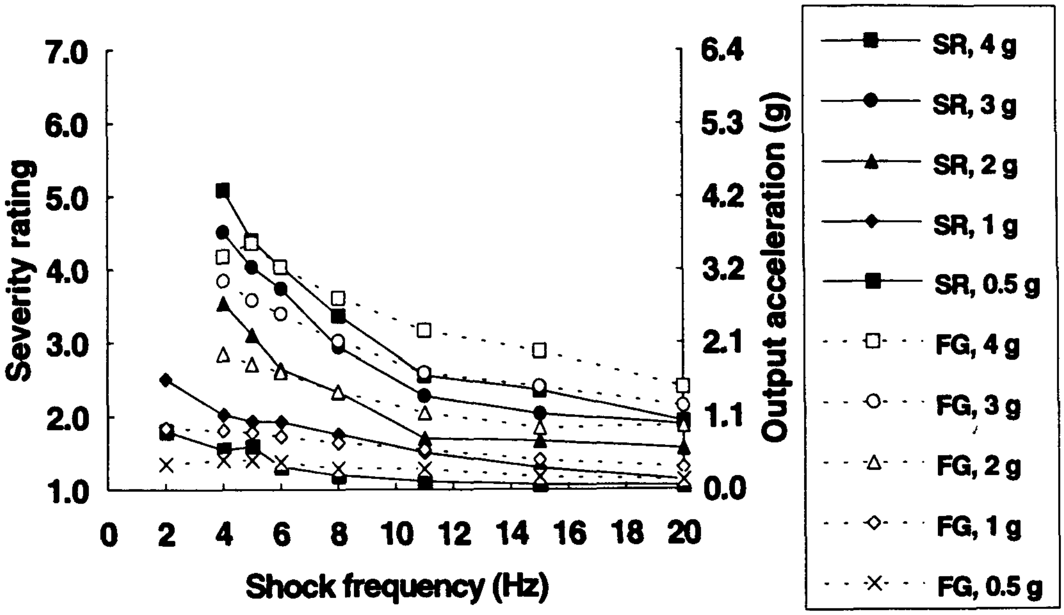

Figure B-15 Comparison between severity rating (SR) and expected output from the Fairley-Griffin (FG) model to negative z axis shocks.

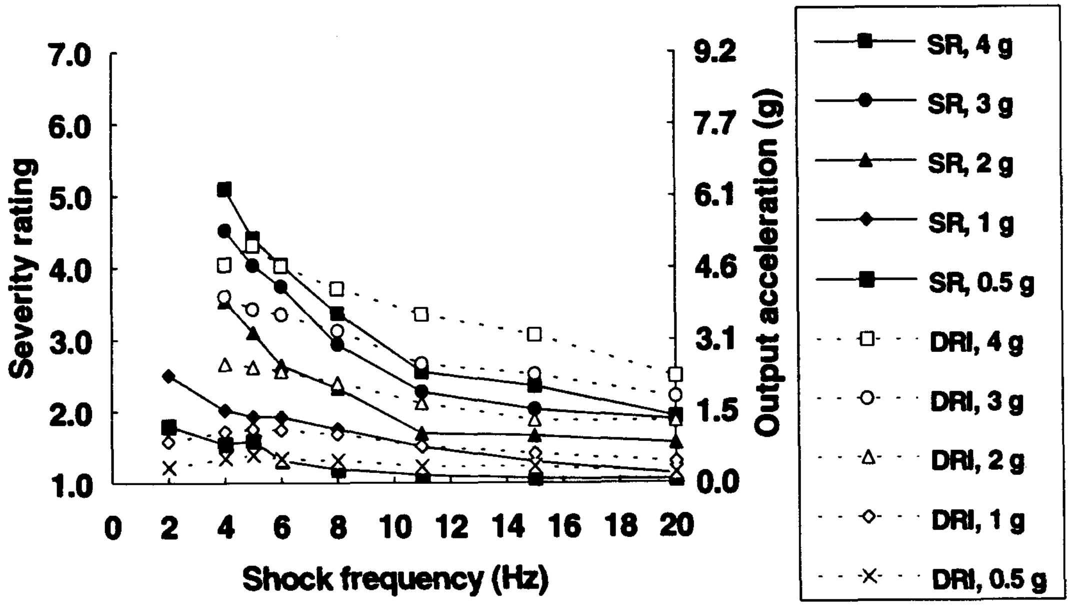

Figure B-16 Comparison between severity rating (SR) and expected output from the DRI model (8.4 Hz) to negative z axis shocks.

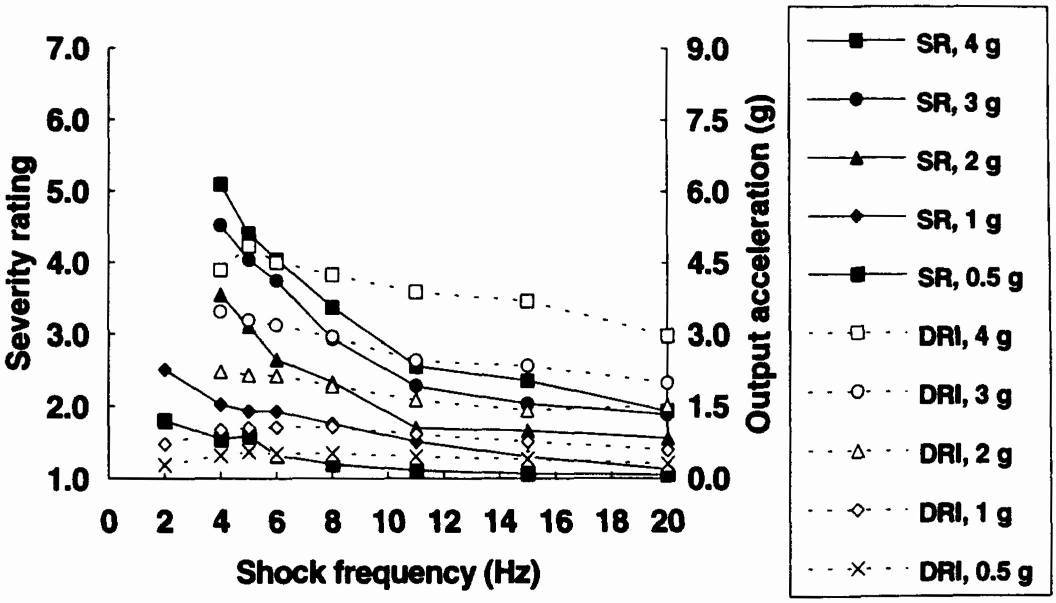

Figure B-17 Comparison between severity rating (SR) and expected output from the DRI model (11.9 Hz) to negative z axis shocks.

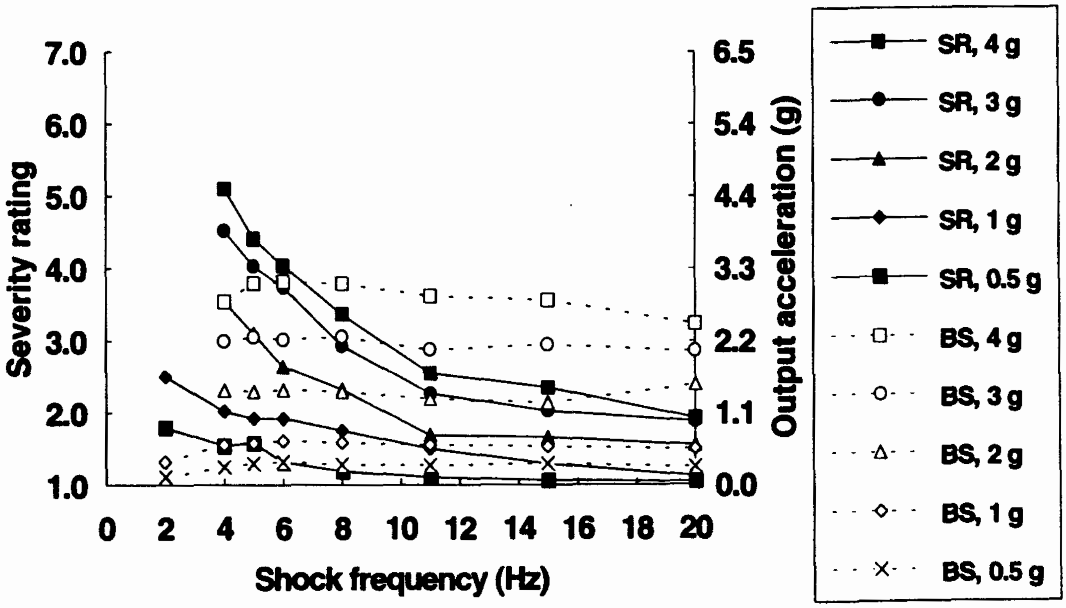

Figure B-18 Comparison between severity rating (SR) and expected output from the BS 6841 W_b filter to negative z axis shocks.

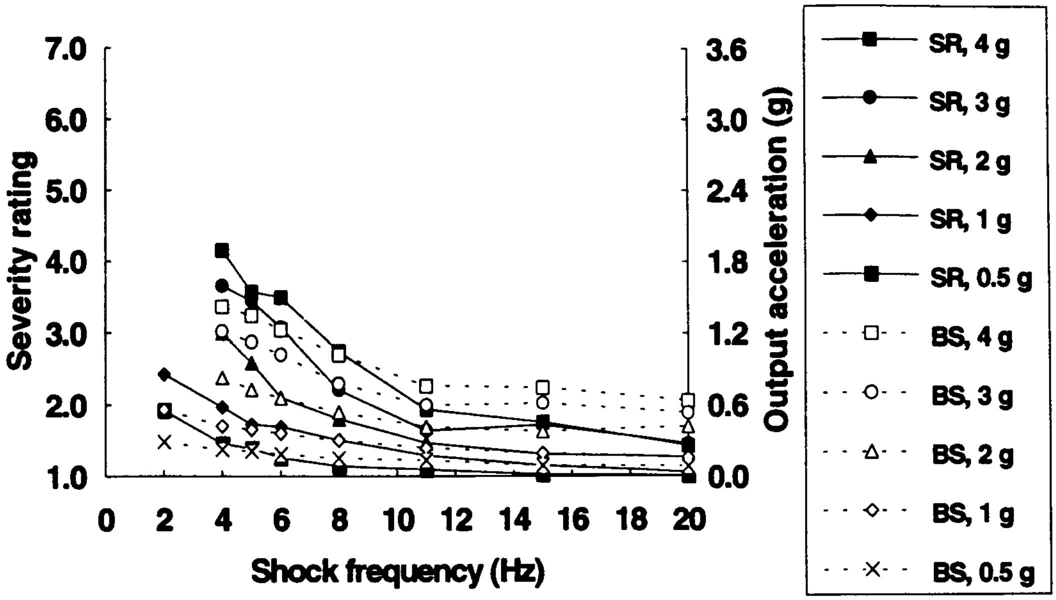

Figure B-19 Comparison between severity rating (SR) and expected output from the BS 6841 W_d filter to positive x axis shocks.

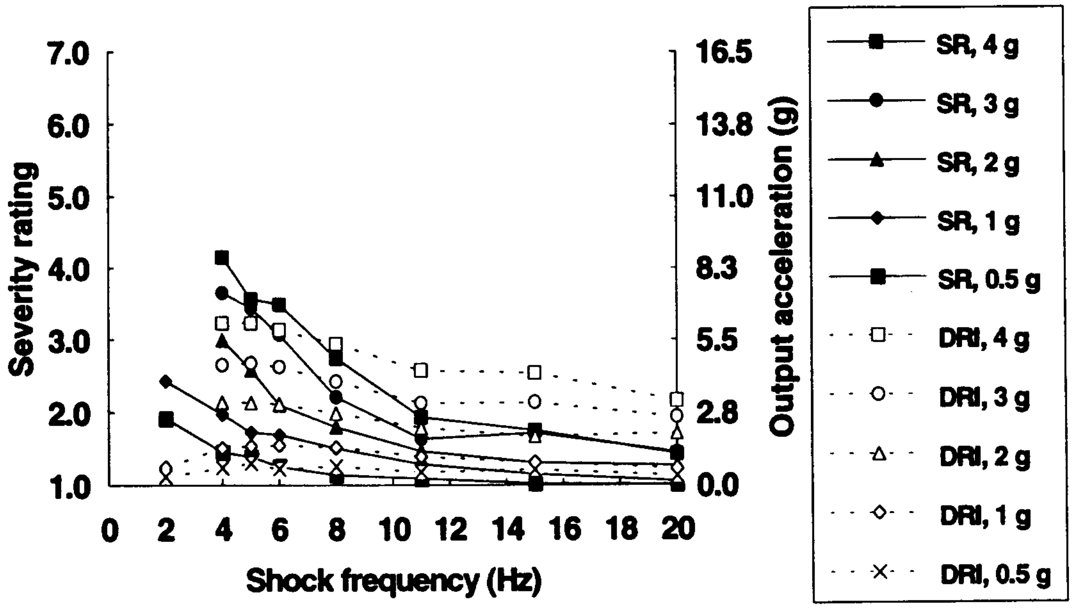

Figure B-20 Comparison between severity rating (SR) and expected output from the DRI model (10 Hz) to positive x axis shocks.

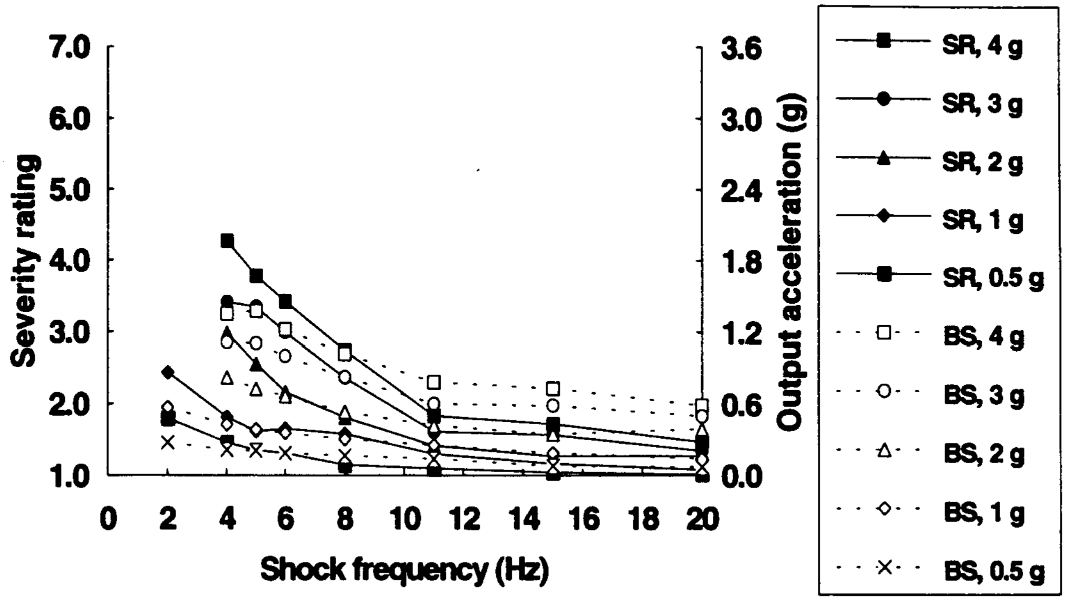

Figure B-21 Comparison between severity rating (SR) and expected output from the BS 6841 W_d filter to positive y axis shocks.

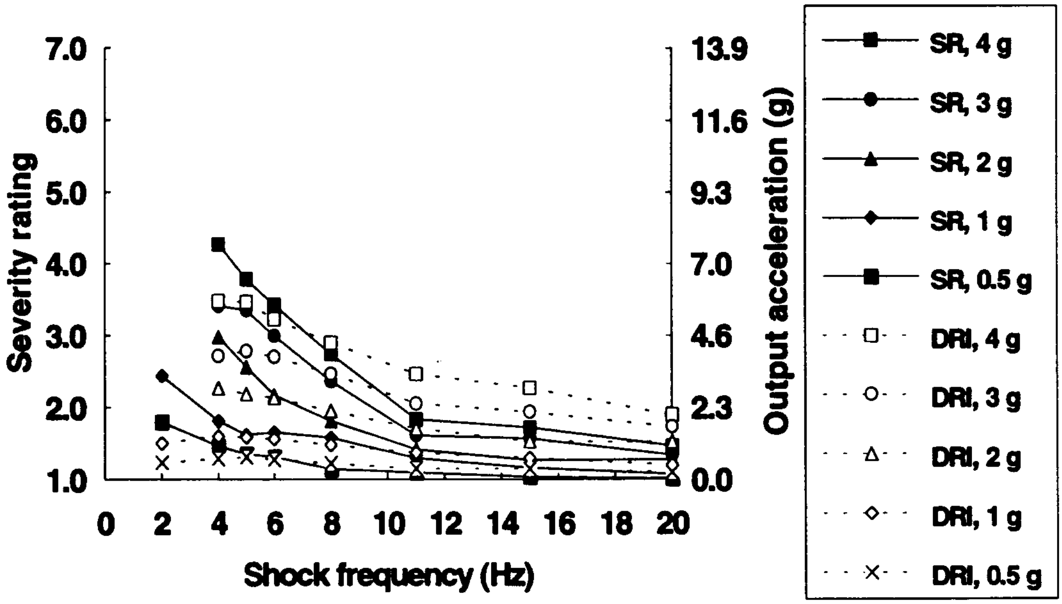

Figure B-22 Comparison between severity rating (SR) and expected output from the DRI model (10 Hz) to positive y axis shocks.

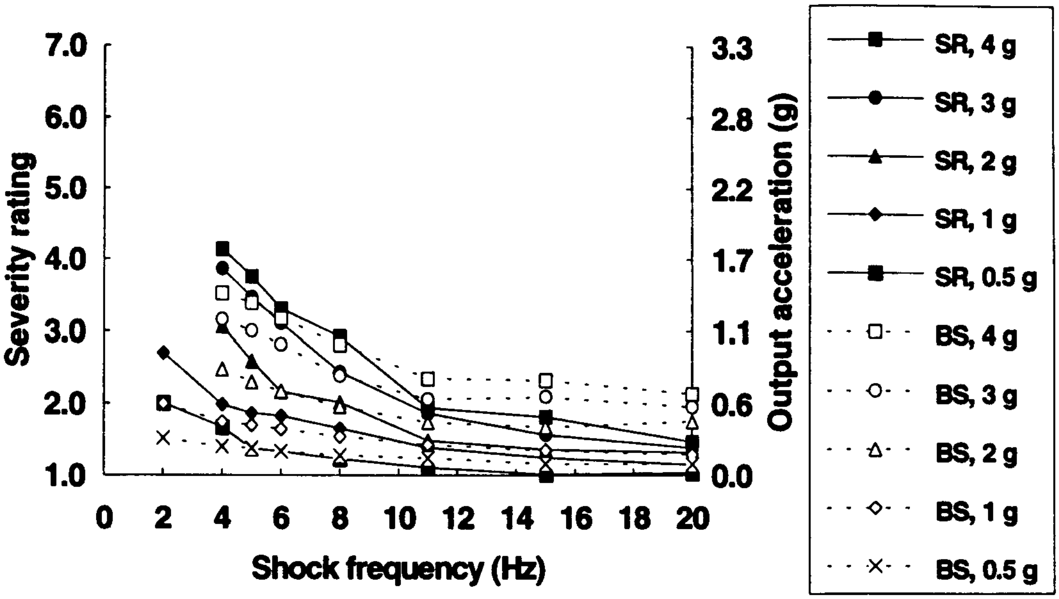

Figure B-23 Comparison between severity rating (SR) and expected output from the BS 6841 W_d filter to negative x axis shocks.

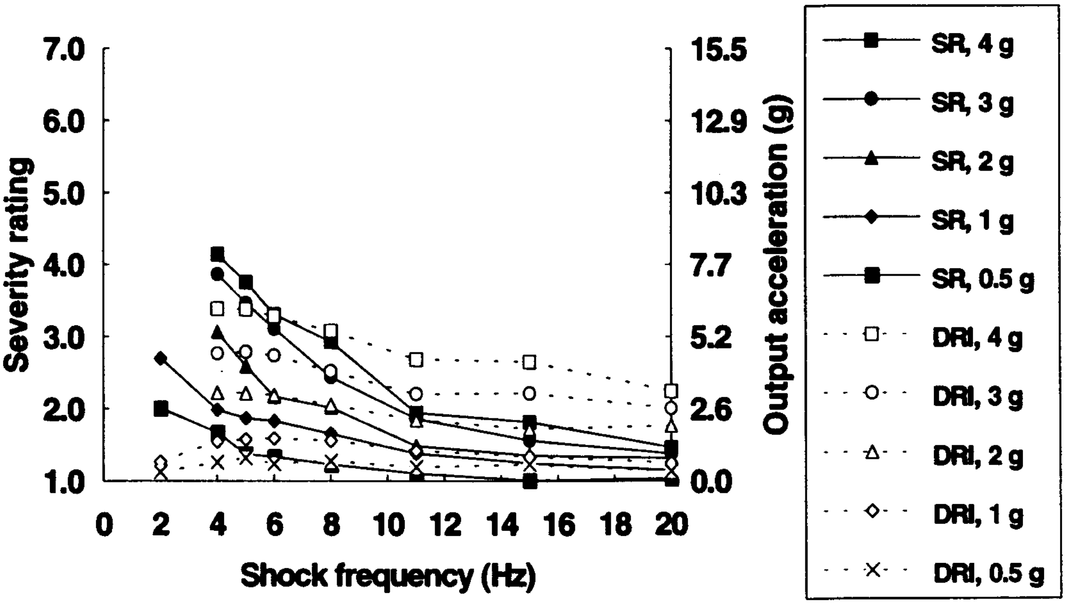

Figure B-24 Comparison between severity rating (SR) and expected output from the DRI model (10 Hz) to negative x axis shocks.

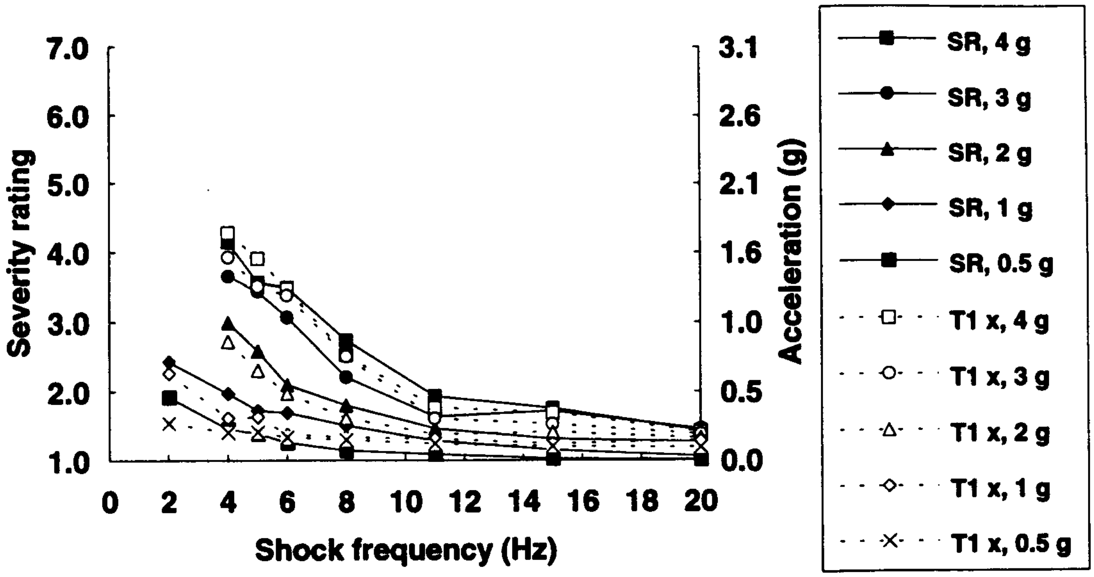

Figure B-25 Comparison between severity rating (SR) and acceleration measured at the thoracic spine (T1) in response to positive x axis shocks (T1 x).

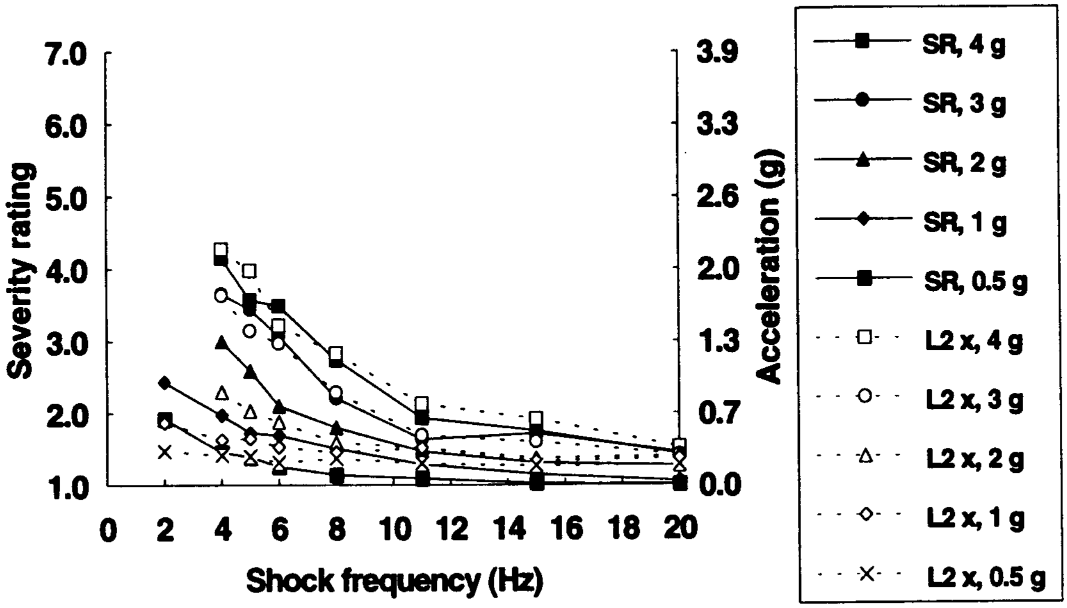

Figure B-26 Comparison between severity rating (SR) and acceleration measured at the lumbar spine (L2) in response to positive x axis shocks (L2 x).

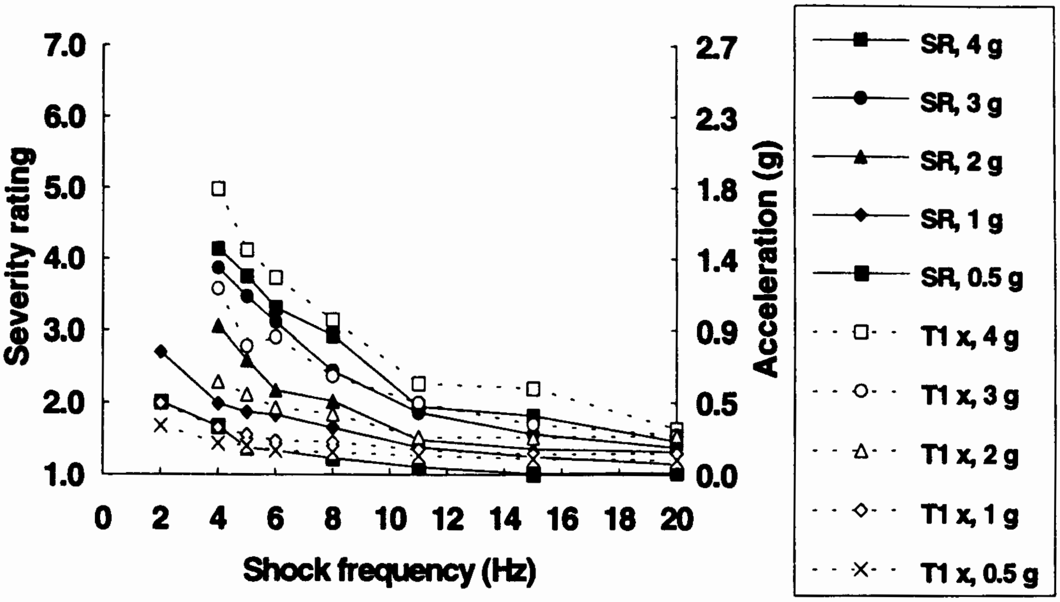

Figure B-27 Comparison between severity rating (SR) and acceleration measured at the thoracic spine (T1) in response to negative x axis shocks (T1 x).

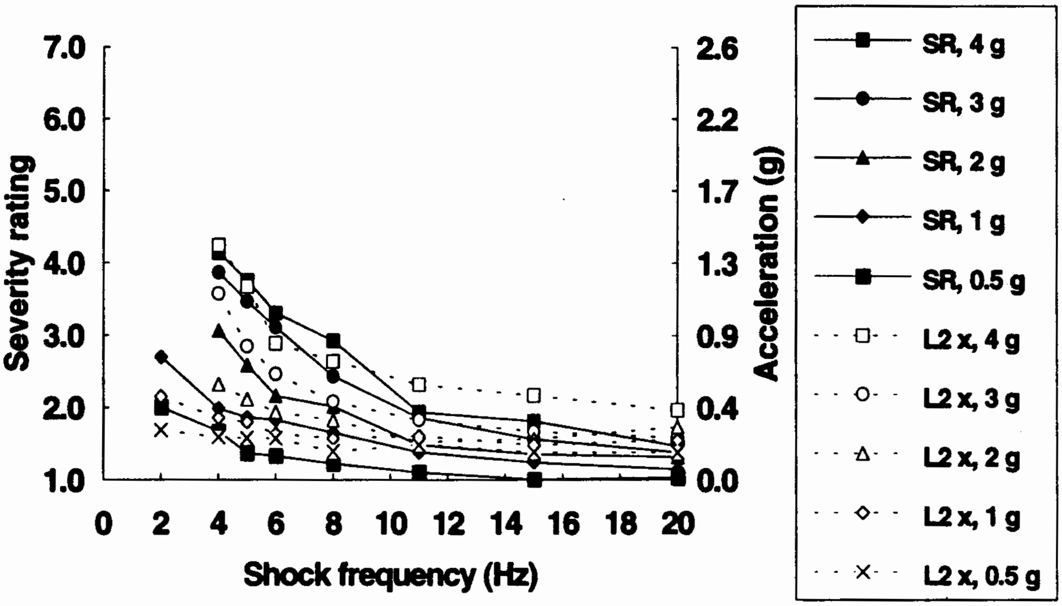

Figure B-28 Comparison between severity rating (SR) and acceleration measured at the lumbar spine (L2) in response to negative x axis shocks (L2 x).

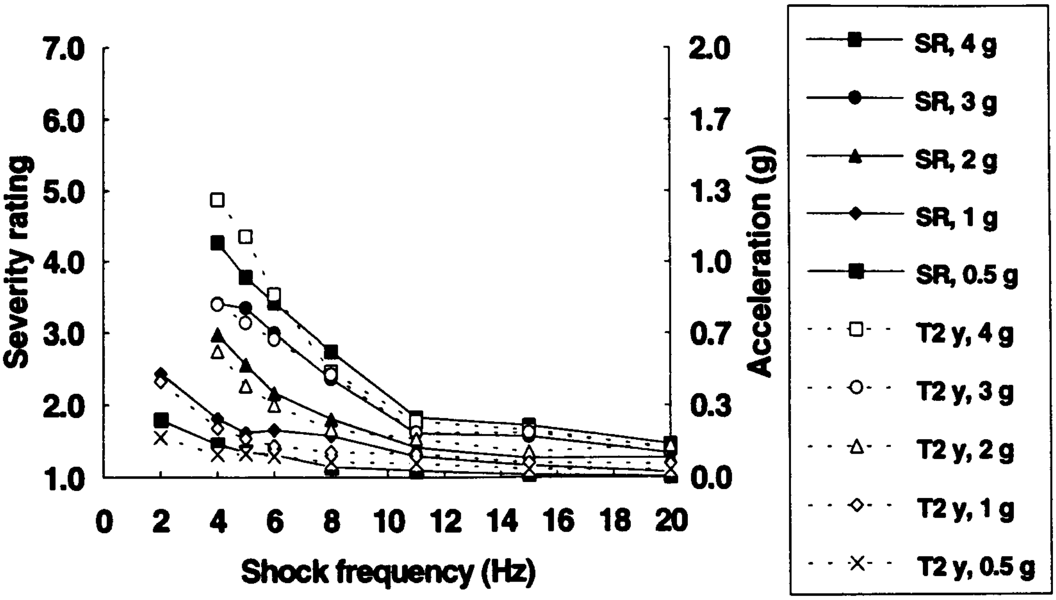

Figure B-29 Comparison between severity rating (SR) and acceleration measured at the thoracic spine (T2) in response to positive y axis shocks (T2 y).

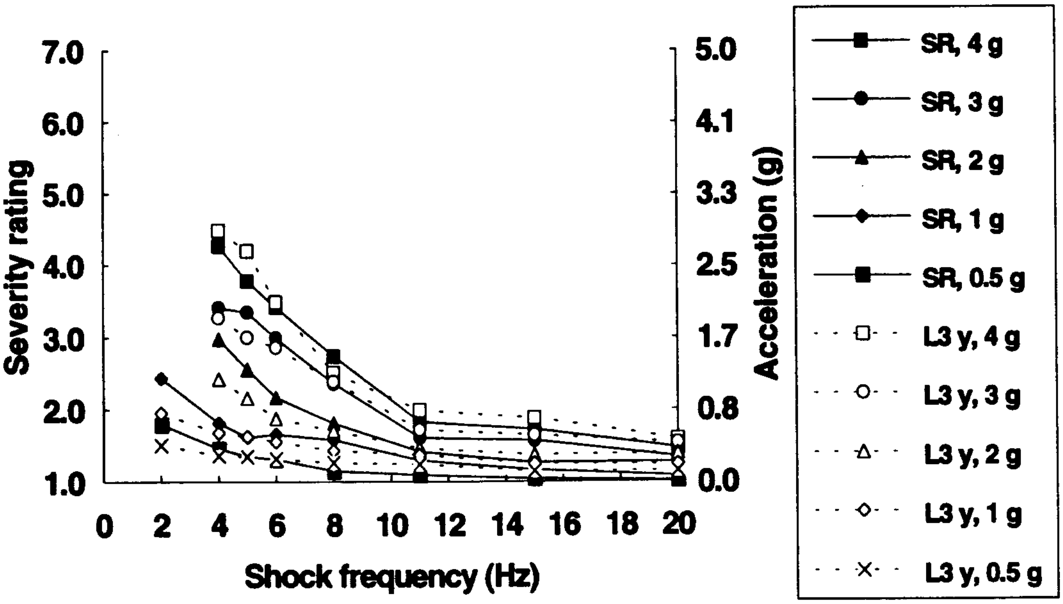

Figure B-30 Comparison between severity rating (SR) and acceleration measured at the lumbar spine (L3) in response to positive y axis shocks (L3 y).

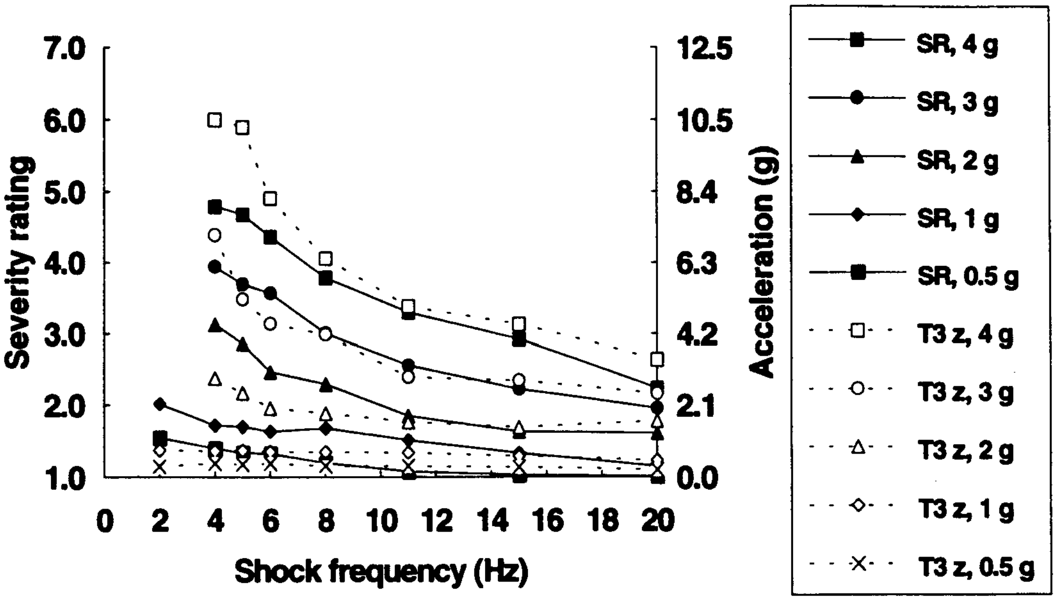

Figure B-31 Comparison between severity rating (SR) and acceleration measured at the thoracic spine (T3) in response to positive z axis shocks (T3 z).

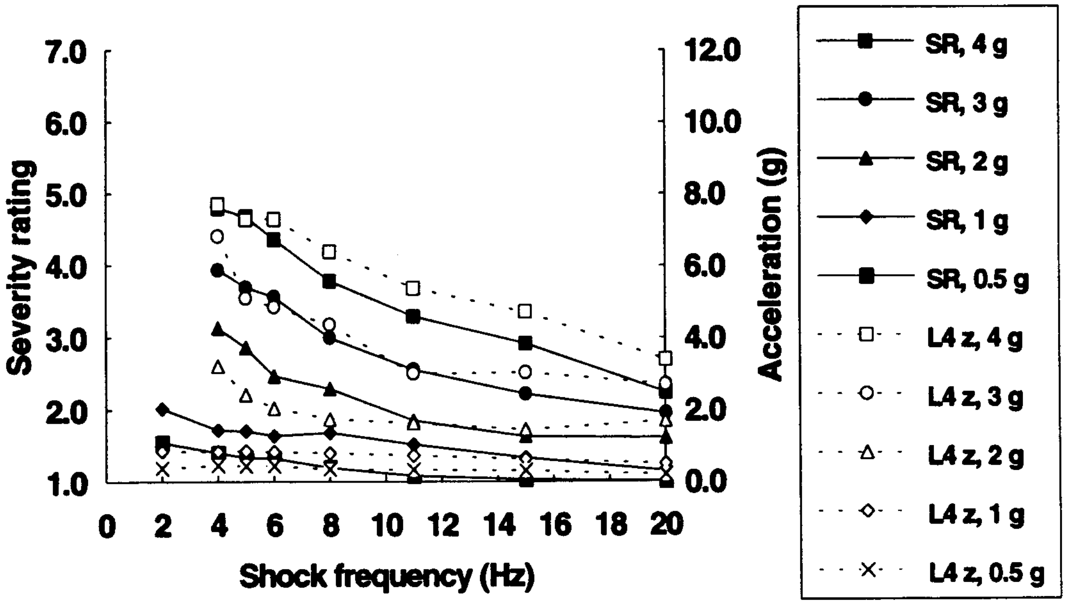

Figure B-32 Comparison between severity rating (SR) and acceleration measured at the lumbar spine (L4) in response to positive z axis shocks (L4 z).

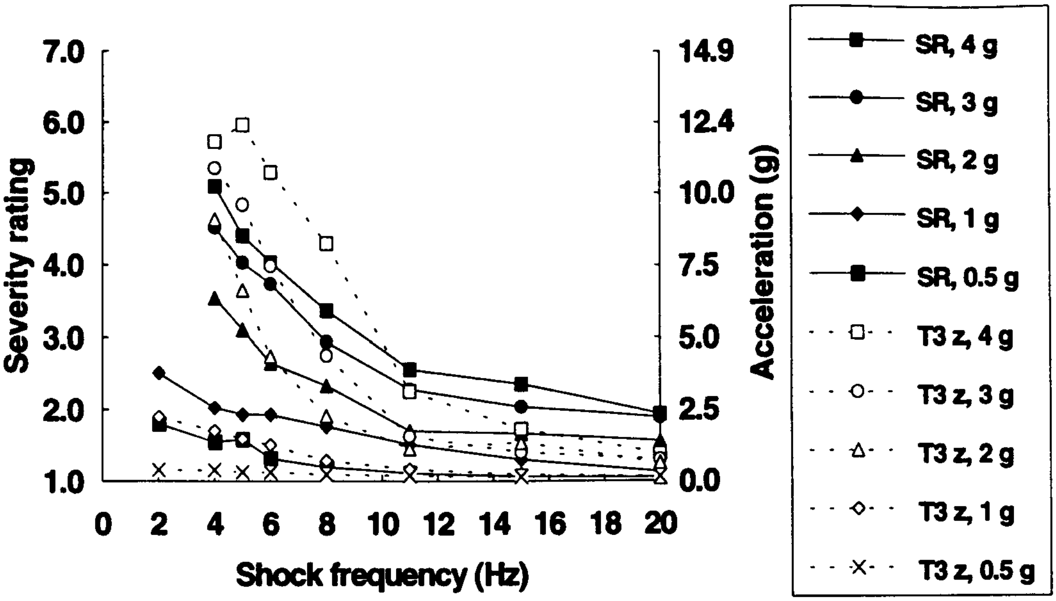

Figure B-33 Comparison between severity rating (SR) and acceleration measured at the thoracic spine (T3) in response to negative z axis shocks (T3 z).

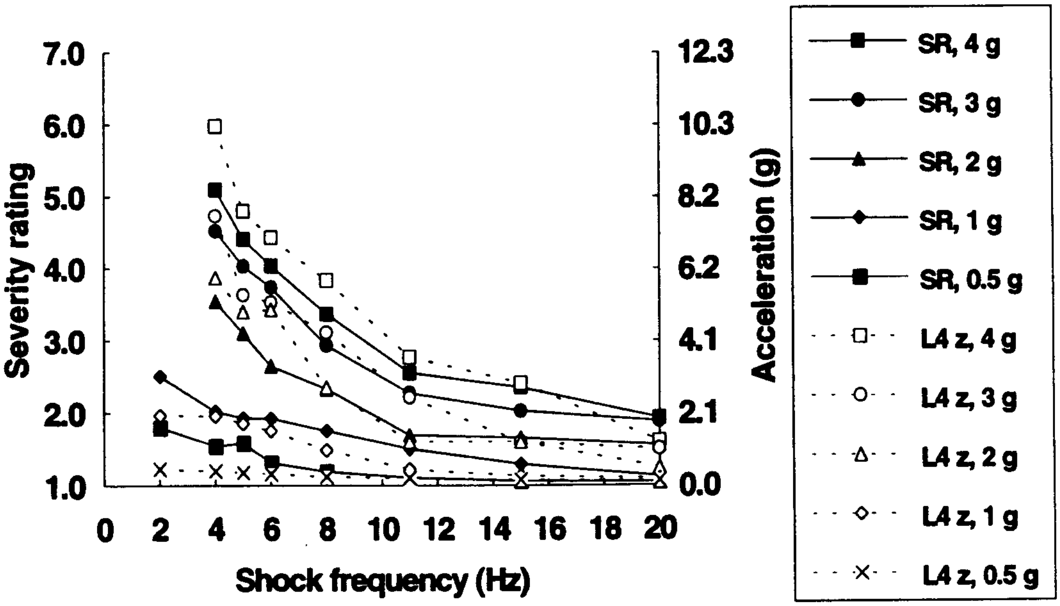

Figure B-34 Comparison between severity rating (SR) and acceleration measured at the lumbar spine (L4) in response to negative z axis shocks (L4 z).

GLOSSARY OF ABBREVIATIONS

ASCC	Air Standardization Coordinating Committee
BS	British Standards Institution
dB	decibel
DRI	Dose Response Index
FG	Fairley-Griffin
g	gravitational acceleration: 9.8 m/s
GEDAP	Generalized Data Acquisition/Analysis Programs
Hz	Hertz (cycles/second)
ISO	International Organisation for Standardisation
L2	second lumbar vertebra
L3	third lumbar vertebra
L4	fourth lumbar vertebra
LT	Long-term
LT1	Long-term experiment 1
LT2	Long-term experiment 2
LT3	Long-term experiment 3
LT4	Long-term experiment 4
LT5	Long-term experiment 5
$ms^{-1.75}$	VDV dose units
ms^{-2}	meters pre second squared
MARS	Multiaxis ride simulator
r.m.s.	root mean square
r.m.q.	root mean quad
ST1	Short-term experiment 1
T1	first thoracic vertebra
T2	second thoracic vertebra

T3	third thoracic vertebra
TGV	tactical ground vehicle
USAARL	United States Army Aeromedical Research Laboratory
VDV	vibration dose value
WBV	whole-body vibration