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POSSIBLE MECHANISMS OF LOW BACK PAIN DUE TO WHOLE-BODY VIBRATION

M. H. Pope†, D. G. Wilder and M. Magnusson†

Iowa Spine Research Center, *The University of Iowa*, *Iowa City*, *IA* 52242-1088, *U.S.A.*

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The investigators describe their multifaceted approach to the study of the relationship between whole-body vibration and low back pain. *In vivo* experiments, using percutaneous pin-mounted accelerometers have shown that the natural frequency is at 4·5 Hz. The frequency response was affected by posture, seating, and seat-back inclination. The response appears to be largely determined by the rocking of the pelvis. Electromyographic studies have shown that muscle fatigue occurs under whole body vibration. After whole body vibration exposure the muscle response to a sudden load has greater latency. Vehicle driving may be a reason for low back pain or herniated nucleus pulposus. Prolonged seating exposure, coupled with the whole body vibration should be reduced for those recovering from these problems. Vibration attenuating seats, and correct ergonomic layout of the cabs may reduce the risks of recurrence.

1. INTRODUCTION

Low back pain (LBP) is the leading major cause of industrial disability in the population under the age of 45 years. The total cost of LBP in the U.S. is 90 billion dollars per annum. In the United States, one million back injuries occur per year, 100 million work days are lost each year, and LBP accounts for 20% of all work related injuries [1].

Work related risk factors are important and thus have some potential for prevention [2]. There is an extensive literature relating exposure to whole-body vibration (WBV), LBP and various spinal disorders [2–6].

Dose response studies are not common although Dupuis and Christ [7] found that, of those with greater than 700 tractor driving hours per year, 61% had pathological radiographic changes of the spine, of those with 700–1200 hours, 68% were affected and with greater than 1200 driving hours, 94% were affected. Low back pain paralleled pathological changes. Hilfert *et al*. [8] gave an analysis of LBP in drivers of earth moving equipment. A clear trend of greater pathological changes on radiographs was seen in the exposed group. The prevalence increased with age. Barbaso [9] also found an increase in the prevalence of both LBP and pathological changes with age in bus drivers.

In this paper a number of studies will be described that have been carried out by the authors' group, to better understand the relationship between WBV and low back pain. These studies include *in vivo* measurements of transmissibility, electromyographic response, *in vivo* creep and changes to a biochemical marker.

2. METHODS

2.1. *IN VIVO* MEASUREMENTS

Pope *et al*. [10] made an investigation of the relative response to vibration, as measured by transducers rigidly fixed to the lumbar spinous processes, compared to those fixed to

†Now at the Liberty-Safework Research Centre, University of Aberdeen, Scotland, U.K.

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the skin. Under local anesthesia, a threaded K-wire was threaded transcutaneously into the spinous process at L-3. Because of the artifact that was identified in the use of skin mounted transducers, it was elected to use the skeletally mounted transducers in the subsequent studies. The pin was placed normal to the gravitational vector with the subject sitting erect. The outcome measure was the transmissibility and phase angle between the pin acceleration and that of the platform. The estimated frequency spectra were subjected to a triangular smoothing filter, which gave a frequency resolution of approximately 0·8 Hz.

Pope *et al*. [11] introduced a new impact system for the human spine (see Figure 1). The apparatus consists of a platform suspended by soft springs and guided by two linear bearings. The vertical resonance of the system was less than 2 Hz. The frame resonance was 60 Hz, and the platform rotational resonance was approximately 20 Hz. Rotation was minimized if the subject stood or sat in the center of the platform. The impact was applied to the center of the platform by a pendulum. The pendulum was released by a disc brake that started the data collection. The study compared the response of the spine to the sinusoidal vibration and impact. The sinusoidal vibration device has been previously described by Panjabi *et al*. [12]. Due to the repeatability and convenience of the impact technique, as well as the similarity of results from this technique with that of the sine excitation, the input technique was used in subsequent work.

Pope *et al*. [13] described tests in which a subject is placed in different controlled sitting postures, and the transmissibility and phase angle determined. The measurements were made by the skeletally mounted transducers described previously. The impulses were likewise imparted by the impact apparatus described above. These highly invasive experiments precluded the testing of a large number of subjects and thus only trends could

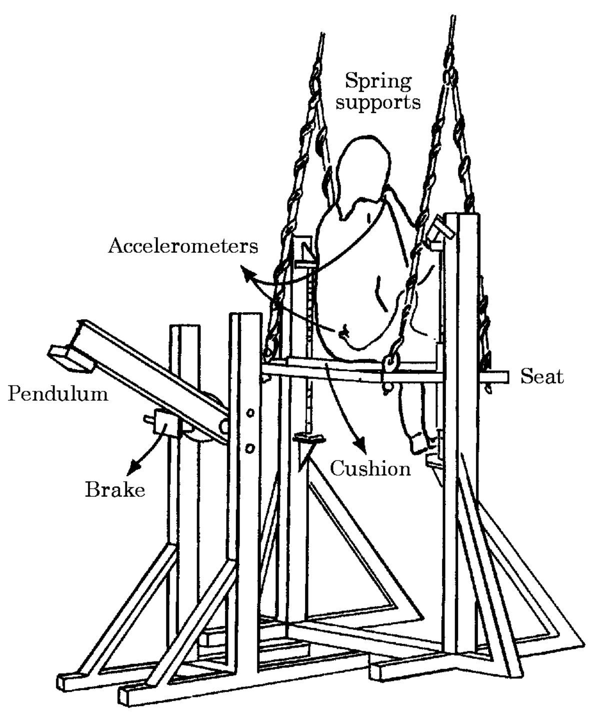

Figure 1. Impact test system consists of a spring suspended platform whose motion is constrained by a pair of linear bearings. Impact energy is imparted to the platform and subject via a pendulum. Accelerometers were attached to the lumbar spine and to a bite bar.

Table 1

Seat materials

Material	Composition
1.	Polyethylene foam
2.	Polyethylene foam (stiffer)
3.	Viscola

be observed and no statistics could be computed. The postures were relaxed and erect, valsalva erect, glutei contracted erect, erect with pelvic support, relaxed neck, neck plus helmet and erect holding a weight.

The same three female subjects were subjected to impacts, but in this experiment they were seated on various kinds of cushions (see Table 1). These cushions represented a wide range of cushions available for seating [14].

Three different postures were studied; an erect posture, a relaxed posture and an erect posture with valsalva. The postures were carefully controlled. Each seat material was studied for each of the postures. Comparisons were also made between the response with a cushion and with the same subject sitting only on the platform.

A number of different conditions were explored to establish the effect on the dynamic response of the standing subject. These conditions included modification of posture, increase of the trunk load moment, the wearing of different types of shoes and standing on different foam materials [15].

2.2. ELECTROMYOGRAPHIC ACTIVITY

The phasic activity of the right (RES) and left (LES) erector spinae muscles were measured in six male subjects who were free of low back pain [16]. The relationship of the electromyographic signal to a given torque demand on subjects was found by measuring the electromyographic signal while performing an isometric pull. The result was an EMG-torque curve.

During vibration, the subject adopted a controlled, slightly lordotic posture. Using a servohydraulic simulator, the subject was vibrated at discrete frequencies between 3 and 10 Hz. The raw amplified RES and LES were sampled at 500 Hz for 4 s. The signals were high-pass filtered (with a cut-off frequency of 30 Hz), rectified and ensembled averaged. The ensemble averaged signals were then simulated and converted to torque using the previous EMG-torque calibration. This is of course, an approximation since the calibration was done statically. From these data, the phase relationship between the input signal, to the platform, and the resulting torque, was established. Output data were the average, maximum and minimum torque as a function of frequency.

The development of fatigue can be studied by analyzing the myoelectric signal from the contracting muscle. Several studies have reported an increase in amplitude of the myoelectric signal during fatiguing contractions [17–19]. A frequency shift, toward lower frequencies has also been shown as an effect of fatiguing contractions [19–23]. Different explanations have been proposed for the increase in amplitude and the frequency shift of the myoelectric signal observed during a sustained, constant force, isometric contraction. These are motor unit recruitment, synchronization, and changes in conduction velocity.

The development of fatigue was studied through the analysis of the myoelectric signals from contracting back muscles [24, 25]. Myoelectric signals were recorded using surface electrodes, were amplified and filtered, and subjected to spectral analysis. The root mean square values were analyzed manually. The muscular activity of the erector spinae muscles was studied in the spines of six male subjects. To ensure muscular activity, the subjects sat in a forwardly bent position, carrying extra weight on the front of the chest. In this position, the subjects were exposed to (1) whole body vibration of 5 Hz and 0·2 g r.m.s. acceleration, and (2) static sitting.

r.m.s. values and mean frequencies for each subject, and each exposure condition, were calculated.

2.3. *IN VIVO* CREEP

Spinal height changes were measured by means of a linear voltage displacement transducer (LVDT) connected to a chart recorder [26]. The transducer was mounted on top of a column which, in these experiments, was tilted slightly backwards. The column was equipped with supports from the head and the pelvis, as well as four pressure sensitive switches, which functioned as posture controls. The posture of the head was controlled by means of glasses equipped with laterally oriented pins attached to the side frame (see Figure 2). The anterior pin was lined up with one of the posterior pins by means of the image from a mirror in front of the subject. A vertical line on the mirror served as control for head posture in the frontal and transverse planes. The transducer registered height changes continuously during the exposure. Height changes were measured in twelve female subjects exposed to static unsupported sitting and seated whole body vibrations. The procedure enabled discrimination between "true" height loss and posture change. The vibration input was 5 Hz frequency and 0·1 g r.m.s. acceleration. Six consecutive exposures of alternatively vibration and quiet sitting were performed in each subject. Exposure time

Figure 2. Subject sitting in the stadiometer. The column is equipped with supports for the head and the pelvis. The posture control system consists of pressure sensitive switches along the spine. The posture of the head was controlled by a system of glasses equipped with laterally oriented pins to line up with the image from a mirror.

was 5 min, and the intermissions between exposure periods were 20 min of lying supine. Each subject attended two sessions on different days.

The effect of backrest inclination on spine height changes during seated whole body vibration was tested [27]. The backrest inclinations tested were 110° and 120°. Comparisons were made with the unsupported sitting in a previous study with the same subjects.

2.4. BIOLOGICAL MEASUREMENTS

In another series of studies biochemical changes due to WBV [28] were measured. The von Willebrand factor (vWf) is a complex protein whose release is a marker for endothelial damage; serum levels of its antigen (vWFAg) can be used as a marker for such changes. The hypotheses tested were that back discomfort and serum vWF levels would increase after WBV but would recover after a period of rest. Subjects acted as their own controls. The levels of back discomfort and vWFAg in 11 subjects were measured following 25 min periods of (1) lying down, (2) sitting still, (3) vibrating whilst sitting at 5 Hz at 3·5 m/s^2 and (4) sitting still. The vibration exposure was at the level of the ISO 2631 fatigue decreased proficiency limit.

3. RESULTS

3.1. *IN VIVO* MEASUREMENTS

The subjects in the relaxed seated posture experienced a transmissibility peak at L-3 at 4·3 Hz coupled with an attenuation peak at 6·4 Hz (see Figure 3). Note that these are trends for the few subjects tested. In comparing the relaxed and erect posture, the response curves had the same general form, except that the peaks were more marked in the relaxed posture. The Valsalva increased the height of the 5 Hz peak of transmissibility, and beyond that point there was decreasing gain with frequency. Contraction of the glutei resulted in a response curve, which was between that of the relaxed and the Valsalva. Placing a block under the pelvis to offer rotational support reduces the gain peak and the gain valley.

Interactions between subsystems were explored by the latter experiments. Allowing the head to nod decreased the 5 Hz peak and resulted in greater attenuation at 8 Hz. A motorcycle helmet caused an additional peak at 10–12 Hz and decreased the 8 Hz attenuation peak. When the subject held an 8 kg mass close to the body, transmissibility above 8 Hz was decreased. Thus, control of the body posture may be a key to obviating the effect of WBV on the spine.

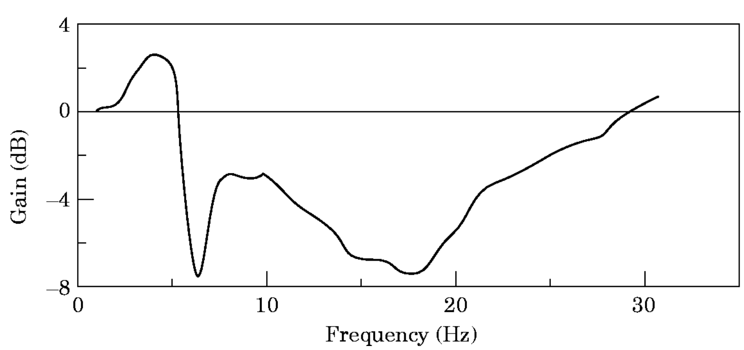

Figure 3. Acceleration gain as a function of frequency due to a relaxed sitting posture. There was a marked amplification peak (gain peak) at 4·3 Hz, coupled with an attenuation peak (gain valley) at 6·4 Hz. The figure represents an example of one subject.

The response curves were compared between subjects seated on no cushion, on two foams of different stiffness and one viscoelastic material. The least stiff material moved the transmissibility peak to below 4 Hz and, at the same time, increased its amplitude. The high frequency response was also markedly changed. The stiffer material tended to increase the frequency of the transmissibility peak and established what we interpreted to be a rotational response at higher frequencies. The viscoelastic material had too little effect, except at frequencies above 8 Hz. The trends between cushion materials were similar in the erect, relaxed and Valsalva postures.

Experiments in the standing posture were carried out at two different impact energies. These demonstrated only slight differences, suggesting a largely linear system. In the erect standing posture, there was a single transmissibility peak at 5·5 Hz. The at-ease posture gave a slightly reduced peak, and a knee bend posture attenuated the response. A pelvic tilt and Valsalva caused the peak to move to 6·5 Hz and 7 Hz respectively, while the adoption of a tip toe stance moved the peak to 3 Hz. Standing on foam materials caused the peak to move to lower frequencies, while the wearing of different shoes did not significantly change the response.

3.2. ELECTROMYOGRAPHIC ACTIVITY

Before each test, at a discrete frequency, the static EMG level was recorded [16]. Higher average EMG levels were found for the vibration condition, compared to the static condition, except at 3, 4 and 10 Hz. The time lag between the seat vertical motion and the EMG activity varied from 30–100 ms at 3 Hz and 70–100 ms at 10 Hz. At 10 Hz there was a trend for the muscle contraction again becoming in phase (or 360° out of phase) with the input signal. At all other frequencies, it was out of phase.

The mean frequency of the EMG signals obtained from the erector spinae muscles, at both the thoracic and lumbar level, decreased with time [24, 25]. The decrease was accentuated by whole body vibration at 5 Hz. The r.m.s. values of the EMG signals derived from the thoracic spine increased with time during both static sitting and vibration exposure. The r.m.s. values during vibration were significantly higher than during static sitting. As noted above, there were phase changes at each frequency.

3.3. *IN VIVO* CREEP

Height loss was demonstrated in all the subjects, and was significant for both vibration and static sitting ($p < 0{\cdot}0005$). This was also true after correction for posture change ($p < 0{\cdot}005$). A larger height loss was demonstrated when the subjects were exposed to vibration, than when not ($p < 0{\cdot}03$), and again after correction for posture changes ($p < 0{\cdot}05$). The height loss was neither time nor order dependent, and did not correlate with either height or weight [26].

The effect of backrest inclination on spinal height changes showed that both of the tested angles of inclination caused significantly less height loss than upright unsupported sitting [27]. The 110° backrest caused less shrinkage than did the 120° during static sitting, whereas the opposite was true when vibration was present, although the differences between the backrests were not statistically significant. Only when the results were compared with results from exposure to unsupported sitting were the differences statistically significant for both static sitting and seated vibrations, when the 110° backrest was used, and for vibration with the 120° backrest (see Table 2). It was concluded that an inclined backrest reduces the effects of vibration. More importantly, emphasis should be placed upon seats and seat materials that can attenuate vibration.

Table 2

The differences (mm) *in height loss* (*positive values*) *or height gain* (*negative values*) *between the three test positions during exposure to no vibration and to vibration*

Exposure	Back inclination (°)	Differences	Significance
No vibration	90–110	1·70	($p < 0{\cdot}05$)
No vibration	90–120	0·73	NS
No vibration	110–120	−0·97	NS
Vibration	90–110	2·35	($p < 0{\cdot}01$)
Vibration	90–120	3·06	($p < 0{\cdot}01$)
Vibration	110–120	0·71	NS

3.4. BIOLOGICAL MEASUREMENTS

Back discomfort and vWf levels were significantly increased following sitting upright, compared with lying flat, and increased further following WBV. They fell thereafter with a period of sitting still upright. These results demonstrate that WBV has a significant effect in increasing back discomfort and the serum levels of vWFAg, and it is possible that WBV may induce vascular changes [28].

4. DISCUSSION

Low back pain is multifactorial in origin. There are few risk factors for low back pain which lend themselves to prevention studies. Risk factors related to the industrial environment LBP and vibration are ones over which one has some control. It is for that reason that it is an attractive proposition to study them. A number of epidemiologic studies have been conducted which suggest that vibration is an important risk factor for low back pain. Vibration also probably combines with other risk factors such as lifting, pushing, and pulling to increase the risk. Certainly, these data have relevance to certain occupations, such as the truck driver who loads or unloads the truck. Studies of the occupational environment reveal that many vehicles subject the worker to levels of vibration greater than that recommended by the ISO [29].

4.1. *IN VIVO* MEASUREMENTS

There is important and wide literature on the human response to vibration. Many of these studies have utilized, as a measure, the transmissibility between the seat and a bite bar or helmet. Therefore, the measures are at an area remote from the usual area of impact (the lumbar spine) and can be affected by the influence of other subsystems, such as head–neck rotation. Indeed, in the authors' experiments which the head–neck system was allowed to freely move, the response did change. An alternative has been to glue or strap transducers to the skin. Although these studies have given some invaluable insight, one has shown that errors occur when transducers are not rigidly mounted. A further problem in some studies is the relative lack of repeatability of the sinusoidal excitation methods, probably due to changes of postures with time. These problems are exacerbated in some machines by the time necessary to set up the machine for few frequencies. The authors have presented, herein, an impact method that is rapid, repeatable, and convenient to use.

It is apparent from whole body vibration data that the human spinal system has a characteristic response to vibrational inputs in a seated posture. One of the more striking features is the presence of reasonances at fairly uniform frequencies for all of the subjects. The first resonance occurs within a band of 4·5–5·5 Hz. Similar, but less tightly defined resonances, are also identified in the 9·4–13·1 Hz range. Using direct measures, one can confirm the resonance at 4·5–5·5 Hz, but can show how it is markedly affected by the pelvis–buttocks system. The response of the human is due to a combination of a vertical subsystem and a rotational subsystem. The latter is characterized by rocking of the pelvis. Hence, pelvic rocking was shown to be an important factor in the first natural frequency response of the seated individual. The 4·5–5·5 Hz resonance is due to biological systems between L-3 and the seat surface, and not to more cranial spine bending or compression. Cushions have not, in these experiments, been found to be very effective in attenuating the dynamic response and, in fact, increased the response.

There are some limitations of these studies. The techniques are highly invasive, and by necessity, limited to a few subjects. The experiments are difficult, and the analysis quite complex. There are some minor non-linearities in the response which should, perhaps, be explored in future work. In a few of the experimental conditions, the gain was not decreasing with frequency, indicating the possibility of an, as yet, unidentified response peak at a higher frequency. This, too, should be explored in future work to assess its biological importance.

For the standing individual, the response is similar in form to the seated posture with a transmissible peak at 5·5 Hz. The response is attenuated by the lower extremities in general, and knee flexion of greater than 30° completely attenuates the response. Thus, workers subjected to a vibrating work surface may find it valuable to adopt a bent knee stance. The time over which this can be done may be, of course, limited by fatigue of the quadriceps. It was interesting to note that no shoes has much success in attenuating the response. The situation may be quite different in gait where heel strike and toe off induce the skeletal impulse. Further work with skeletally mounted accelerometers during gait is needed to confirm if this is, in fact, a different situation.

4.2. ELECTROMYOGRAPHIC ACTIVITY

These studies indicated that maximum strain occurs in the seated operator's lumbar region at the first natural frequency. In addition, studies reported herein have monitored the timing of the back muscle response with respect to the vibration stimulus. At many frequencies, the muscles' responses are so far out of phase, their forces are added to those of the stimulus. Thus, the muscles have an important role in adding to the effect of vibration. The fatigue that was found in muscles, after vehicular vibration, is indicative of the loads in the muscles.

Exposure of the seated subject to whole body vibrations of 5 Hz, in a position that ensures back muscle activity, increased the rate of development of fatigue in the erector spinae muscles, as compared to the same conditions without vibrations. The underlying causes for the fatigue, as detected by the mean frequency of the electromyographic signals, seemed to be different in the thoracic and the lumbar pars of the spine. Increased r.m.s. values in the thoracic region were expected when the mean frequency decreased during fatiguing contractions at constant force. A decline in the mean frequency, not accompanied by increased r.m.s. values, indicated that a fatiguing contraction with constant or decreasing muscular activity was at hand. Unloading a vehicle, after exposure to WBV could present a problem for the tissue of the back.

4.3. *IN VIVO* CREEP

When the spine is axially loaded it will compress and thus, become shorter. The viscoelastic behavior of the motion segment of the spine is well described in several studies, most of which, however, have been performed during *in vitro* conditions. Dirnual changes in body height, as a reflection of loading and unloading, were first demonstrated by

DePuky [30]. It was shown that the human being became shorter through the day, and regained height during the night. The technique was revitalized, and has been used, to measure spinal height changes following activities known or assumed to increase the load on the spine [31–34].

In the present study, it was demonstrated that the sitting posture, in itself, always caused height loss in the subjects, provided that the sitting exposure was preceded by a less loading activity such as lying down. The immediate increased spinal height change, as measured in the current study of vibration, thus, reflected increased spinal load. These results are in agreement with those of Klingenstierna and Pope [35] and Sullivan and McGill [36], but in contradiction to those of Bonney [37] and Althoff *et al*. [38]. Due to many important differences in methodology, such as exposure time and type and direction of vibration input, direct comparisons are difficult to make. Bonney [37] exposed the subjects to combined vertical and horizontal vibration for 30 min in a driver's posture which included an inclined backrest and foot support. The strikingly surprising results of Althoff *et al*. [38] that both static sitting and vibration during sitting caused increase in spine height compared with standing must also be attributed to the difference in methodology. In their study, all tested exposures were compared to 30 min of standing. It is possible that the decrease in height from the standing measurement was due to the compression of the lower extremity joints, and thus the decrease in height from the seated exposures in fact reflected recovery from extremity joint compression. In the present study, an inclined backrest was shown to reduce the load on the spine and could reduce the effects of vibration in such a position.

4.4. BIOLOGICAL MEASUREMENTS

Von Willebrand Factor was increased in the blood after exposure to whole body vibration. This implies that there are vascular changes. These vascular changes could result in nutritional compromise of the tissues around the spine.

In summary, after exposure to whole body vibration, the muscles are fatigued and the discs compressed (i.e., less capable of absorbing and distributing load). In this condition, the spine is in a poorer condition to sustain larger loads. Thus, it would seem reasonable to recommend the avoidance of heavy lifting immediately after vibration exposure [39].

The laws of mechanics offer an encouraging note [40]. If one considers that deformation of the spine, due to vibration, occurs from the work performed on the body by the vibration's kinetic energy, two things become very clear. In the simplest form, the work performed on the body is equal to the kinetic energy applied to the body. The equation for that kinetic energy is $0{\cdot}5(mv^2)$ (where m = mass and work = kinetic energy). Because velocity = acceleration × time ($v = at$), solving the kinetic energy equation in terms of acceleration and time yields an equation where kinetic energy equals $0{\cdot}5(m(a^2t^2))$. Upon using that formulation, it is then apparent that the work performed on the body is reduced by 34% if each of the acceleration and exposure time are decreased by 10%. This is significant because small changes in acceleration level and/or exposure time can lead to large changes in the total work performed on the body.

Sensitivity to vibration for any structure or mechanism is not as simple as portrayed above. A structure or a mechanism can exhibit a peak response to vibration at a particular frequency due to its natural frequency. Because the seated human's response to vibration is relatively distinct, reducing or eliminating vibration transmission in the 4–6 Hz range is a good first step toward improvement.

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