Whole-body vibration and shock: A literature review

Extension of a study of overtravel of seat suspensions

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Whole-body vibration and shock: A literature review

Extension of a study of overtravel of seat suspensions

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Published information on the effects of occupational exposure to whole-body vibration and shock is reviewed. No information was found which could be used to evaluate occasional shocks in comparison with more continuous vibration. Knowledge of health effects of whole-body vibration is compared with that of noise-induced hearing loss and of effects of hand-transmitted vibration. Whole-body vibration (WBV) is also compared with other stressors associated with low back pain (LBP). The literature shows that LBP, or 'lumbar syndrome' can be associated with occupations, but not specifically with WBV. Only one study has been found which was so structured that vibration magnitude could be assessed independently of time. In many cases, posture or manual handling is probably more important than vibration exposure. Studies of the mechanism of degeneration of the spine suggest that peak accelerations may be more appropriate than time-averaged measures such as rms for evaluating health risk. It is suggested that health guidance in standards on WBV should be based on evaluation methods for repeated shocks. Future work should integrate the evaluation of vibration, posture and manual handling loads on the spine.

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WHOLE-BODY VIBRATION AND SHOCK: A LITERATURE REVIEW (EXTENSION OF A STUDY OF OVERTRAVEL OF SEAT SUSPENSIONS)

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Summary

A previous, shorter review of the published work on health effects of whole-body vibration had shown that there was apparently very little information to help with evaluating the relative importance of continuous vibration and isolated shocks. It had further shown that even the claimed health effects of whole-body vibration are based on weaker evidence than has generally been assumed.

This more extended review also sets out two prerequisites for assessing the findings of research into health effects of whole-body vibration:

- Comparison with criteria used to assess the health effects of other, similar environmental stressors (noise and hand-transmitted vibration)
- Comparison of whole-body vibration with other stressors that have been associated with low back disorders, namely posture (including prolonged sitting), and manual handling (lifting, pulling, pushing).

The literature is then reviewed in two main sections. First, an historical overview is used to illustrate the development of knowledge, or more usually opinions, about the subject, from 1945 to the present. This is followed by an assessment of the evidence published in relation to each of a number of occupations for which researchers have claimed an effect of whole-body vibration on low back disorders.

From the historical overview it appears that whole-body vibration was originally suggested by medical practitioners as a likely cause of back trouble when this was first observed among operators of new types of machine and vehicle. By 1970, this suggestion appears to have been accepted with little question, and with little effort to compare vibration with other possible causes of back complaints. Comprehensive measurement of vibration magnitudes was not feasible before about 1970, and for some years after that it was a separate activity from studies of occupational health. Even now, only one study has been found in which there is a clear distinction between effects of vibration having different magnitudes. There is also only one study in which both vibration and postural stress have been compared on a similar numerical basis, and this, for tractor drivers, shows a greater effect for posture than for vibration.

Historically, there have also been attempts to understand the mechanism whereby vibration, and other stresses, can lead to degeneration of elements of the lower back. These have indicated that cycles of relatively high magnitude acceleration are probably more important than the lower levels of vibration that often contribute more to the time-averaged measures of exposure defined in ISO 2631.

The review of occupations shows that in general the evidence does associate occupations with elevated risks of disorders, but does not distinguish between vibration and the other stressors as contributors to that risk. What are often claimed to be vibration studies are usually occupation studies. Furthermore, a number of general patient studies also reviewed show that the incidence of low back disorders among a general population is high (between 30% and 60%) and differences between occupational groups small. Specific studies of occupational groups, carefully controlled, are needed to show significant effects. The ten groups reviewed are operators or drivers of: Agricultural tractors; Earthmoving and construction machines; Industrial (fork-lift) trucks; Helicopters; Transport “tugs”; Overhead cranes; Rail and subway vehicles; Military vehicles; Road vehicles; and standing operators of concrete plant.

A summary of the likely causes for elevated risk of low back disorders in the various occupations follows. In this, it is suggested that continuous vibration is unlikely to be a serious contributor to damage. In most occupations, posture is likely to be a significant factor, and probably the main factor for pilots of helicopters and operators of overhead cranes. In some occupations, such as farming, manual handling has in the past been an important factor that has generally been overlooked. And in those occupations in which dynamic loading is significant, it is the peaks of occasional transient vibrations or shocks that are most likely to contribute to any damage.

There is a brief discussion of health criteria in standards (ISO 2631, BS 6842) and in some national guidelines on compensation for occupational diseases. It is suggested that guidelines for compensation should not involve vibration requirements, but should specify only the diagnosable physiological damage and a history of occupational use of any of a prescribed list of machines or vehicles. It is further suggested that the method, developed by ISO/TC108/SC4/WG10 for evaluating repeated shocks, should also be tested as a possible measure for more continuous vibration. This is supported by a short discourse on aspects of measurement, in particular the trade-off between magnitude and duration of exposure, and the importance or otherwise of frequency weighting.

It is suggested that future research should be targeted at two aspects of the subject. First, health studies should be integrated with more specific evaluation of subjects' exposures to vibration and shock, with measurements made in such a way as to enable alternatives to rms or VDV to be extracted, in particular the method of ISO/TC108/SC4/WG10, or some equivalent count of "fatigue cycles".

Secondly, a more integrated approach to research into low back disorders should aim to find a common method for rating the severity of postural and manual handling loads as well as shock and vibration. A particularly useful outcome would be a set of methods for assessing occupational exposures to the combined stresses.

In the meantime, more effort should be devoted to assessing all three groups of stresses in relation to any future health studies.

And exposure magnitudes and histories should be more closely linked with individual subjects whose health is under research. There appears to be little value in trying to correlate cause and effect from questionnaire surveys.

In conclusion:

- Vibration has not been shown to be the main cause of lumbar syndrome in those occupations in which it is known to be a significant health risk
- There has been a shortfall in the available vibration exposure data for association with the health data
- There is a lack of a relevant method for quantifying postural stress in field studies to provide a similar association with health data
- There is a lack of data on any measure other than frequency weighted rms acceleration, and specifically to test the hypothesis of a fatigue mechanism
- There is insufficient data even to suggest a possible relationship between reducing vibration magnitude and reducing the incidence of back problems.

WHOLE-BODY VIBRATION AND SHOCK: A LITERATURE REVIEW (EXTENSION OF A STUDY OF OVERTRAVEL OF SEAT SUSPENSIONS)

1. INTRODUCTION

1.1 The original review

For several decades there has been a strong body of opinion that mechanical vibration and shock cause significant damage to the health of people exposed to them. This was recognised by, and incorporated in, the first International Standard on human whole-body vibration (ISO 2631-1974), development of which began in the mid-1960s, and it is nominally the main mechanism responsible for the German occupational disease classification 2110 (Dupuis, 1994) and the French occupational disease compensation tables Général No 97 and Agriculture No 57 (Anon 1999). Furthermore, this opinion underpins a proposal for a European Directive the intention of which is to protect workers by controlling the allowable exposure to physical agents, and which has recently been revised so that the single agent of vibration can be addressed in an independent document, with other agents to be dealt with later.

The information presented here has been reviewed as a result of one of the outcomes of a more focussed literature study (Lines & Stayner, 2000) into the contribution to vibration exposure of mechanical shocks to the operator's body arising from overtravel of the seat suspension on work vehicles. In that review, seven specific objectives were addressed which were chosen to ensure a logical approach to the main subject. The first two of these objectives, necessary to provide a basis for the rest of the study, were framed as questions as follows:

A. What are the types of physiological damage that operators of work vehicles and machines suffer which may be claimed to result from exposure to vibration and shock? And how much is known of the extent to which such damage is prevalent?

B. What methods are available for quantifying vibration and shock? And which of these are relevant to an assessment of their severity in terms of likely physiological damage?

What was found in the literature relevant to these two objectives fell short of what had been anticipated. The link between physiological damage and vibration exposure was less strong than expected, and consideration of health effects had played little or no part in the development of measures used to evaluate vibration and shock.

Nevertheless, current standards do contain some guidance on health effects of exposure to whole-body vibration. This guidance is based on the hypothesis that there is a simple relationship between the risk of damage and some combination of vibration magnitude and duration of exposure. In the form in which it has been generally accepted, this hypothesis assumes that the risk is proportional to the time average, or time integral of a function of frequency weighted acceleration. And this function is either the second power of acceleration (root mean square, rms, as in ISO 2631, 1974) or the fourth power (Vibration Dose Value, as in BS 6841: 1987).

Instead of supporting this hypothesis, consideration of all the health studies reviewed, and in particularly in the light of recent research reports from Germany (see below), led to an alternative hypothesis being formed:

1. For vibration and shock with peak values not exceeding some threshold, which has yet to be properly researched but may be between 1 ms^{-2} and 10 ms^{-2}, the dynamic loads are of very little importance, and it is the postural loads which are responsible for the damage to the operators' backs.

2. For vibration and shock with peak values exceeding the above threshold, the dynamic loads contribute to the risk of damage to the operators' backs such that increasing the magnitude or the frequency of occurrence of these dynamic loads increases the risk.

It will have been observed that this hypothesis is concerned with the possibility of damage to operators' backs. Although there have been suggestions of numerous other effects which might be associated with exposure to vibration, it is low back pain and damage to vertebrae and intervertebral discs, "lumbar syndrome", for which the most cogent evidence has been published. Lines and Stayner (2000) therefore concentrated on this type of physiological damage, and so does the present study.

1.2 Objectives of this review

The objectives of the Lines and Stayner (2000) review precluded an extensive study of the evidence for health effects of vibration. This was because, when that review was planned, the need for such a study was not foreseen. However, in the light of what was found in that relatively cursory review, and in the context of somewhat stringent proposals to control vibration exposure in the workplace, a more extensive review of that evidence is appropriate.

Two questions underlie this concern about the value of controlling vibration exposure:

1. To what extent will controlling vibration exposure lead to a lower incidence of back problems?

2. Are the presently defined measured values of vibration magnitude relevant to the risk of back problems?

If the link between vibration exposure and risk to health is less strong than is presently widely assumed, then introducing a policy of stringent vibration control could have the undesirable result that the effect is far smaller than anticipated. This raises the question of what effect the limits to exposure to whole-body vibration are expected to have, which will be considered in relation to the control of other environmental stressors in a later section.

If the wrong measured values are used to assess health risk, then costs could be incurred in pursuing technical developments which have less effect on reducing the incidence of back problems than if the right feature of vibration or shock had been addressed. An example of this may be found in current debate over the revision of a test code for seats for agricultural tractors. In this case, there is a compromise to be reached between a high enough level of damping to control the shocks arising from suspension overtravel, and a lower level of damping which would reduce the transmission of shocks and vibrations which are small enough to be within the range of free travel of the suspension. Such guidance on health effects as may be found in current standards (ISO 2631-1, 1997; BS 6841: 1987) encourages the use of as low damping as possible, whereas those people who have to use the seats are more concerned with avoiding suspension overtravel, particularly hitting the bottom stop and so prefer heavier damping. This is a result of using time-averaged vibration magnitudes that do not reflect adequately the importance of occasional high acceleration events. The 4th power, rmq, measure is better in this respect than the 2nd power rms, but when shocks are relatively infrequent, even rmq may underestimate their importance.

The present review sets out to contribute to a discussion of these questions by re-examining the history of research into the health effects of whole-body vibration. The objective of this is to assess the extent to which the evidence supports either of the two hypotheses described in section 1.1, above.

This is followed by a review of different classes of machine or work vehicle, to assess the importance of vibration in the risk of spinal damage for the operators.

From this, the possible contribution of other stressors, specifically posture and manual handling, to the risk in each machine class will be assessed.

In order to promote discussion, some comments are made on the health guidance criteria in existing standards, and some are made on what measure of shock or vibration is appropriate for assessing the effect on health.

As an introduction to the reviewing process, some parallels are drawn with the approaches used for the two similar environmental stressors of noise and hand-transmitted vibration, and a brief introduction is made to other stressors which have been associated with low back disorders.

2. APPROACHES TO ENVIRONMENTAL STRESSORS - NOISE, HAV, WBV

2.1 General

In relation to controlling the exposure of workers to environmental stressors for reasons of health, a number of questions need to be addressed. These are set out here, and will be asked in relation to both noise induced hearing loss and hand-arm vibration syndrome (HAVS) before considering whole-body vibration.

2.1.1. Is there an effect which is widely recognised?

2.1.2. Is the effect specific to the stressor? Can its occurrence be distinguished from the occurrence of the same, or a similar effect due to other causes?

2.1.3. Can the effect be found in a large proportion of an exposed population?

2.1.4. Can it be shown that by reducing the stressor the effects are reduced?

2.1.5. Is there a measure of exposure magnitude which can be related to the health effect?

2.1.6. Is there a "dose-effect" relationship, and if so, what is the trade-off between stressor magnitude and time, and what is the relevant measure of stressor magnitude? The test for this would be to show that a large magnitude for a short time can have a similar effect to a smaller magnitude for a longer time, primarily when applied to exposure within a working day.

2.1.7. Is there a relationship between the extent of the effect, or the numbers of people affected, and the exposure "dose"?

2.1.8. Can we estimate the benefit of controlling exposure to the stressor, e.g. in terms of the proportion of the exposed population for which the risk of the effect will be less than a distinguishable threshold?

One thing, which is clear, is that questionnaires and opinions will not provide adequate evidence to answer most of these questions satisfactorily. And if we cannot provide positive answers to most of these questions, then there should be a strong warning that attempts to reduce the incidence of back trouble by controlling vibration may prove unproductive.

2.2 Case of noise and hearing loss

2.2.1 Is there an effect which is widely recognised?

Exposure to high levels of noise results in hearing loss. This was recognised by a government report in the early 1960s (Wilson, 1963). The possibility had clearly been accepted in the research community before publication of that report, and must have been quite widely recognised for the report to be commissioned.

2.2.2 Is the effect specific to the stressor?

Hearing loss is common among the ordinary population. In general it occurs with gradually increasing severity as old age approaches, but there are several medical conditions which also give rise to deafness. What distinguishes noise-induced deafness is that in many, though not all, cases the effect shows a strong effect of frequency. Regardless of the frequency of the noise which causes the damage, the sensitivity of the affected ear is reduced first in the octave band centred on 4 kHz. (Burns & Robinson, 1970)

2.2.3 Can the effect be found in a large proportion of an exposed population?

Exposure to the same level of noise for the same length of time results in different degrees of hearing loss in different individuals. Any attempt to deduce cause and effect relationships therefore relies heavily on statistics (Burns & Robinson, 1970). It has been shown that with the levels of noise which were common in many industries in the 1960s, large proportions of the exposed groups suffered hearing loss to a significant degree more than the usual age-induced or presbyacusis effect.

2.2.4 Can it be shown that by reducing the stressor the effects are reduced?

Burns & Robinson (1970) reported the results of several studies, both cross-sectional and longitudinal, from which could be deduced clear evidence that exposure to higher levels of noise increased the rate at which hearing loss built up, e.g. Figure 1. The corollary to this is that reducing the level of noise must reduce the incidence or the severity of hearing loss.

2.2.5 Is there a measure of exposure magnitude which can be related to the health effect?

Burns & Robinson (1970) investigated the correlation between the degree of hearing loss and several measures of noise exposure, including a number of different ways of evaluating noise level (e.g. Fig.1). The best correlation was found for the dB(A) level which was exceeded for 2% of the time, but the difference between this and the energy averaged dB(A) value was small, and the latter allows a relatively simple "dose" calculation. It should be noted that the correlation was proved before the mathematical convenience was accepted.

The A weighting was not shown to have any particular physiological foundation, but was selected because, as for energy-equivalence, it was shown to have as good a statistical association with hearing level as any of the other weightings tested.

2.2.6 Is there a "dose-effect" relationship:

The degree of hearing loss was found to be dependant on both noise level and duration of exposure (Burns & Robinson, see also Figure 1). Furthermore, this effect of duration was found to be relatively consistent between and within days. This allows a consistent means of estimating a daily dose and a lifetime dose.

The large body of data on which the Burns & Robinson report was based allowed the comparison of exposure to a large magnitude for a short time to be compared with lower noise levels for longer times, and to establish a relationship between both the extent of the hearing loss, and the numbers affected, and the overall "lifetime dose". This has been confirmed by other researchers, and the relationships are now enshrined in standards for estimating hearing loss of exposed workers (ISO 1999: 1975; BS 5330:1976).

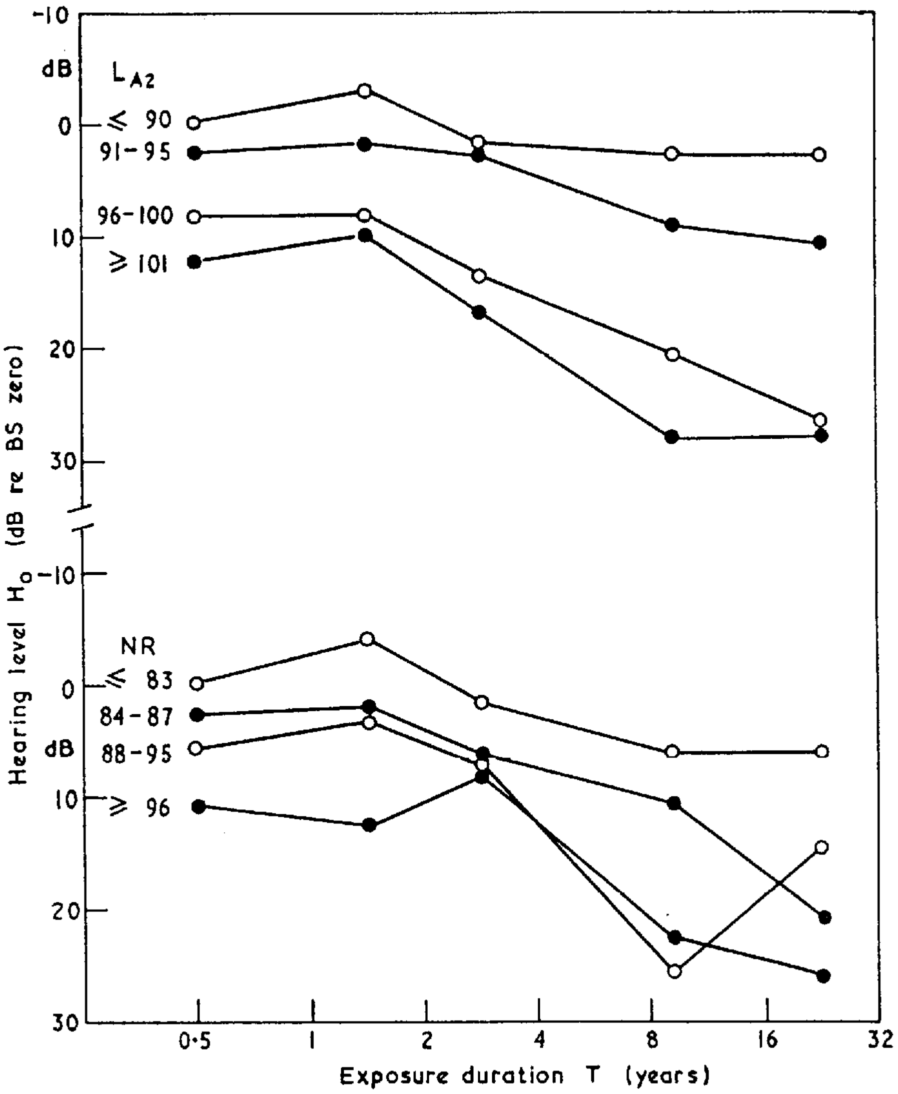

Figure 1. *"Illustrating how hearing loss is more closely correlated with one measure of noise (dB(A)) than another (NR). Frequency 4 kHz, 418 subjects"* After Burns & Robinson (1970)

2.2.7 Can we estimate the benefit of controlling exposure to the stressor

Noise induced hearing damage is irreversible, but reducing the daily, or the lifetime dose can slow down the rate of onset of deafness. This is clear from the analysis of the mass of data which has contributed to BS 5330, and the standard provides a method of estimation of the effect of different exposure doses, and therefore of any benefit of controlling exposure, in terms of the proportion of an exposed population suffering a specified degree of damage.

In other words, for a given amount of noise reduction, it is possible to estimate how many people will benefit by suffering from a smaller amount of hearing loss.

It should be noted that although BS 5330 provides a somewhat idealised set of calculation methods, it is based on a large body of real world data, the analysis of which led to the relationships used in those calculations.

It should further be noted that action levels and other mechanisms used in the control of noise exposure are based on a combination of knowledge of the effect of a particular noise level, together with the cost of achieving that level in a range of industrial situations.

And finally it should be noted that action levels are not set so as to protect 100% of an exposed population for a working life of 40 years. Rather, they are set so as to provide that after a working lifetime exposure of 40 years, some 90%, or 95% of the exposed population will suffer less than 30dB hearing loss averaged over frequency, approximating to the level at which it starts to become an impediment to speech recognition (Tomlinson, 1970; Robinson & Shipton,1973; Noise at Work Act,1989).

2.3 Case of HAVS

2.3.1 Is there an effect which is widely recognised?

Hand-transmitted vibration can affect the exposed person in a number of ways. These include vascular damage, resulting in finger blanching (vibration white finger or VWF); sensori-neural, resulting in loss of feeling in the fingers; musculo-skeletal, e.g. damage to joints in the hand and wrist; and Carpal Tunnel Syndrome. The association of these effects is supported by different amounts of evidence in each case, and it is believed that each type of effect can exist either with or without association with any of the others (Royal College of Physicians, see Tyler *et al* 1993).

In the UK, VWF is widely recognised, the others less so. In fact VWF has been a reportable occupational disease since 1986 (Department of Health & Social Security, 1985), and HAVS in general has been reportable since 1995(D.H.& S.S., 1995), although only VWF is as yet compensatable.

2.3.2 Is the effect specific to the stressor?

Finger blanching occurs in 4% or 5% of men of working age, and about twice as many women “constitutionally” (Royal College of Physicians - Tyler *et al*, 1993), and is known as Raynaud’s disease (or phenomenon). There is nothing that at present is known to distinguish between the VWF and constitutional Raynaud’s disease from observation of the symptoms alone.

There is some suggestion that damage to the nerve receptors in the fingers is a distinct effect of vibration exposure, but the evidence on this effect is relatively scarce, and it has in the past been confused with the effects of finger blanching.

The other components of HAVS are not specific to vibration exposure.

2.3.3 Can the effect be found in a large proportion of an exposed population?

The magnitude of vibration found on power tools in several industries is sufficient to have affected the majority of those using the tools after only a few years of exposure. A prime example is to be found among chainsaw operators in the forestry industry (Taylor *et al* 1974). The chainsaw was introduced to replace the axe and the hand saw over a very short period in the 1960s, and within only about 4 years it was found that almost all workers were suffering from VWF.

High proportions of affected workers were found in other industries, e.g. fettling work in foundries, involving pedestal and hand grinders (Pelmear *et al* 1974) and chipping hammers; construction workers using percussive pneumatic drills; and stoneworkers in quarries (Bovenzi 1994).

The situation with regard to the other components of HAVS is less clear. For example, Carpal Tunnel Syndrome affects only small numbers in both exposed and non-exposed populations.

2.3.4 Can it be shown that by reducing the stressor the effects are reduced?

By 1970, large employers in the forestry industry had instituted a policy of buying only those chainsaws that were provided with effective anti-vibration mounts for the handles. This reduced vibration magnitudes from about 500 microns (m x 10^{-6}) (peak) to about 100 microns (peak), and the rate of onset of VWF was reduced (Taylor *et* al 1977). So reducing the cause can reduce the effect.

The author of this report is unaware of any comparable examples for the non-vascular symptoms.

2.3.5 Is there a measure of exposure magnitude that can be related to the health effect?

Both the International Standard (ISO 5349: 1986) and the British Standard (BS 6842: 1987) specify the same measure of vibration magnitude, namely the rms averaged acceleration, weighted according to the same frequency sensitivity curve.

The frequency sensitivity curve has been extrapolated from a relationship found for subjective sensitivity tests, and has no particular association with the physiological health effects (Gemne & Lundström, 1994). However, as mentioned above, the A-weighting used for noise measurement also has no particular basic relationship with physiological damage.

Of more concern in relation to the frequency weighting is the prominence that it gives to handling artefacts that are sensed in the lowest frequency bands, in comparison with the more continuous vibration that occurs at higher frequencies. This may also lead to some tools, such as sand-rammers that have very low operating frequencies, having apparently unreasonably high vibration emission values.

Considerable efforts have been devoted to establishing a cause and effect relationship between vibration exposure and VWF. Even so, it is undeniable that in comparison with the example of noise induced deafness, the dose-response relationship for VWF is very tentative indeed. There are several reasons for this, not the least being the latency period of exposure before finger blanching symptoms are presented, and the lack of a progressive, numerical scale of damage even when the symptom is present. In fact, latency period itself may provide the effect most easily converted to a numerical scale. However, it should be noted that "latency" is a term that is open to a number of different interpretations when used for a group of subjects. For blanching, Griffin (1990) suggests a 33-point scale, but this is even more difficult to administer, and particularly to replicate, than is the simpler Stockholm Workshop Scale (Gemne *et al* 1994).

Before the development of ISO 5349, there were several ways in which the vibration was evaluated, but none of these has been compared with frequency-weighted rms acceleration in statistical correlation tests with the data on exposure and latency period in a manner analogous to what Burns and Robinson did for noise and hearing loss (Gemne & Lundström, 1994).

It is also apparent that work aimed at associating hand vibration exposure with vascular and other symptoms has been concerned more with duration than with magnitude, simply because individual studies have been confined to groups of workers with similar magnitudes, whose exposure can be distinguished only by duration of employment (e.g. Taylor *et al* 1974, Pelmear *et al* 1974, Bovenzi 1994). It is therefore scarcely surprising that alternative measures of exposure magnitude have not been tested, and rms was the most widely recognized way of quantifying a varying electrical signal.

Therefore, and largely by default, frequency-weighted rms acceleration is the only generally accepted measure for evaluating hand-transmitted vibration.

2.3.6 Is there a "dose-effect" relationship:

BS 6842, based on such evidence as there was in 1987, advises that the development of VWF symptoms is affected by both the magnitude of vibration and the duration of exposure within the working day. It also advises that the development is affected by the duration of a lifetime exposure. However, the relationships with time are not consistent between and within days, which greatly complicates the development of a dose-effect relationship. So we can say only that VWF is dependant on both time and magnitude of vibration.

In compiling the evidence on which the table in Appendix A of BS 6842 is based, and the equivalent in ISO 5349, it is presumed that researchers took data from groups of workers exposed to different magnitudes of vibration, and for different daily durations, as discussed above. However, it is unlikely that this evidence is on a scale comparable to that of the noise studies, if for no other reason than that far more people are exposed to noise than to vibration.

Similarly, there may be some data which associates the extent of VWF, either in terms of the numbers affected or in terms of the median latency period, with the duration and possibly also magnitude of vibration exposure (e.g. Nelson 1988). However, the relatively extensive guidance that was provided in ISO 5349 does not command sufficient scientific respect for it to be retained in the latest revision of that standard, which is likely to follow the more limited approach provided in BS 6842.

There are no widely accepted claims for dose-effect relationships for the other types of symptom.

2.3.7 Can we estimate the benefit of controlling exposure to the stressor

BS 6842 does allow a similar type of calculation to be made for VWF to that which BS 5330 provides for noise-induced deafness. However, in the case of VWF this is limited to estimation for the 10% most sensitive members of an exposed population, and refers to the onset of finger blanching, with no quantification of its severity.

Certain occupational health specialists have been known to use this relationship to calculate allowed daily exposure times to specific power tools, but the degree of precision which may be used has to be treated with considerable caution.

Any benefits in relation to HAVS components other than finger blanching are purely conjectural, but it is common to claim that they are likely to be similar to those for VWF.

2.4 Case of WBV

2.4.1 Is there an effect which is widely recognised?

There are numerous health effects which have been associated with work environments in which whole-body vibration is indicated as a particular stress. However, only damage to the back, manifest as non-specific Low Back Pain or diagnosable damage to vertebrae or intervertebral discs, is a widely accepted effect (Seidel & Heide, 1986). In the definition of the German Bk2110, this group of symptoms, provided that it includes diagnosable components, is known as "lumbar syndrome".

It is an objective of this report to investigate the extent to which the whole-body vibration stress is the relevant feature of the work environment in relation to this type of symptom. At this stage it can be said only that "lumbar syndrome" is associated with many work environments in which whole-body vibration also features.

2.4.2 Is the effect specific to the stress?

It has been a major difficulty for those who have tried to establish any form of relationship between whole-body vibration and lumbar syndrome, or other forms of back trouble, that the symptoms are so prevalent in the general community that most people have suffered from them by the time they reach the age of retiring from work (e.g. Palmer *et al* 1999). The effect is quite clearly not specific to the stress.

2.4.3 Can the effect be found in a large proportion of an exposed population?

As mentioned above, the effect can be found in a large proportion of any population, exposed or not, which makes it difficult to distinguish the effects of exposure.

Much of the published research discussed below has been concerned with trying to make an effective distinction between exposed and non-exposed populations. It is an objective of this review to investigate the degree of success with which this distinction has been made.

2.4.4 Can it be shown that by reducing the stress the effects are reduced?

It is another objective of this report to discover if it has yet been shown that reducing the stress of whole-body vibration can actually reduce the incidence of back trouble in an exposed working population.

There is no comparable example to that of the chain saw for hand-transmitted vibration. Nor is there comparable data to that for noise-induced deafness that would allow estimates of damage risk for different magnitudes of vibration, and hence enable any benefit of reducing vibration magnitude to be estimated.

2.4.5 Is there a measure of exposure magnitude which can be related to the health effect?

It was observed in the earlier review (Lines & Stayner, 2000) that most researchers who had found a correlation between lifetime "vibration exposure" and the incidence of back problems had done so only by virtue of duration of exposure. Attempts to relate the symptoms to the magnitude of the vibration element in the working environment had not been found to be very convincing. Again, this is an aspect which will be visited again in this report.

Also to be discussed again is the more specific question of the relevance of measures of vibration magnitude to health effects.

2.4.6 Is there a "dose-effect" relationship:

The reported data will be further reviewed with particular reference to this, but as found by Lines & Stayner (2000), and other reviewers (e.g. Kjellberg et al 1994) the evidence is weak.

2.4.7 Can we estimate the benefit of controlling exposure to the stress

Unless or until we can define a dose-effect relationship, any benefits from controlling exposure to whole-body vibration will remain conjectural.

However, this and other of the aspects of whole-body vibration exposure are the subjects of this report, and will be discussed in greater detail below. In particular, some suggestions will be made as to what research might be most profitable in terms of providing useful estimates of the benefits of vibration reduction.

2.5 Summary of environmental stressors

The three stressors (physical agents) of noise, hand-transmitted vibration and whole-body vibration are compared on the basis of the above 6 arbitrary criteria in Table 1. The statements for whole-body vibration draw on later sections of this report.

Table 1: Criteria for assessing environmental stresses (noise and vibration)

	Stressor		
Criterion	Noise	HAV	WBV
1. Effect widely recognized?	Yes	Yes	Yes
2. Effect specific to stressor?	Yes	No	No
3. Effect in most exposed people?	Yes	Yes	Yes*
4. Reducing stress reduces effect?	Yes	Yes	Not proven
5. Effect related to magnitude of stressor?	Yes	Probably	Not proven
6. Dose-effect relationship?	Yes	Possibly	Not proven

* The effect is found in most people, whether exposed or not.

3. OTHER STRESSORS

3.1 General

In a review of epidemiological research into risk factors in low back pain, Hildebrandt (1987) ranked four generic groups of factors according to the simplistic criterion of frequency of quotation, as follows:

- Heavy physical work
- Prolonged sitting (posture)
- Heavy manual handling, heavy or frequent lifting, trunk rotating, pushing/pulling
- Vibrations

With the exception of heavy physical work, which is not generally associated with those occupations for which vibration is thought to be a risk factor, these factors are discussed briefly below.

3.2 Posture

The additional stress on the musculature and intervertebral discs of the lumbar spine that arises from sitting was at first not considered by those who studied occupational back problems in relation to whole-body vibration. Rosegger & Rosegger did indeed mention postural stress in tractor driving, but this was in the context of twisting or leaning in the constrained workspace on a farm tractor. It seems likely that sitting in a normal relaxed posture was considered to be a beneficial alternative to standing to work.

By the 1970's, research into low back pain had started to inform opinion that this was not the case. In Sweden, Andersson and colleagues (Andersson *et al* 1974, Andersson & Örtengren 1974) used the direct (and highly invasive) measurement of pressure in intervertebral discs between L3 and L4 to investigate the effects of sitting postures. They showed that sitting flattened, or reversed the lumbar curve and tilted the pelvis, acting to alter both the shape of the intervertebral discs and their internal pressures. Compared with standing, they found higher pressures for all sitting postures except when the backrest was inclined to 20^{o} or more behind the vertical. As mentioned elsewhere, Troup (1978) considered that posture was the primary cause of back trouble, with vibration and shock being possible contributing factors.

Those studying helicopter pilots had considered posture a factor since the 1960's (Sliosberg 1962), but this group does often have an extreme posture (see also section 5.6).

Several authors have expressed the opinion that posture could be a factor in the development of low back troubles, but few have gone to the trouble to avoid postural differences between their control groups and their groups with vibration exposure. Even fewer have included a quantification of posture, to enable quantifiable comparison with vibration, or any other factor. The only example found in the present review has been that of Bovenzi & Betta (4.6.3 and 5.3, below), who appear to have shown a much stronger correlation between posture and back pain than that caused by vibration exposure.

Magnusson & Pope (1997) warn against ignoring postural stress, but treat this as a factor which exacerbates the stress due to whole-body vibration.

It was not until the studies presented by Seidel et al in 1997 that an attempt had been made to compare and combine the stresses arising from both posture and vibration. In one hypothetical estimate (Annex A), these authors suggest that the effect of bending forward from a normal "driving" posture could be equivalent to a hundredfold decrease in the number of cycles to failure of an equivalent vibration magnitude. Much of this work is hypothetical, but it raises two important questions that deserve attention. First is the need to find a reliable and quantifiable way of describing seated working postures, so that the epidemiological studies can proceed with more complete information. Second is the relationship between dynamic loading on the spine and fatigue development of degeneration, considered elsewhere (4.6.6 below).

3.3 Manual handling

There is a long history of studies of posture and lifting which have been made with the intention of reducing the incidence of damage to the lower back. These studies have been suggested by the coincidence of lifting heavy objects, or of bending to lift with a poor posture, with the triggering of acute spinal damage, in particular disc prolapse. The rationale is that because these incidents can trigger damage, they may also be to some extent responsible for it, and so the highly prevalent disease of low back pain may also be associated with lifting.

Palmer *et al* (1999) found that work involving lifting or moving weights of more than 10 kg by hand, or working with hands above shoulder height for more than one hour a day, was associated with higher risk estimates for sciatica than was exposure to whole-body vibration. Although the "hands above shoulder height" is nominally a postural effect, it is more closely associated with a lifting action than with the seated postural stresses considered above.

Several of the occupations which are associated with exposure to whole-body vibration also involve an element of manual handling, whether it be as a routine part of the work, or as an occasional, infrequent activity.

Drivers of delivery vehicles, are an example of the former, but drivers of heavier trucks are usually not, at least not at the present time, because their loads are moved with mechanical aids, either lift trucks or on-board cranes. Not many years ago, this was not the case and subjects in some of the earlier studies would probably have had to move heavy items manually.

Drivers of farm tractors are an example of the latter. Mechanical handling aids have led to the introduction of sacks and bales which are too heavy to be manoeuvred by hand, but there are many stages in the farming system where smaller items have to be moved, and there are times when machine preparation or breakdown lead to intense physical exertion. A considerable amount of research effort has been devoted to the ergonomics of shearing sheep, but this has had little impact on the need for the shearer to lift, push and pull a heavy animal while stooping to use the clippers. Similar, occasional manual handling is a requirement of many jobs in the earthmoving and construction industries.

In comparison with the stresses of vibration exposure, to which numbers can be attached with apparent ease, what is missing is an equivalent way of quantifying the stress that arises from these manual handling activities. What has also been missing up to fairly recently is any sign of an attempt to make such quantification, however approximate this would have to be. The gap has been filled by work, mainly at Ohio State University (Marras *et al* 1993, 1995, Granata & Marras, Marras 2000). This has included an epidemiological correlation of "dynamic" load on the spine with low back pain, together with the development of a model of the musculo-skeletal system that allows the estimation of these dynamic loads. In this context, dynamic loads are defined as a more practical alternative to the simple static loads that had previously been used to estimate stress on the spine from a combination of weight lifted and position of its centre of gravity. They are based on observation of practical work conditions, and are considerably higher than the static estimates.

In this sense, the work of this team is closely parallel to that of Dr Seidel and his colleagues, whose models can clearly be used for ergonomic stresses similar to those from variations in sitting posture. There would probably be some benefit from combining these two lines of study.

The author of this report has not found an equivalent body of occupational epidemiological studies for manual handling and low back pain to compare with that for whole-body vibration.

3.4 Case of high work platforms

In the cases of several types of machine and vehicle the operator or driver has a work position that is a metre or more above ground level. Common examples are farm tractors, earthmoving machines such as wheel loaders, and heavy goods vehicles (trucks). The drivers of these naturally use steps for access, but for egress they are often tempted to jump down from their machines.

It has been suggested that the jarring load on the spine of such an exercise contributes to a hastening of the development of back problems, and that this may be exacerbated by the exposure of the operator to vibration during the period before jumping off the machine, or by being constrained in a relatively fixed seated posture during that period. This was, for instance, suggested by Wilder, in presenting a paper on muscular response to sudden load (Wilder et al, 1997).

It is not clear how such occasional loads could be quantified in a way that would enable this factor to be included in a study which also involved vibration exposure.

3.5 Combination of stressors

There are very few epidemiologic studies that have investigated low back disorders in relation to more than one risk factor. Only that by Flenghi (reported in Meyer *et al* 1998) attempted to find associations with posture, manual handling loads and vibration. This found the strongest associations to be with manual handling and vibration, but it is not possible to separate the effects of vibration from those of posture or prolonged sitting. The authors regret being unable to support any dose-response relationships. However, this is not surprising as their work concentrated more on examination of the subjects than of the stressors, which, in common with many of the other studies, were assessed only from responses to questionnaires.

3.6 Summary

Three additional sources of stress which could contribute to the development of back trouble have been suggested as being associated with some, if not most of the occupations for which whole-body vibration is claimed to be a major cause of the observed symptoms.

Postural stress arises in the first instance, and in most of the occupations, simply from sitting down. In some cases, particularly those of helicopter pilots, but also drivers of lift trucks who have to operate in both forward and reverse directions, this stress may be even more severe. In all cases, the posture is maintained throughout the work periods when vibration is present, and so duration of vibration exposure is also duration of postural stress. Postural stress is not easy to quantify, but this has been attempted at least once (Bovenzi & Betta).

Manual handling occurs infrequently, and separately from vibration exposure, in several types of work. This also is difficult to quantify in field studies, although methods have been developed for general lifting operations. There appear to be no instances where this has been included in the analysis of any study of whole-body vibration effects.

Any risk arising from operators jumping down from machines with high work platforms has yet to be quantified, and again, this does not appear to have been included in any analysis of whole-body vibration effects.

Thus we have occupations which are associated with elevated risks of back trouble and which involve exposure to stresses from vibration, posture, and often also manual handling and jumping down from high work platforms. It is surely a primary requirement that the proportion of risk that can be attributed to vibration should be distinguished from that due to the other three factors. Yet we have very little comparative information about the relative importance of these contributing factors.

4. HISTORY OF RESEARCH RELATED TO WHOLE-BODY VIBRATION - AN OVERVIEW

4.1 General

Research into the effects of whole-body vibration has encompassed numerous aspects of the subject. In the laboratory, controlled tests have been used to investigate the effects on subjectively assessed "comfort" and objectively assessed performance at various tasks, and dynamic response functions such as vibration transmission and mechanical impedance have been measured. There have also been laboratory investigations into the association between short-term vibration exposure and some observable physiological changes.

In the field, there have been measurements and surveys of the vibration to which people are exposed in work or transportation.

There have also been numerous surveys or studies of aspects of the health of workers in specific occupations. With a very few exceptions these have been included in the canon of "vibration" research simply because the authors have suggested vibration as one of the stressors contributing to the observed effect.

What can be achieved in the laboratory and what can be measured in the field have been dependant on the technology available, and the latter limitation on information from the more historic reports is discussed in Lines & Stayner (2000).

What can be learnt from investigation is also dependant on what is already known, and that is the reason for organising this overview into loose historical periods. In the context of the present review, this historical overview is necessarily brief, but it is intended to illustrate how knowledge of the effects of whole-body vibration has progressed in the course of the last half-century. A slightly more comprehensive review is included at Appendix A, with published reports arranged according to occupational groups.

4.2 Before 1945

Vibration began to become a recognisable environmental stress with the proliferation of mobile machines, such as farm tractors, motor vehicles and aircraft in the 1920s and 1930s. In the motor industry, engineers such as Olley (1934) had worked on suspension development to improve subjective assessment of vehicle comfort, without any particular interest in the underlying human response sensitivities.

One of the few research studies conducted before 1945 was that of Reiher & Meister (1931). These authors accepted that *"the deleterious effects of street and machine vibrations are known"* and wished to find some parallel relationships between vibration and human sensation to those being developed for noise. They conducted laboratory experiments on a mechanical test rig capable of sinusoidal oscillations at frequencies between 5 Hz and 60 Hz in either horizontal or vertical directions. Their tests involved subjective rating of sensation with subjects either standing or lying on the platform, and covered a range of acceleration magnitudes from about $50mm/s^2$ to about $10m/s^2$. They used these to estimate the thresholds of perception and the equivalence of responses at vibration magnitudes up to what were subjectively rated as *"unpleasant, believed dangerous for long periods"* and *"very unpleasant, believed dangerous for short periods"*. They considered that the risk to health, or at least the seat of the sensation, resided in *"the soft material of the brain, eyes, muscles and joints"*.

Although the Reiher & Meister paper was translated by the U.S. Air Corps in 1946 *"because of the current interest in interpreting the effect of structural vibrations upon airplane passengers and crew"*, it does not contribute anything to knowledge of the effect of vibration or shock on the seated subject or on the spine in particular. Nor does their 1932 paper on shock contribute knowledge of this type, being concerned with effects similar to those felt by the standing operator of a drop-hammer press or forge. These papers do however provide a precedent for using subjective assessments of sensation as indicators of possible risk to health.

4.3 1945 - 1960

In the 20 years from 1945, laboratory studies of vibration effects were restricted to what could be done using mechanical test rigs. These were used for developing seat suspensions (Radke, 1957) and occasionally for studying human response on complete machines (Dupuis, 1960, 1961).

At the Max-Planck Institut für Arbeitsphysiologie, Dortmund, Dieckmann (1957) carried out some basic experiments on vibration transmission and mechanical impedance of standing and sitting subjects. It is not clear from the English language paper how many subjects he used, nor what were their characteristics. Nor is it clear what vibration generators he used, except that there were two, one for the range 1 Hz to 8 Hz, and another for 5 Hz to 100 Hz. This was a landmark study, in that it provided the basis for the development of the German standard VDI 2057, with the frequency weighting and "strain" assessment of the "k-factor". The strain assessment appears to be based on a combination of subjective assessments and "vegetative" reactions such as skin capacitance. The exposure limiting strain of k = 100 was equivalent to an acceleration of about 500 cm/s^2 for vertical vibration, and about 200 cm/s^2 for horizontal, at the frequencies of greatest sensitivity (i.e. weighted). K = 100 was defined as the upper limit for man, where k = 10 is the limit which should be allowed in industry *"for only a short time"*. It is not readily apparent which axis was used for the horizontal experiments, but from the comparison with the vertical tests, specifically a description of the elliptical motion of the head, it was probably the longitudinal (anterior/posterior) direction.

In this period, studies of human tolerance levels to short term vibration were started in the U.S.A. (Ziegenruecker & Magid, 1959; Magid *et al*, 1960) using a mechanical shake table and a long-stroke "vertical accelerator" that was probably one of the first electro-hydraulic devices used with human subjects. These led to frequency contours for a subjective tolerance limit that influenced the frequency sensitivity contours in the original development of ISO 2631. However, when the subjects were asked what sensations caused them to stop the test, i.e. defined when they had reached their tolerance limits, the reasons included: *Abdominal pains, chest pains, testicular pain, head symptoms, dyspnea, anxiety and general discomfort*. The list did not include back pain. It is difficult to envisage how such data from continuous sinusoidal oscillations with amplitudes greater than 15 ms^{-2}, at frequencies between 4 Hz and 8 Hz, can relate to occupational low back disorders which result from much longer exposure to lower magnitudes of vibration. However, the magnitudes and frequencies of the ultimate accelerations are not incompatible with the most severe shocks that are encountered from time to time on off-road machines.

Griffin (1990, section 5.7.1) observes that the contours obtained at the high levels of vibration stress used by Magid *et al* differ significantly from those obtained by his own laboratory at lower, but still very disturbing, levels. He also argues that *"the definition of the frequency dependence of the effects of vibration on health from considerations of discomfort or pain is suspect because these sensations may not imply harm and harm may occur without these sensations"*. He goes on to say *"Even so, with the current limitations on knowledge there is much to be gained by the use of frequency weightings which conform to subjective impressions of severe discomfort and possible harm. There are, at least, insufficient data to be sure that motion which causes severe discomfort may not also cause some harm"*. It will be argued below that a sensation of general discomfort, or of discomfort related to one specified organ or set of organs is of little relevance to damage caused to a different specific organ.

Laboratory studies may not have got under way to a significant extent during this period, but field studies did. Griffin (1990) reports a possible 18 studies between 1949 and 1960 (rising to 31 if the period is extended to 1965), nearly half of which involved drivers of farm tractors. These all refer to health surveys. Equipment for field measurement of vibration during this period was as restrictive as the equipment for laboratory investigations (Lines & Stayner 2000) and allowed little more than a few "snapshots" of conditions that were pre-selected to represent the more severe of working conditions.

Clayberg (1949) described many health effects among drivers of, and riders in military transport, one of which was what was more commonly known as "jeep back". *"Intervertebral disc syndrome: Jarring of vehicles having few, poor, or no springs for protection of the spinal column of riders is an infrequent but important item. The writer has examined officers compelled to ride for prolonged periods of duty in jeeps over rough roads, and such officers have developed severe low back pains, causing retirement from service with substantial diagnosis of intervertebral disc hernia or rupture, operative procedure being required in some cases. Enlisted men are as often affected".*

Fishbein & Salter (1950) report a questionnaire survey of US orthopaedic surgeons, in which they asked *"Have you seen patients in whom disorders of the spine and supporting structures might be ascribed to driving in trucks or tractors?"* 378 out of 1474 replied, of whom only 109 indicated "none". From the remainder they had an estimated total of nearly 8,000 cases. The interest appears to have been restricted to the **occupation** of driving trucks or tractors, not to vibration as a component of those occupations.

One of the more widely quoted studies was that made by Rosegger (Rosegger & Rosegger 1960) into the health of drivers of farm tractors in what was then the German Democratic Republic. The location is significant, because it was associated with a relatively regimented system of farm work in which it was possible to distinguish between groups of workers who did little but drive tractors, and others whose duties did not include tractor driving, but who otherwise came from the same social and economic group. Although more recent researchers have found fault or shortcomings with details of the selection or analysis of data, this study, in common with others before and since, does show that relatively large numbers of the chosen occupational group suffered a relatively high incidence of symptoms at a relatively early age. Although the medical examinations involved an extensive battery of tests, the main effects were found in the gastro-intestinal system and the lumbar-thoracic spine. The authors put forward the opinion that the stomach disorders were mainly the result of poor and irregular eating habits. With regard to the symptoms of back trouble, they made the following comment: *"it will be noted that the majority of tractor drivers without pathological finding in the thoracic and lumbar vertebra have been engaged in that occupation for not more than 2 years, whereas only one-fifth of those who have been tractor drivers for more than 4 years, for example, is without pathological finding."* They also attempted to compare different tractor models, an exercise which could only have been attempted in an Eastern Bloc country. Although they did not find any differences, this in itself could be significant, because they were comparing both wheeled and tracklaying machines, which are now known to have widely differing vibration characteristics. Again, although the authors admit that *"it remains to be established in what form tractor driving has an adverse effect on the spine"*, they then opine that *"The shocks and vibrations encountered in tractor driving are transmitted to the spine in the form of micro-trauma . . . This continuous action causes fatigue in the functioning of the intervertebral discs which, in this condition, are more susceptible to degenerative deformation . . . Moreover. . . faulty posture is fairly common in tractor driving. . "* From this they go on to conclude more decidedly that *"tractor driving may have considerable ill-effects on the health of the operator. This is largely due to the effects of vibration and shocks* *continuously acting upon the human body. . and partly to the need to keep the body in cramped condition and unhealthy posture for long periods"* The postures with which they are concerned are illustrated as twisting to observe rear-mounted implements, and leaning to compensate for tilt of the tractor when one wheel is in a furrow. They do not seem to have considered that the sitting posture *per se* could add to the stress on the lower back, which is slightly surprising in view of the depth to which they discuss factors affecting the development of the spine in young people.

The importance of reports such as this by the Roseggers is that in "identifying" vibration as a major cause of the occupational disease they have encouraged the view that vibration exposure is the most important part of the occupational stress. This in turn has led, perhaps unintentionally, to attempts to study vibration stress in isolation, a feature which has been reversed only by the much more recent work of Seidel and colleagues (see below).

To summarize, this is the period in which whole-body vibration was suggested by some of the medical profession as a possible contributory factor in the development of back problems in some occupational groups. The techniques were not available at the time to investigate these claims in any scientific manner.

4.4 1960 - 1970

This period was important in the development of awareness and knowledge of human response to whole-body vibration for two reasons. First, the relatively ready availability of electro-hydraulic and electro-dynamic vibrators resulted in an increase in the number and range of laboratory studies. And secondly, a working group of ISO/TC 108 was convened to develop standard guidance on human response to vibration, which eventually resulted in the publication of ISO 2631 - 1974 (and indirectly ISO 5349 for hand-transmitted vibration).

The new generation of laboratory test facilities was used by many workers to obtain more data on frequency contours for equivalent sensation (comfort) (e.g. Chaney, 1964; Miwa, 1967a,b), a subject that was pursued well into the next decade, together with the development of psychophysical rating scales for magnitude estimation based on the techniques of Stevens (1958). However, this became for many years an academic exercise, because the ISO Working Group settled on a set of frequency weighting curves by the mid-1960s, Figure 2 (Guignard, 1967), that were widely used unchanged for the next 30 years (see also section 7, below). As mentioned above in relation to the work of Magid & Coermann, there is little basis for any association between subjectively based equivalent comfort contours and risk of damage to the spinal column.

The new test facilities were used also for studies of the effect of whole-body vibration on aspects of human performance, such as visual acuity (Lange & Coermann 1962) and motor control mechanisms (Coermann et al 1962), but these probably have less relevance to health effects than do the short term tolerance experiments of Ziegenruecker & Magid or Magid et al, mentioned above.

Potentially of more relevance were the laboratory studies of physiological effects of vibration. Griffin (1990) reports 14 cardiovascular, 6 or more respiratory, 2 or 3 endocrine/metabolic (more in animals), 20-30 motor response (muscular/emg), a number of studies associating vibration with hearing (mostly hand-transmitted vibration), 3 or 4 central nervous system (EEG), and two studies of effect on the length (sitting height) of the spinal column. These were for the roughly 25 year period 1960 - 1985 (spinal length 1987-88).

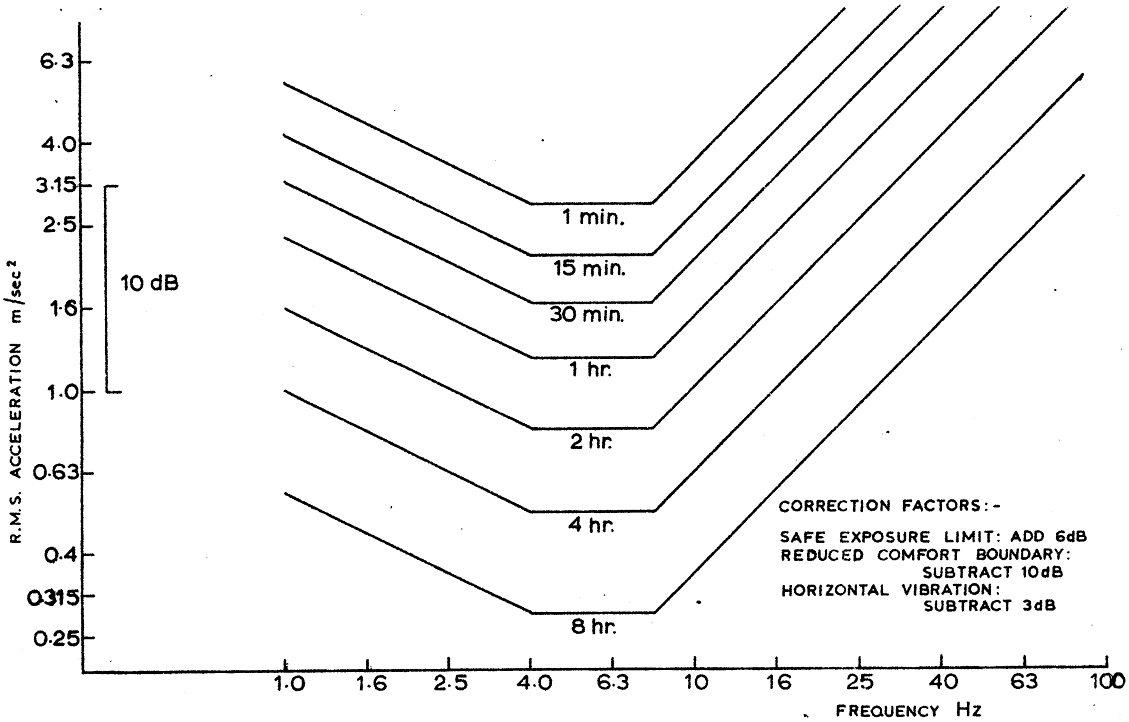

Figure 2: Frequency weighting curves (z-axis FDP) proposed for ISO 2631 (after Guignard 1967)

From this period, only those studies of the body's dynamic response, such as those carried out at Bad Kreuznach under Dupuis (1966) (see also Sandover & Dupuis 1987) which extended the work of Dieckmann (above) and at military laboratories in the USA (e.g. Edwards & Lange 1964), appear to have any direct relevance to the potential for vibration exposure to lead to damage to the spinal column or to the lower back in general. What these show is that the musculo-skeletal system possesses a somewhat resonant response, with motion entering at the seat/buttocks interface being magnified at certain frequencies, and at certain locations within the body. Specifically, they show that the largest motion occurs, under sinusoidal vibration at least, in the upper lumbar and lower thoracic region of the spinal column (Dupuis 1966). This suggests that this is the part where damage caused by vibration and shock is most likely to be found. It does not imply directly that because there is resonance there will be damage, as suggested in the English translation of Dupuis & Zerlett (1986). If the resonance were undamped, or damped to only a very small extent, such might be the case, but then this would also magnify the response to heel strikes when walking, and be a cause of very frequent harm. It is probable that this statement has become distorted in translation.

The other specific finding was that the frequency of maximum response (in the lumbar/thoracic region) to vertical motion is at around 5 Hz, varying between different subjects, generally in the range 4 Hz to 6 Hz. This was taken into account, together with the tolerance results of Magid et al, in formulating the frequency sensitivity curves of the first edition of ISO 2631.

For the period 1961-1970, Griffin (1990) lists 35 reports of occupational health studies associated with vibration exposure. About 25% of these involved each of two groups of occupations, one was universal, including drivers of farm tractors and earthmoving machines. The other group was confined almost exclusively to eastern bloc countries, and involved workers in the concrete industry. These are thought to have formed a special case, and are discussed further in Annex A. They are not thought to have contributed directly to the development of knowledge or awareness of whole-body vibration as a health problem in the rest of the world, and there seems to have been little discussion of their relevance to other forms of exposure to whole-body vibration.

One of the most widely quoted studies which started in this period but was reported later by Christ and Dupuis (1968) and Dupuis & Christ (1966, 1972) which provided both cross-sectional and longitudinal information on a group of (initially) young drivers of farm tractors. This involved thorough medical and X-ray examination of the subjects, but only subjective interpretations of the risk factors. They showed, e.g. from the first examination (Table 2a), that both subjectively assessed pain and x-ray findings increased with annual tractor usage, although there was actually quite poor correlation between the two indicators. It is interesting to observe the frequency of these findings in a group of young men (average age 17 years). After the full ten years, they showed that the more serious x-ray findings had increased consistently over time (Table 2b). It should be noted that the authors were careful not to identify risk factors definitively. *"The authors did not risk, however, attributing the deterioration found . . . to exterior influences (i.e. whole-body vibration stress) in the tractor drivers after an observation period of 5 years. The number of cases was insufficient and the examination time period too short. There is only the well-founded suspicion that whole-body vibration stress may cause injury to the spinal column"* (Dupuis & Zerlett) and with regard to the second follow-up: *"the authors do not believe it appropriate to make clear-cut, definitive statements on the causes of damage to the spinal column, especially with regard to the progressively decreasing number of probands available, after an observation period of 11 years. They concur, however, that the degeneration established in the spinal column . . . which had occurred in the last 5 years in one fourth of the drivers examined, could possibly be regarded as partly "premature" and "exogenous"*. It is clear, from this and other parts of their discussion, that Dupuis and Christ were of the opinion that vibration was the only "exogenous" stress of any significance in tractor driving. The possibility of apportioning risk between vibration and other factors was never seriously considered.

Table 2a: Incidence of complaints and x-ray findings among young tractor drivers related to annual hours of tractor use (after Dupuis & Christ 1966)

	<700 hrs/yr	700-1200 hrs/yr	>1200 hrs/yr
X-ray findings	61	68	94
Back pain complaints	39	52	56

Table 2b: Comparison of tractor drivers in longitudinal study (from Dupuis & Christ 1972)

Year of examination	1960-61	1965-66	1970-71
No. of patients examined	211	137	106
Average age (years)	17.4	23.0	29.3
Radiological findings (%)			
A. Serious	50.2	68.7	80.1
B. Somewhat unfavourable	22.3	10.2	8.5
C. Probably no influence	14.7	13.1	5.7
D. No pathological findings	12.8	8.0	5.7
Total	100	100	100

This, in common with other generally less thorough studies, demonstrated quite convincingly that the occupation of tractor driver was associated with an acceleration of damage to the lower back. As was the case with Rosegger & Rosegger, the authors suggest that the shock and vibration to which the drivers were exposed was a major contributing factor to the physiological damage. In the later review (Dupuis and Zerlett, 1986) the "resonance" of the lower back (see above) is invoked as justification for this suggestion.

It was certainly quite widely accepted that occupations associated with exposure to relatively severe whole-body vibration and shock could lead to increased risk of back trouble. It was also quite widely held (e.g. Matthews 1964, 1973, 1975) that engineering measures aimed at reducing the severity of the vibration would lead to improvements in the health of the workforce. Such measures would include effective suspensions for machines, or, where that was not practicable, for the operator's seats.

During this period it was practicable to measure only quite limited examples of the actual vibration exposure (Lines & Stayner, 2000). This was partly because of the size of the measuring and recording equipment, and partly because the subsequent analysis was very time consuming, particularly when this included frequency decomposition. In consequence, the measurements were usually restricted to those working conditions which were expected *a priori* to be relatively severe. It was not considered practical to attempt to describe by measurement the distribution of vibration magnitudes which would be representative of the full range of occupational exposure.

Methods of frequency analysis which are now familiar and in general use could at that time be applied only with considerable effort. As a result, those examples of vibration which were measured were analysed rather simply so as to obtain estimates of peak magnitudes and dominant frequencies. There was no concept of a single number to quantify vibration severity. Amplitude analysis (Bjerninger) was more common than frequency analysis (Matthews). It may be observed that, military and aviation interests excepted, much of the research into occupational health, vibration measurement, and the development of means of reducing vibration was at this time associated with agriculture. To some extent this may have been because mechanisation was being introduced to farming at this time, but it probably also owes something to the existence, most widely in Europe, of research institutions whose aim was primarily to increase food production. At the time, equivalent institutions did not exist for other industries which have since been found to provide occupational exposure to whole-body vibration, such as the construction industry for which earthmoving machines were also beginning to be introduced in larger numbers.

The International Organisation for Standardisation set up a Working Group to provide guidance on the various aspects of human response to vibration (Guignard, 1967). The members clearly envisaged vibration as mostly a continuous phenomenon, and in the first place usually sinusoidal or periodic. Magnitude was therefore familiarly expressed in terms of rms values, and application was limited to vibrations whose "crest factor" was less than 6 so as to ensure that they were not significantly dissimilar from the basic sinusoidal form. The Group used available laboratory data to support proposals for frequency sensitivity curves, which were to be the same for all types of human response, including health, performance and comfort. And the Group proposed a form of equivalence, or trade-off, between magnitude and duration of continuous exposure for the same effect.

In summary, this decade was when interest in whole-body human vibration started to expand rapidly. However, the methods available for data acquisition and analysis still did not allow easy investigation of real-life vibration exposure, so that more effort was devoted to studies of the "effect" than to the "cause". Facilities for laboratory studies began to be more widely available. The discussions which were to lead eventually to the standard ISO 2631 put in place a trade-off between vibration magnitude and time which remains to this day as the most widely accepted measure of risk-related severity. This was achieved without the benefit of any studies of epidemiology or attempts to measure cause and effect. Not only was the vibration "cause" not investigated, but the health "effect" was thought to include a multiplicity of possible damage risks, so that many physiological effects were studied in relation to occupational exposure to vibration. However, the most common health effect was damage to the spine and associated systems, and nearly all the occupations with which this damage was associated involved a seated operating or driving position.

4.5 1970's and 1980's

These decades witnessed the continued interest in laboratory studies of subjective response to whole-body vibration, studies of its effects on performance and physiological indicators, and the extension of studies of body dynamics. As indicated above, the direct relevance of much of this work to an understanding of any relationship between vibration exposure and back trouble is slight. It will be noted below that some of these studies lead to the incorporation of a different frequency weighting for vertical (z-axis) vibration in BS 6841 to that in ISO 2631, and eventually to a change in ISO 2631 itself.

Towards the end of this period, Spång and Arnberg (1990) investigated subjective reactions to simulated vehicle vibration, with particular attention to shocks. This work seems to be the source of the running rms or Maximum Transient Vibration Value (MTVV) which has been provided in ISO 2631-1 (1997) as an alternative to VDV for motion with high crest factors.

A study made towards the end of this period by Dupuis et al (reported 1991) into the transient response of the spine, provided a useful insight into the amplitude non-linearity of spinal z-axis response (Figure 3). This shows, for example, that the transmission between the seat and the lumbar spine, which exhibits a small attenuation when the vibration magnitude is low, increases as the magnitude increases, until a seat vibration of 5 ms^{-2} is roughly doubled in amplitude at the lumbar spine.

Also of relevance were the continuing, and new studies of occupational health. The conclusion of the longitudinal study of Dupuis and Christ, discussed above, was reported in 1972, and there were several studies in the U.S.A.

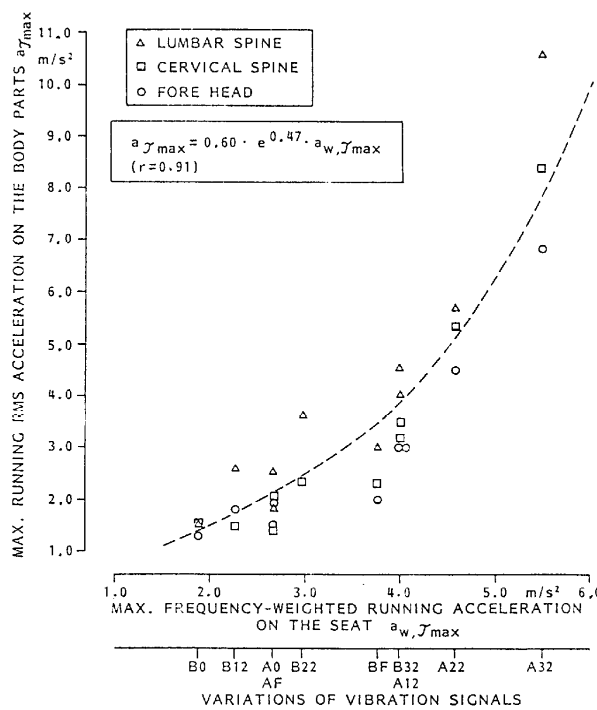

Figure 3. *"Maximal running rms acceleration at the body parts depending on maximal frequency-weighted running rms acceleration at the seat"* After Dupuis *et al* (1991)

Kelsey and colleagues reported on patients from a general population in Connecticut, U.S.A. who presented for lumbar surgery. They analysed risk factors for two independent groups of patients, first from 1971-1973 (217 cases, Kelsey 1975, Kelsey & Hardy 1975), and then from 1979-1981 (325 cases, Kelsey *et al* 1984). For the first group they found that sitting for more than half the time at work increased the relative risk in the patient group compared with matched and unmatched controls, while sitting in a car increased the risk, and driving a truck increased it further. *"The estimate of relative risk indicates that people who drive cars are more than twice as likely to develop acute herniated intervertebral disc as people who do not drive cars"*. At this time the authors suggested that *"prolonged sitting . . is detrimental"* and that *"lack of physical activity . . could be relevant to their increased risk"*. In the second study, in which the authors were concerned also about the possible effect of cigarette smoking, they also claimed that *"there is good evidence that vibration contributes to this (driving motor vehicles) increased risk"*. They support this claim by quoting six references, two of which are papers on seat design, and none of the others is found on inspection to contain any stronger evidence than an association between occupation and risk (Gruber & Zipermann, Pope *et al* 1980, Troup). All of which make this one of the most obvious cases of "proof by repetition" of an unproven hypothesis. A second aspect of these two studies is the disparity, almost amounting to a contradiction, between the findings in relation to the possible effect of lifting. In the fist group of patients, lifting had an effect which was insignificantly small, whereas in the second group, albeit in combination with twisting, lifting *"is estimated to be associated with a sevenfold increase in risk"*. It may be that the questions were administered differently in the two studies. However, the possibility needs to be considered that the statistical tests required greater homogeneity than was actually present, and that sample sizes therefore need to be much larger. This could present problems for other research in this area.

Gruber & Ziperman, in a study of over 1400 male motor coach operators (drivers), found that they showed higher prevalence rates for many diseases, including displacement of the intervertebral disc. They used three control groups: professional drivers with less than five years experience; a large group of adult males in the general population examined during a national health survey; and a group of male office workers. They suggested a mechanism for vibration to be among the causal factors, but, in common with others who have made their investigations from the point of view of occupational health, this suggestion was purely conjectural. They observe that *"At the present time it would be scientifically inaccurate to state that whole-body vibration is solely responsible for any of the several significant differences observed in the prevalence rates between the study group and any or all of the comparison groups. This study is merely the second step in a series of studies that will be necessary to establish accurately any effect or lack of effect of whole-body vibration on workers exposed to vibration in their job environments"*.

Milby and Spear analysed sickness claims from heavy equipment operators. They claimed to identify "vibration exposed" groups, and even the degree of vibration exposure. However, they appear to have selected "vibration exposed" and "control" groups on the basis of job or machine descriptions, which may not be unreasonable, and have estimated classes of severity of exposure purely on the basis of hours worked, which of course is hardly a measure of vibration. What they did not find was any higher morbidity in the vibration exposed group than in their control group. They postulated, and made further analysis (Spear et al, 1976) to support the idea that people likely to be at higher risk of vibration damage were more likely to find employment which does not involve exposure to vibration. This so-called "healthy worker effect" has been invoked on several occasions in the history of research into the occupational effects of vibration. Some care needs to be taken in following this hypothesis if it is not to appear as an apology for a particular study failing to show what the researchers desired.

Pope et al (1980, and other dates), investigating patients in general practice, list a number of activities as potential "sources", including particularly truck driving**.** (See also 5.2.2 below)

In Europe, Zerlett (1986, also Dupuis & Zerlett 1986) followed up a questionnaire survey of operators of earthmoving machinery with X-ray examination of the spines of the majority of the group and found that most of them had disorders of the lumbar spine (see also under Köhne *et al,* 5.4 below).

Two reports from Japan may be of interest. In 1982, Kanda et al reported a high incidence of vertebral deformations among the crew members of high speed ships, which they attributed to the shock and vibration on these vessels. The vessels concerned were of 65 to 189 tons, and sailed at speed of up to 30 knots. The authors used DRI (see discussion under Payne, below) to evaluate the crews' exposures, but some data suggests peak vertical accelerations frequently in excess of 1g, and occasionally as high as 3g. It is to be expected that crew of smaller high speed boats would be exposed to higher magnitudes, but even so these authors reported "wedge-shaped deformations" of the lumbar sections twice as often as in *"workers of twenty kinds of occupations"*.

In the other, Konda et al (1985) reported a questionnaire survey of drivers of container trucks at ports, from which they attributed a high incidence of low back problems to vibration and posture. They suggested that *"large shock and vibration from the coupler are partly responsible for the induction of low back pain"*, but do not show any measured values.

By the end of the 1980s there had been so many occupational health studies that reviewing them became a significant activity in its own right. Seidel & Heide (1986) and Hulshof and van Zanten (1987) published critical reviews of the effects of whole-body vibration (followed by Kjellberg et al in 1994). These reviews were very critical of the epidemiological standards used in the published surveys (more below, perhaps), and in particular noted that almost without exception the health studies had been conducted either without any measurement of vibration exposure, or else completely independently of exposure measurements.

One of the results of the development of ISO 2631(1974) was that it provided a method and a rationale for using a single number to represent the magnitude of vibration exposure. This number took into account the human "frequency response", and used simple rms averaging to integrate over time vibration magnitudes that could vary considerably over time. This approach was also used in BS 6841, with the difference that in this case the averaging or integration involved the fourth power instead of the second power of the instantaneous, frequency weighted, acceleration. Acceptance of this approach enabled researchers to embark on larger scale field surveys of vibration magnitude than had previously been practicable, e.g. Stayner & Bean (see also Stayner et al 1975), Graef, Boulanger et al (1989), Danière et al (1987). These surveys provided more information about the range of vibration magnitudes encountered in the use of farm tractors, earthmoving machines and industrial trucks. However, the information still fell short of what is required to estimate total, long-term exposure patterns in a form analogous to that which had long been available for noise.

Of greater concern than the lack of data in terms of the distribution of e.g. hourly rms values, is the way in which this development appears to run counter to the intentions of those who originally drafted ISO 2631:

"Various methods of rating severity of exposure and defining limits of exposure based on laboratory and field data have been developed in the past for specific applications. None of these methods can be considered applicable in all situations and consequently none has been universally accepted.

In view of the complex factors determining the human response to vibrations, and in view of the shortage of consistent quantitative data concerning man's perception of vibration and his reactions to it, this International Standard has been prepared ***first, to facilitate the evaluation and comparison of data obtained from continuing research in this field****; and second to provide guidance as to acceptable human exposure to whole-body vibration".*

It is not clear whether this pious hope has been mis-represented or mis-interpreted, or whether the drafting committee considered that they had effectively solved the problem set in the first of the two paragraphs above. What is clear is that those whose primary concern is with the medical effects have been happy to accept the received definition of the cause, and in that sense the comparison of data has been facilitated. On the other hand, continuing research into the relative importance of different characteristics of vibration, or of the combination of vibration and shock found in real working environments was quite clearly not facilitated. On the contrary, it was effectively stopped for about 20 years.

The problem is that the wide acceptance of one single number approach to evaluating vibration exposure, or at most two effectively similar approaches if we include VDV, discouraged for two decades the investigation of alternative forms of evaluation. Of particular relevance in the light of more recent developments was the loss of data on **amplitude distribution**. The approaches of frequency weighted rms acceleration, or of VDV, or even of frequency analysis were based on the assumption that all measured vibrations have amplitude distributions that are close approximations to normal or gaussian. Very little interest was taken in the extremes, or "tails" of the distribution, except to try to relax the limitation on so-called "crest factor" in ISO 2631 so as to extend the range of conditions for which the single number could be used. The crest factor limitation was considered to be an awkward impediment which had to be circumvented rather than an indication that other features of the shock and vibration history should be measured and recorded.

One exception to this general acceptance of the ISO 2631 principle was the approach taken by Payne (Payne 1965, Payne & Band 1971). In contrast to the generalised approach to frequency weighting adopted in ISO 2631 and BS 6841, Payne and colleagues concentrated only on the transmission of z-axis forces or accelerations upwards through the spine. This approach originated in work aimed at evaluating the severity of shock acceleration waveforms encountered in operation of aircraft ejection seats. This approach is clearly quite appropriate to a discussion of the health effects of vibration and shock when these are restricted to the condition of the back. They are possibly less appropriate when extrapolated to attempt to use them as predictors of more generalised subjective sensitivity or comfort evaluation, and by doing this Payne (1976, 1978, 1996) invited criticism which extended to a more general disregard for his approach than was perhaps justified.

At the heart of Payne's approach were a number of dynamic models of the musculo-skeletal system of the seated subject, through which seat acceleration is modified to estimate acceleration at the most vulnerable section of the spine. In principle this is consistent with the work of Dieckman and of Dupuis, in that it describes a relatively simple resonant system. The damping of these models is very much lighter than other frequency response functions for the spine, for which the proposed explanation is that this relates to very high magnitudes of shock excitation, and is in fact an extension of the non-linearity found by Dupuis et al (above). The credibility of Payne's approach has not been helped by the suggestion of precision implied by parameters defined to 3 or more significant figures.

Among those who have supported the Payne approach, at least as applied to the potential for shocks to damage the spine, Sandover also made a personal contribution to the discussion of damage mechanisms (Sandover 1981, 1983). Although his study involved detailed kinematic calculations aimed at estimating intervertebral loads, the main thrust of his contribution was to suggest that damage, for example micro-fractures to vertebral end-plates, could arise in a manner analogous to the fatigue mechanism in engineering materials. This could provide an explanation for damage caused by vibration whose fluctuating loads are of much lower magnitude than the loads which experiment has shown to have observable effects with a single application. At the time, and without the knowledge of the amplitude distribution, or more specifically the distribution of peak accelerations or forces, this theory provided a rationale for the belief that all vibration could be harmful, if only it was endured for sufficiently long. Viewed in combination with the later work of Seidel *et al* (below) Sandover's proposition was to take on a different significance.

In a separate development during this period, research was also undertaken to reduce the postural stress experienced by drivers of farm tractors. This was principally aimed at alleviating the extra stresses identified by Rosegger & Rosegger, i.e. those arising from twisting in the seat to look to the rear and those caused by leaning to counteract the tilt associated with working with a wheel in the furrow (Bottoms (1978), Donati *et al* (1984), Whyte & Barber (1985)). However, others were also pointing out that even the ordinary seated posture is not well suited to the way that the human musculo-skeletal system has developed in order to support walking and standing on two legs (Troup). In particular a Swedish team (e.g. Andersson *et al*) made a significant study of the effects of posture on spinal loading.

To summarise, during this period further evidence was collected which associated back trouble with particular occupations. However, although these occupations were selected because they included some degree of operator exposure to vibration, none of the published research attempted to investigate the cause as well as the effect. Instead, the cause-effect relationship proposed in ISO 2631 was generally assumed to be appropriate, and it could be said that ISO 2631 had indeed encouraged the gathering of simple data, but stifled research. Also during this period the knowledge of body dynamics was enhanced, and some proposals were in circulation relating to shock response of the human spine, although these found little favour beyond the application to aircraft ejection systems. A fatigue theory was put forward to provide an explanation of how low level vibration could contribute to low back pain. And postural stress was receiving attention, although generally quite separately from vibration.

4.6 More recent studies

4.6.1 General

The last decade has seen progress on several fronts. First, there has been a number of epidemiological studies which have been designed specifically to overcome some of the criticisms raised in the review papers already mentioned, and so to demonstrate a link between vibration *per se* and back trouble. Those by the Coronel Laboratory, by Dr Bovenzi and co-workers, and by Schwarze et al will be considered here in some detail. Then there have been some more comprehensive measurements of vibration, some of which allow evaluation by alternative methods to the rms frequency weighted values of ISO 2631. Of potentially great significance is a body of work published by the laboratory of Dr Seidel, where possible injury mechanisms have been investigated, thus putting into discussion the basis for evaluating vibration exposure. And there have been studies of numerous other aspects of human response to vibration, of which those related to dynamic response are of particular interest.

4.6.2 Coronel laboratory

Staff of the Coronel laboratory have undertaken a series of studies of different occupations, including: Crane operators (Bongers *et al*, 1988); Tractor drivers (Bongers *et al*, 1989); Helicopter pilots (Bongers *et al*, 1990); and Lift truck drivers (Boshuizen *et al*, 1992). Unfortunately, from the point of view of associating the effect (low back pain) with the cause (vibration exposure), most of these studies were based on either long-term sick leave or disability pensioning records, or on self-reported incidence of low back pain. Little effort seems to have been directed to correlating the exposure histories of individuals to any aspect of vibration with these effects. Instead, daily average vibration levels have been estimated for types of machine, and exposure doses calculated using these average values together with years of operating the machines.

4.6.2.1 Fork-lift truck drivers and freight-container tractor drivers

The case of fork-lift truck drivers and freight-container tractor drivers (Boshuizen *et al*, 1992) is one example. The researchers used a questionnaire survey of the health of 242 drivers and 210 other workers (the reference group) at six harbour companies. They also measured representative vibration magnitudes at each of the companies, on examples of each of the relevant machines. They found that *"Young drivers, also those who received a low WBV dose, had a much higher prevalence of both short- and long-lasting back pain than did the reference group. With increasing age, this higher prevalence disappeared. The oldest workers with little exposure even had less long-lasting back pain than the reference workers of a similar age. With increasing WBV dose, the longer lasting back pain seemed to increase up to a WBV dose of 15 year-m^2/sec^4."* However, they also found that "*The dose was strongly correlated with the duration of exposure, because . . of the vehicles used most (small fork-lift trucks. Large fork-lift trucks, and freight-container tractors) were all 0.8-1.0 m/sec^2."* Although the authors noted that *"There was a large difference, however, in the distribution of vibration over time: small fork-lifts have a high vibration level when moving forward or backward but compensate for this with low vibration levels during the relatively long periods of manipulation with the loads. large fork-lifts and freight-container tractors, however, have a lower vibration level when moving, but spend less time on manipulation"* this feature was not pursued. It was assumed reasonable to use the accepted second-power relationship to integrate vibration exposure over time. It is not clear whether, by not investigating any difference between drivers of large and small trucks, the authors missed an opportunity to confirm that integration over time of the second power of vibration acceleration is appropriate, or whether any effect (increased risk of back trouble) was too small to make such a distinction. The researchers also tried to study the effects of prolonged sitting and awkward posture (twisting), which they assessed from questionnaire responses. They concluded that *"in our data, no convincing evidence for a major role of either sitting uninterrupted, looking backward, or WBV exposure were present"*.

4.6.2.2 Agricultural tractor drivers

The study of agricultural tractor drivers (Boshuizen *et al* 1990) has been quoted as one of the few in which there is evidence that, in combination with other information, contributes to establishing a dose-effect relationship. If this is the same study that is reported more fully in Bongers *et al* (1989), for which the HSE has an unpublished translation, then this evidence is no better than that for the lift truck drivers, above. It would appear that all the vibration measurements were made over a three day period, so that only a limited number of field tasks could be included. This, coupled with the use of some tractors with suspensions resulted in the conclusion that average magnitudes of vibration in field work were 0.6 ms^{-2}, and on the road were 1.1 ms^{-2} (root-sum-of-squares). It may be that these values were typical for a workforce employed in the specialised business of land reclamation, and therefore relevant to the worker population under study. However, they are not typical of farm work in northern Europe, because they exclude most of the more severe field tasks (Graef, 1979; Stayner & Bean, 1975; Lines *et al*, 1994, 1995). This is a minor criticism compared with the difficulties raised by trying to correlate averaged vibration magnitudes with risk of injury, using mainly exposure time as the variable. This study does not allow comparison of high magnitudes of vibration for a short time with low magnitudes for longer, because all are combined using the assumption of an equivalent energy dose. The wide range of operator vibration severities found by Lines et al, and formerly by Stayner & Bean, and which could possibly be associated with differences in injury rate, is lost. In particular, what is lost is the effect of different operators working on the same task being consistently exposed to vibration whose magnitude, and possibly most importantly whose shock content, can vary by perhaps as much as 2:1 as a result of operator choice of speed and efforts to avoid potholes or other local rough surfaces. Furthermore, any attempt to compare rms acceleration (equivalent energy principle) with any other evaluation is excluded for lack of data. In consequence, all that can be claimed for this study is similar to what Rosegger & Rosegger and Christ & Dupuis claimed in earlier decades, namely that the occupation of tractor driver is associated with an increased risk of low back problems.

4.6.2.3 Helicopter pilots

In their study of helicopter pilots (Bongers et al 1990) submitted a questionnaire to 163 helicopter pilots and 297 non-flying air force officers. They also measured vibration on two examples of each of 4 types of helicopter. However while they found that *"a very high prevalence of back pain was found for a relatively young and carefully selected population"* (68% compared with 17% overall), they also noted that *"due to the similar flight career of most pilots, exposure time in hours of flight and accumulated* (vibration) *dose are highly correlated"*. Thus their main finding seems to have been that *"the pilots with back pain had significantly more total hours of flight, hours of flight per day, experienced mental stress and tension and were sitting more often in a bent forward and twisted posture than those without back pain"*.

4.6.2.4 Operators of Bridge Cranes

Bongers et al (1988a,b) studied operators of bridge cranes, first with regard to disability pensions, and then in relation to sickness absence. From their group of 743 crane operators, they found 27 disabled by intervertebral disc disorders, compared with 8 from their control group of 662, giving an adjusted Incidence Density Ratio of 2.0. However, for sickness absence of 28 days or longer, *"the previously established excess risk for permanent work disability because of lumbar spine disorders for crane operators is not confirmed"*. They also commented that *"in order to keep an eye on their work . . the operators have to bend forward and turn backward. This strained sitting posture, along with temperature changes and shift work, are concomitant occupational stress factors . . . which may be associated with back trouble"*. However, they do not quantify these effects for comparison with vibration. Instead they start from the hypothesis that *"exposure to whole-body vibration causes adverse health effects, especially back disorders"*, equate crane operation simply with vibration exposure, and discuss evidence for an exposure response relationship.

4.6.3 Studies of Bovenzi and co-workers

Bovenzi has studied 'bus drivers (with Zadini, 1992) and farm tractor drivers (with Betta, 1994). The latter was one of the few studies in which postural stress was reported in a quantifiable way.

4.6.3.1 Bovenzi and Zadini (1992), urban bus drivers

The study of 234 urban 'bus drivers has several advantages if it is to be used to indicate a vibration dose response effect. It included drivers who used 'buses with quite different vibration magnitudes (a_{wz} from 0.2 ms^{-2} to 0.6ms^{-2}), and the vibration magnitudes were claimed to be consistent over time, i.e. drivers' exposures could be estimated with a reasonably high degree of precision, unlike the tractor drivers in the Dutch study discussed above. Also, the work organisation followed a regular routine, which further added precision to exposure estimates, even when these were based on responses to questionnaire. Statistical analysis showed that odds ratios were significantly different, separately, for "equivalent vibration magnitude", total time of exposure to WBV (driving time), and a composite "total vibration dose" in years-m^2/s^{-4}, for many of the tested effects. The effects studied included low back symptoms, leg pain, acute low back symptoms, "LBP", disc protrusion and sick leave due to "LBP", either during the lifetime, the previous 12 months or the previous 7 days. The data is presented after adjustment for other factors. It could be significant for separating the vibration magnitude and the duration effects more clearly than other studies. The authors claim that they have shown that there is a risk attached to vibration exposure at lower levels than are suggested in ISO 2631 to require caution. For the purpose of establishing a dose-effect relationship between vibration and, e.g. lumbar syndrome or "LBP", it would have been useful if the analysis could have indicated the effect of vibration magnitude and of time on the prevalence of symptoms. This is not immediately apparent from the odds ratio presentation. It would also have been useful to compare those drivers (if any) who had used only the older, higher vibration 'buses with those who had used only the newer, lower vibration ones. The "equivalent vibration magnitude", let alone the "total vibration dose", is calculated according to an assumed equal energy principle, as being the simplest thing to do. It would have been useful if the dose relationship could have been developed from the combination of magnitude and duration effects which this study provides rather than the other way round. One minor quibble is that it is not clear on how many replicates the vibration data is based. Without further information, it is reasonable to assume that each vehicle was subjected to one test, on one route, and that the routes were not the same for each type of bus. Some indication of the likely variability would have been useful in confirming the original supposition that the vibration magnitudes were known with an acceptable degree of precision. Some indication of the amplitude distribution of the acceleration levels would also have been of interest, but it is unreasonable to expect that to have been of concern at the time when the study was made. The study did also use a control group of 125 maintenance workers, but it was noted that there were some differences between the bus drivers and the controls with respect to working postures, dynamic muscular activity, walking, etc, and it was concluded that, as well as WBV, *"it is likely that the accumulation of seated and twisted postures during bus driving contributes to the excess risk of LBP"*.

4.6.3.2 Bovenzi and Betta (1994), agricultural tractor drivers

This study of 1115 tractor drivers, like that of the Dutch group (above), suffers from trying to characterise a highly variable vibration exposure by the data from a small set of measurements. In contrast to the urban bus drivers (above), tractor drivers experience a wide range of vibration magnitudes and a wide range of daily exposure durations. The estimates of vibration magnitude are based on a more representative set of measurements than those of the Dutch group, but in this case the approach is hampered by a simplistic assumption that there is a systematic difference between tractor types (see also 5.3 below). In this study, lifetime LBP, acute LBP and sciatica are shown to increase gradually with hours of driving. However, one of the most useful contributions may be the attempt which was made to quantify postural stress as well as vibration dose. Table 3, below, is taken from the paper.

Table 3: Odds ratios[a] for the combined effect of total vibration dose and postural load on the occurrence of chronic low back pain[b]

Total vibration dose		Postural load (grades)		
(years m^2/s^4)	1 (mild)	2 (moderate)	3 (hard)	4 (very hard)
5	1.29	1.79	2.5	3.48
10	1.41	1.96	2.73	3.79
20	1.55	2.15	2.99	4.16
30	1.63	2.27	3.16	4.39
40	1.70	2.36	3.29	4.58

[a] With reference to control subjects exposed to mild postural load and unexposed to vibration

[b] Quantitative logistic regression analysis was performed by expressing total vibration dose on a logarithmic scale and postural load on a linear scale. Odds ratios are adjusted for age, body mass index, education, sport activity, car driving, marital status, mental stress, climatic conditions and back trauma

The authors' comment that *"awkward posture at work was a very important predictor for the occurrence of LBP among tractor drivers. Moreover, there was evidence of a linear trend of increasing LBP prevalence with increasing postural load in both the tractor drivers and the controls"*. It is interesting to conjecture the effect on Table 3 above of treating vibration and postural stresses in a similar way, i.e. of comparing only vibration magnitude with postural load. Both will have been experienced by the subjects over time, yet in the comparison time is combined only with vibration. It is also of interest to guess at how much the different vibration dose categories depend on duration, and how much on magnitude of vibration. As mentioned elsewhere, in this context, vibration magnitude should not be confused with some equivalent daily measure of severity, because that by its nature must include a relationship with time. It may be worth noting that these authors estimate average daily driving time for tractor drivers as low as 2.7 hours, so on many days the drivers are not constrained to sit in restricted postures for long periods, but may have the benefit of more varied muscle activity.

4.6.4 Study of Schwarze et al

One of the most interesting studies to date has been that published by Schwarze et al in 1997 (Schwarze et al 1998). This included operators of lift trucks and truck drivers as well as operators of earthmoving machinery. One of the objects was to avoid difficulties with control groups by comparing groups of machine operators which were distinguished only by the amount of vibration exposure, although a non-exposed control group was used in the first comparisons. The comparisons were made with 388 drivers/operators in 1990-1992, with a follow-up on 281 of these four years later. In the case of the follow-up cohort, it was noted that "all exposed subjects aged more than 50 years at the time of the first examination were omitted as the prevalence of lumbar syndrome was so high that only a few new cases could be expected".

This was a large and thorough investigation, and it would clearly have been impractical to include all the details in the published presentation (Schwarze et al, 1998). The aims of the present review are to highlight the main findings of the study, and to evaluate these findings in relation to the criteria necessary for identifying a dose-effect relationship for whole-body vibration and spinal injury. It may be that this evaluation poses some questions which would be answered by the findings of the investigation, but which are less easy to answer on the basis of the published information alone. In that case, it is to be hoped that the relevant information will eventually be published to dispel any doubts about the conclusions of the research team.

The first point to be made is that Schwarze et al show a similar convergence of the prevalence of lumbar syndrome in different occupational groups as do Palmer et al (see 5.2.3 below). Thus they give:

Non-exposed controls	58%
Drivers of lift trucks	65%
Truck drivers	64%
Operators of earthmoving machines	60%

These are approximate figures extracted from graphs. On this basis alone, there would clearly be a very weak case for establishing the existence of an occupational disease, or for putting in place restrictions aimed at remedying it. However, the researchers found that the control group had been made up of people who had apparently selected themselves, in many cases because they either had back trouble, or had a personal interest in back trouble, and were therefore not considered reliable. It is not clear why this selection bias did not also operate for the members of the other groups, but presumably it did not, and we should accept that in reality exposed occupational groups could really be expected to show greater prevalence of lumbar syndrome than the non-exposed groups.

To avoid this problem, the researchers went on to select groups on the basis of their estimated exposure to vibration, not distinguished by the type of machine which they operate except in so far as these contribute to the vibration magnitude, and claim to show that those with higher vibration exposures are more likely to suffer from lumbar syndrome.

They placed their subjects in three groups of “low”, “medium” and “high” exposure to vibration.

The “low” vibration subjects had daily magnitudes of 8-hour equivalent continuous z-axis rms vibration below a reference level. In fact, the analysis was repeated for each of three reference levels of $0.4ms^{-2}$, $0.6ms^{-2}$ and $0.8ms^{-2}$.

The “medium” and “high” vibration subjects were distinguished according to their lifetime exposures, calculated as the sum of daily rms magnitudes (squared) x number of days. This allowed the combination of exposures on different machines, but only days with $a_{zw(8h)}$ greater than the reference level were included in the sum. Lifetime exposures less than 1414 m^2s^{-4} x days were placed in the “medium” group. Those greater than 1414 m^2s^{-4} x days were in the “high” group. Apparently there were also some analyses made with a “very high” group, whose lifetime exposure exceeded twice the level for “high”, but these were not shown, and would have probably included only a small number of subjects.

The analysis of the first examination results was presented as below (Table 4a). In addition to the prevalence of lumbar syndrome in the whole cohort, prevalence was also calculated when subjects who had shown symptoms before the end of their first year of exposure were eliminated. This was done in order to remove subjects who might have been about to develop the symptoms as a result of some preceding event or of pre-existing health problems.

Table 4a: Prevalence of lumbar syndrome in original group of Schwarze *et al* 1998

Prevalence of lumbar syndrome %			
Exposure group	Low	Medium	High
Analysis base			
All subjects (388), reference 0.6 ms^{-2}	55.5	65	73
Subjects with no symptoms before 1 year's exposure			
Reference 0.6 ms^{-2}	39.5	59	72
Reference 0.8 ms^{-2}	50	57	72

Now, although this appears to show strong evidence of a continuous trend for increasing prevalence with increasing exposure, there is a confounding influence of age. The low and medium exposure groups have similar mean ages, but the high exposure groups are both older by 4 or 5 years. The researchers therefore used a method for adjusting for age (the Mantel-Haenszel estimate), and found that the differences between the medium and high exposure groups, which could be attributed to exposure alone, became very small, e.g. 33% and 35%.

The two apparently significant effects are, first, that between the low exposure and the medium exposure groups there is a significant increase in prevalence of lumbar syndrome. And secondly, if the low exposure criterion level is increased from 0.6ms^{-2} to 0.8ms^{-2}, the prevalence in the low exposure group increases from about 40% to about 50%. The researchers observe that *"a limit for daily reference exposure of* $a_{zw(8h)} = 0.8ms^{-2}$ *does not represent the threshold of hazard to health".*

The differences in approach between this, and other studies of whole-body vibration and the work on noise and hearing loss deserve some comment. In the case of noise, with a relatively clear and quantifiable effect, there has been little practical interest in establishing a threshold below which negligible hearing loss is likely, let alone any suggestion that such a threshold should be used to restrict exposure in the workplace. In the case of whole-body vibration, where there is a supposed effect that is widely prevalent in the population in general, and whose association with vibration exposure has proved difficult to quantify, there is apparently considerable concern to establish just such a threshold. There is clearly some inconsistency in the treatment of these two forms of environmental stress.

Schwarze et al analysed their follow-up data to see how those without symptoms at the time of the first examination developed, i.e. they were interested in those who developed new symptoms. This reduced their subject pool to 111, so that the reliance which can be placed on any findings is somewhat reduced. What they found, for comparison with the above Table 4a, was:

Table 4b: Prevalence of lumbar syndrome in follow-up group of Schwarze *et al* 1998 - those who developed new symptoms after first examination

Prevalence of lumbar syndrome %			
Exposure group	Low	Medium	High
111 subjects, reference 0.6 ms^{-2}	46	43	67

Even after adjusting for age, the high exposure group exhibits a greater prevalence than the medium exposure group, but there is no difference between the medium and low exposure groups. These appear to be quite contrary to the result of the first examination. However, the researchers found that the latter "result" was largely affected by the selection of the two groups, and that this was coloured by their exposures before the first examination. When they re-distributed the subjects according to whether or not they had exceeded 0.6ms^{-2} during only the intervening four years, they found a greater relative risk for the medium exposed group. This enabled them to conclude that *"even without taking the cumulative doses into account, a higher risk of low back disorders seems to be associated with a continuous exposure to vibration with a daily reference exposure of* $a_{zw(8h)} > 0.6ms^{-2}$*".*

These researchers do, at first reading, appear to have made a case for some sort of vibration exposure limit at $a_{zw(8h)} > 0.6ms^{-2}$. However, this does seem intended to eliminate **all** cases in which symptoms of lumbar syndrome could be associated with vibration exposure, and it does seem also that the effects which can be attributed to vibration are not large in relation to the overall likelihood of subjects developing the symptoms. The research has not answered the question "what level of vibration exposure would need to be set to eliminate 90% (or 95%) of vibration induced cases?". The target seems to be 100%, and that would still leave a high prevalence of the symptoms.

The main difficulty with this study lies not with the analysis of physiological symptoms, but with the assessment of exposure, be it to vibration or to postural stress. In the first place, it would appear that any differences in postural stress were ignored as being too difficult, which weakens the results in comparison with those for agricultural workers by Bovenzi and Betta. Clearly all exposed persons, operating whatever machine, were assumed to have similar postural loads.

Secondly, and possibly of equal importance, it turns out not to be clear how intensity of vibration exposure, i.e. magnitude, is differentiated from duration. The entire edifice of $a_{zw(8h)}$ and lifetime exposure is based on the assumption made originally in the drafts of ISO 2631, dating back to before 1970, that everything is governed by a second power law, i.e. that rms calculations are all that is needed, and that average vibration levels are more important than less frequent shocks.

In particular, it would be useful to know the extent to which the values for $a_{zw(8h)}$ were affected by magnitude of even the continuous rms acceleration, and how much they depended on daily hours of use of the machines. What is of interest here is to separate vibration intensity from exposure to the other stresses associated with machine operation. For example, in the low exposure group, were the actual magnitudes of vibration low, or were these particular workers only on their machines for shorter times than the others?

We already have some indication that the members of the high exposure group are in that group because they are older. It seems reasonable also that they have had more years (and therefore days) of lifetime exposure. If this is not the case, it needs to be demonstrated. Otherwise the exposures we are comparing are not necessarily and specifically vibration exposures at all, but could equally be postural.

So-called “intensities”, or “severities”, of vibration exposure need to be clearly distinguished from durations if a dose-effect is to be demonstrated, and even if vibration is to be shown to be a significant contributor to the development of lumbar syndrome.

Therefore, although the investigation reported by Schwarze et al was a very thorough attempt to associate vibration with lumbar syndrome, it has not been reported in such a way as to support the conclusion that “a considerable number of cases of lumbar syndrome (about 27 to 35%) can be attributed to whole-body vibration.” Also, by not allowing comparison with any other indicator of vibration exposure, the report does not provide any new evidence in support of the use of rms acceleration calculations as the most appropriate measure.

In relation to the possible indicators of vibration severity, or more specifically the severity of those features of vibration and shock which may be found to be associated with lumbar syndrome, it should be remembered that $a_{zw(8h)}$ is a measure that leaves much to be desired. To take two extreme examples, first, many road vehicles driven for more than 8 hours a day would exceed the proposed limit of $a_{zw(8h)} = 0.6\text{ms}^{-2}$, although this is an environment in which the dynamic load on the spine is relatively small (see under Seidel *et al* below). But secondly, the operator of a machine who endured shocks of 10ms^{-2} (rms averaged over 10 seconds) 8 times in a day would not exceed it. 10ms^{-2} (rms averaged over 10 seconds) is considerably higher than the most severe shock that the author has found in a study of accelerations likely to cause overtravel of seat suspensions. It is an experience that few subjects would willingly repeat. The decision that this is less damaging than driving a lorry all day may possibly be correct, but the evidence for it has not been presented.

4.6.5 Reports of vibration magnitude data

The above study by Schwarze et al used, for estimating vibration exposure, a data-base of working vibration magnitudes being built up by HVBG, together with operators’ estimates of daily exposure durations. Their estimates would in general relate to machines of the same type, possibly used in similar conditions, and could vary by considerable amounts from the actual exposures of the operators themselves. Some indication of the variation may be found in the spread of vibration magnitudes for similar agricultural tasks (Lines, Styles & Whyte) for which a variation of ±30% or even ±50% could well be expected. This would make more it difficult to establish a dose-effect relationship than if in each case the effect could be associated with the actual relevant dose. Another feature is that the dose estimation is restricted, as encouraged by ISO 2631, to frequency weighted rms acceleration magnitudes. If, as will be suggested below, the damage is more likely to correlate with the accumulation of severe peak loads, then the ability to distinguish the real dose-effect becomes even more remote. In the face of these potentially confusing factors, together with the general intrusion of postural stress, the success of this study in showing any evidence of a dose-effect relationship is a considerable credit to its authors.

The HVBG database, referred to above, is one of the more extensive surveys to be made more recently. In another, Lines, Stiles & Whyte repeated the earlier Stayner & Bean survey of farm tractor drivers. They found that the vibration magnitudes had changed little in 20 years, despite the fact that noise and general ergonomics aspects of tractors had improved dramatically. Their study also produced recorded data which could be analysed in more ways than simply to provide frequency weighted rms values. They used it to compare the different BS and ISO frequency weightings, and to include VDV assessment of severity (see also 5.3 below). These recordings were also used by Lines & Stayner to extract information on the relatively small number of high acceleration events encountered in actual field work, which were generally associated with overtravel of the seat suspension mechanisms.

Similar re-analysis was also made by Sandover of data from a study by Wickström et al (1987, 1991) of forestry and harbour vehicles, and may be possible with data obtained in other more recent surveys in which the actual acceleration time histories were recorded, such as Village et al (1989), Golsse & Hope (1987).

4.6.6 Studies by Dr Seidel and colleagues

However, more important than these two gradual advances in knowledge of occupational damage and vibration exposure at this time may be the contribution to the philosophy of the approach to the question of lumbar syndrome or spinal damage made by the research team under Dr Seidel, in Germany (Seidel 1993a,b; Seidel *et al* 1980, 1986, 1995, 1997, 1998).

Dr Seidel and his colleagues have collated, together with the findings of epidemiological research, also the results of *in vitro* studies of strength and fatigue tests of segments of the spinal column, and his own laboratory's studies of body dynamics and muscle response. From all of these he has postulated a model for estimating the load at the intervertebral joints, and comparing this with load patterns likely to cause "failure". "Failure" is defined in terms of the initiation of micro-fractures in the vertebral endplates. Although this definition of failure is as yet somewhat unclear, the link between load pattern and damage is fairly clear, and follows on closely from the approach propounded by Sandover (1983, 1998a).

A significant development of this model has been the inclusion, as part of the calculations used to estimate loads, of the three features of age, body type and posture. Age, and to a lesser extent gender, may affect the capacity of components of the spine to support loads, in a way equivalent to reducing the ultimate yield stress of a specimen of mechanical material. Somatype could be related to the ability to withstand loads through a simple relation with the cross-sectional area of intervertebral discs, and so also with the pressure caused by any selected load.

Posture may be associated with damage in several ways. First it can affect the shape and static distortion of intervertebral discs (as Andersson *et al*). Secondly, it can alter the mass distribution of the body, thus changing the dynamic load in response to acceleration. And thirdly, it can alter the muscle tone, and so affect the dynamic response of the spinal system in a manner analogous to altering stiffness and damping. Seidel and colleagues therefore conducted their experiments with three somatypes, described as "frail", "robust" and "intermediate", and in three postures, described as "upright", "driving" and "bent forward".

An important aspect of this model is that it provides a possible explanation for the difficulty that researchers have had in demonstrating a dose-effect relationship from epidemiological data. It is consistent with the data of Bovenzi & Betta insofar as that shows the importance of postural stress. And it suggests that the estimation of dose would be more consistent with the effect if it were based on the counting of cycles of an equivalent fatigue function. By analogy with the fatigue of engineering materials, it is postulated that the likelihood of damage is related to a combination of the number and magnitude of peak load cycles, as described by Miner's Rule. This proposes that the lower is the peak magnitude, the greater is the number of cycles that are needed to produce an equivalent effect, generally evaluated as a proportion of the number of cycles to failure at some chosen magnitude of load. It is further hypothesised that as the load magnitude is reduced, the number of cycles to failure tends to infinity, and that there may be a level beyond (below) which the vibration becomes more or less harmless. This lower limiting bound for vibration "fatigue" is suggested to be dependent on body somatype, subject's age, and posture. Even if the concept of a "safe" lower limit for vibration cannot be confirmed, the model clearly shows that the postural stress can be of sufficient magnitude greatly to exceed the vibration component of load in many cases. Seidel *et al* show suggested relationships for combinations of age, somatype, posture and cyclical load (vibration), and suggest that in the some cases failure can be predicted with decreasingly small accumulations of vibration, and even with no cycles of vibration (Figure 4a).

Taking this theoretical process a stage further, Seidel *et al* suggest a relationship between peak acceleration level and number of cycles to failure (Figure 4b). From this it can be seen that it is possible for a bent forward posture to reduce the spine's resistance to dynamic load by a factor of as much as 100 compared with a driving posture. It must be stressed that these are purely hypothetical figures. Nevertheless, they raise the question about the relative value of controlling vibration exposure and improving posture.

4.6.7 Vancouver studies

Another recent contribution to the discussion of the mechanisms of spinal damage under shock and vibration has come from the Simon Fraser University at Vancouver (Cameron et al 1996, Robinson et al 1995, Roddan et al 1995, Nicol et al, Village et al, Vukusic et al). The team working there with Morrison has studied the dynamics of the spines of military personnel under combinations of relatively severe shock and vibration. They have used a technique based on neural networks to derive models which allow the prediction of intervertebral forces from acceleration at the interface between the seat and the body, and thence to estimate the risk of damage in a similar way to that proposed by Seidel et al. From the publications available, it does not seem as though Morrison et al have included posture as a contributory stress. However, this may be justified by the particular severity of the dynamic conditions with which they were concerned.

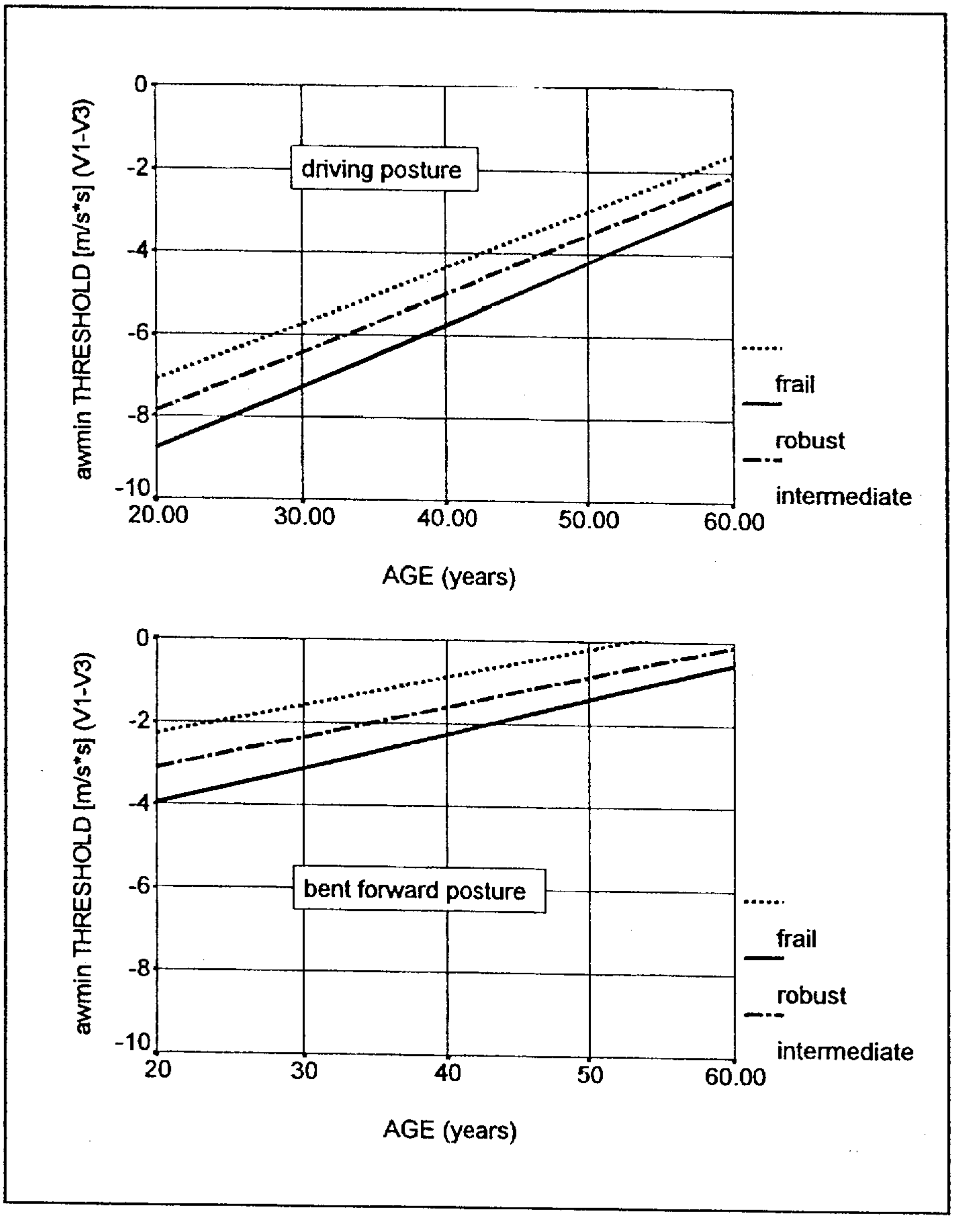

Figure 4a: Theoretically calculated values of "threshold" peak acceleration corresponding to the fatigue limit for lumbar vertebrae, plotted as a function of age, somatype and posture (from Seidel *et al*, 1997)

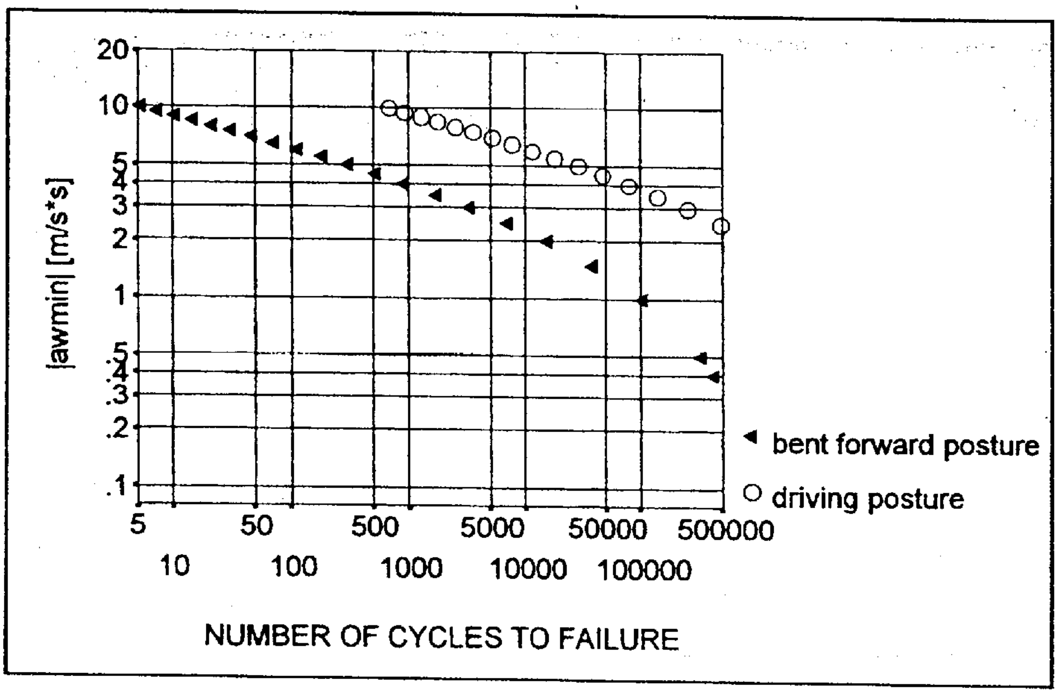

Figure 4b: Estimated number of cycles to failure by fatigue as a function of the magnitude of the frequency weighted peak upwards acceleration acting on a 40 year old male of the "intermediate" somatype (from Seidel *et al*, 1997)

Their "model" takes into account the non-linear nature of the body's response, which changes with the magnitude of the applied stress as well as the frequency (e.g. Dupuis et al 1991), and provides a time domain process for modifying the acceleration waveforms. It is argued that this approach provides more representative series of peak acceleration values, which are then more suitable for calculation of, for example, the equivalent number of cycles of a specified standard peak stress for comparison with S/N criteria for fatigue life. Their contribution to more general work conditions may be to provide a more comprehensive dynamic response function with which to replace the older concept of a generalised frequency weighting, which was not originally developed to be used in the time domain, and which does not address the problem of amplitude non-linearity.

The drawback to the Vancouver model is that it is not based on any physically recognisable concept. This makes it difficult to propose alternatives of a generally similar nature with which to compare it in order to find the simplest practical method. As most recently proposed, this model required a large number of parameters, each defined to many significant figures, far exceeding in complexity and precision the models of Payne et al.

4.7 Summary

By 1945 vibration had been identified as a potential problem, generally the interest was in connection with periodic types of excitation such as were found in piston engined aircraft. The subject was also found to be suitable for experimental study in the laboratory, using mechanical vibrators which generated sinusoidal motion.

Between 1945 and 1960, a number of medical surveys raised the possibility that several occupations which involved vehicle driving or the control of mobile machines could be associated with the development of problems with the spine, and particularly with the lower back. Although several authors, including Rosegger & Rosegger, identified both posture and vibration as possible contributory risk factors, posture was considered a significant stress only if it involved twisting and lateral bending. The potential for simple and nominally "correct" sitting postures to increase the risk of back trouble was given rather little attention. Instead, "vibration" was the aspect considered to be most important.

In the 1960s, the improvements in laboratory vibration facilities allowed earlier studies to be repeated and extended, so that, *inter alia*, it became widely known that the spinal column of the seated person exhibits a form of resonance at between 4 Hz and 6 Hz, such that seat motion is amplified in the vertical motion of the lumbar/thoracic section. This information was combined with results of subjective tolerance trials in the development of frequency "weighting" curves incorporated in the first drafts of the standard which was eventually published as ISO 2631.

During the 1970s and 1980s back trouble was further associated with particular occupations. Because these occupations included a vibration component in the operator's environment, the researchers tended simply to assume that vibration was the important factor, and made little effort to test it against other possible factors. Reviewers in this period found that epidemiological studies had been poorly controlled and contained little actual vibration data on which to base any correlation. This was found despite the gathering of considerable amounts of field data, reported separately, which had been encouraged by ISO 2631. This data was generally restricted to frequency weighted rms accelerations, and so could not be used to test for the relevance of any other measure of vibration intensity. At this time too, knowledge of body dynamics was further enhanced, and a fatigue theory for how vibration might damage the spine was propounded. Posture and postural support were suggested as confounding factors, and were separately studied with the aim of reducing stress in tractor driving.

More recently, occupational health studies have been improved with regard to the epidemiological techniques, but rather less satisfactorily with regard to estimates of the exposure to vibration and shock of the subjects. One (Schwarze et al) may have shown some evidence for a dose effect relationship between vibration exposure and lumber syndrome. One (Bovenzi & Betta) has provided some relative quantification of the two stresses of vibration and posture. Only one (Bovenzi & Zadini) has shown separate effects of vibration magnitude and duration of exposure. Seidel and colleagues have developed an hypothesis for the mechanism which links exposure to vertical vibration with risk of damage to the intervertebral joints. This hypothesis also includes the effects of posture, and the calculations suggest that posture can often be more important than vibration, that it is the cycles of peak vibration (or shock) which contribute most to the fatigue life, and that continuous vibration at a low level may be relatively unimportant.

5. DEVELOPMENT OF KNOWLEDGE OF WBV EFFECTS BY OCCUPATIONAL GROUP

5.1 Introduction

The historical overview of the knowledge base and research into the links between back problems, "lumbar syndrome", or related physiological damage and occupational or environmental stresses has led to two provisional conclusions.

First, there appears to be a general weakness in the evidence that vibration is a major causal factor, and secondly, there appears to be good evidence that postural stress is a more important causal factor than vibration, at least in relation to the mechanisms postulated for the development of spinal damage.

The purpose of this section is to review the reports of research into "vibration" injury in relation to the general questions concerning environmental stresses set out in 2.1 above, with the added requirement that it is probably necessary to distinguish between injury caused by vibration and that caused by postural stress.

The reports are grouped by classes of machine or occupation to aid discussion of the relative importance of vibration and posture, or other factors, and the characteristics of the vibration, for each separately. The machine classes on which the use of suspended seats is common are treated first, because these include some of those for which there is the greatest amount of exposure and epidemiological data, namely agricultural, earthmoving and construction machines, and industrial (lift) trucks. Other groups include helicopters, rail and subway vehicles, cranes, transport tugs and road vehicles. The case of the Russian concrete industry is also included because it may contribute to knowledge in this subject, although this particular situation is believed now to be of only historic interest. In a preliminary section, some studies of a more general nature will be reviewed.

5.2 General patient surveys

General patient surveys take two forms. In one, a representative whole population is studied to investigate the prevalence of, e.g. low back pain, and any differences in this prevalence between occupations. In the other, only those with symptoms are studied, with the aim of identifying the causes, or risk factors, which might include participating in certain activities or occupations. Such studies are of value in providing indicators of the potential prevalence of risk in global populations, and preliminary indications of occupations or activities which may appear sufficiently risky to warrant more specific investigation. Information concerning any particular occupation is necessarily diluted by the large numbers of other people in the studies, such that relatively few subjects can be compared with well-defined occupational histories. Also, the large numbers and variety of occupations preclude any practical possibility of estimating exposure to vibrational, or postural stress in other than extremely crude and general terms. Studies of specific occupational groups allow these deficiencies to be more easily remedied.

Griffin (1990) lists 135 reports of field studies concerned with whole-body vibration and health, of which 10 reports were of studies of low back pain or disc prolapse in general populations. These were either complete patient groups from a general practice, e.g. Frymoyer et al (1980, 1983), or patients presenting with some particular complaint such as disc prolapse (Kelsey et al, 1984) or sciatica (Weber, 1978). In general, these studies simply associated complaints with occupations, or sometimes other factors selected by the authors *a priori* as potential risk factors.

Magora (1970a,b and 1974) interviewed 3316 subjects from 8 occupational in Jerusalem, of whom only 429 complained of back pain in the year prior to interview. The earliest ages of onset of low back pain were found in bank clerks, workers in heavy industry (paper mill and tyre factory), farmers and nurses. It may be relevant that the work of farmers was described as standing and walking with prolonged physical effort. The author concluded that posture and lack of movement was responsible in the case of bank clerks, and heavy lifting in the other cases. Vibration exposure did not feature.

Weber (1978) investigated 280 patients admitted to hospital as presenting symptoms of sciatica, with particular interest in progress after treatment. As a by-product, he makes a few epidemiological observations: with regard to the occupations of the patients, *"no profession showed any striking preponderance"*, also the author *"can neither confirm nor contradict the opinion of Kelsey et al that there is an association between low back disorders and driving"*.

5.2.1 Studies in Connecticut

The work of Kelsey (Kelsey 1975, Kelsey & Hardy 1975, Kelsey et al 1984) has been discussed elsewhere (4.5 above). She studied more severely injured spines, i.e. with herniated (prolapsed) discs, compared with controls, and did find a relationship with prolonged driving, eventually claiming that a (male) lorry driver was 2.86 times more likely to develop a problem than one who had not driven a lorry, that longer hours of driving cars increased the risk, and that it was even possible to associate greater risk with driving older vehicles. They also attributed greater risk to those who smoked cigarettes, explicable as an effect of reduced nutrition of the discs themselves.

The evidence of Kelsey's group is generally quoted in support of the case against whole-body vibration. While this has probably been more easily accepted than that reported by Weber, at least by people concerned about whole-body vibration as a health hazard, it actually relates only to the occupation of vehicle driving, and not specifically to the particular aspect of vibration exposure. In this context, it should be noted that long hours of driving, particularly in a heavy lorry, generally translate to long hours in a single, fixed seated posture, with little opportunity to change this, and with only occasional breaks for exercise.

The findings of this group on the effect of lifting, as also discussed elsewhere, are unfortunately contradictory.

Palmer et al have been somewhat critical of aspects of these studies, and imply that any effects, i.e. differences between drivers and others, may be smaller than the authors claim. For example, the suggestion that patients can be differentiated according to the age of car they drive, which the authors ascribe simply to vibration characteristics without presenting any information on the allegedly different vibration magnitudes, could be confounded by differences in social class or selection. Palmer et al also observed that drivers of lorries and vans were not identified in the second study, although they had been indicated in the earlier one.

5.2.2 Studies in Vermont

The set of studies from the U.S.A. (Frymoyer et al 1980, Pope et al 1980, Frymoyer et al 1983, Damkot et al 1984) used analysis of medical records from general practice to try to establish figures for the prevalence of low back pain, and questionnaires or interviews to associate this with occupations or activities. In the first case, of 3920 patients, 11% of males and 9.5% of females were shown to have reported low back pain during a 3 year period. Later, of 1221 males, 46.3% reported moderate back pain, and 23.6% severe back pain. It is assumed that this sub-group was selected specifically to have groups of roughly comparable size for comparison of the associations with occupational factors. Potential sources of low back pain were identified as: driving cars, buses, trucks, tractors, heavy construction equipment, lifting heavy weights, using jackhammers, chainsaws, rototillers or snowmobiles, and participation in jogging or skiing. Smoking cigarettes was also detrimental.

It is tempting to identify the use of jackhammers, chainsaws and rototillers as sources of vibration stress, but it should be recognised that the use of these tools involves the application of considerable physical strength. It may be equally correct to associate any low back problems amongst users of these tools with the lifting of heavy weights and awkward postures.

The driving occupations all involve the postural stress of the normal seating position, and may in some cases be further exacerbated by the operator having to twist for rearwards observation. Some of the driving occupations may also involve high magnitudes of shock loads, see later sections.

Jogging and skiing are associated with more than usual magnitudes of shock, "jarring" the participant's back. The use of snowmobiles provides a combination of jarring and postural stress.

As with the Connecticut studies, a contradiction was found in relation to heavy lifting. Frymoyer *et al* (1983) found that for their sub-group of 1221 people, heavy lifting was a risk factor. Damkot *et al* (1984) found for their sub-group of 303 people no effect of lifting between groups with no symptoms of low back pain, moderate symptoms or severe symptoms.

Once again, although driving occupations are indicated as increasing the risk of low back pain, there is no evidence to distinguish the stress of prolonged sitting in a fixed posture from any which may arise from vibration or shock. Moreover, Palmer et al (see also below) describe the differences found by Frymoyer et al as "very modest".

5.2.3 Recent study in Great Britain

More recently, Palmer et al investigated the possible health effects of occupational exposure to whole-body vibration in the UK (Palmer et al 1999). This study, which raises doubts about the importance of whole-body vibration as a risk factor in the wider population, was based on a postal questionnaire with nearly 13,000 responses, supplemented with workplace visits to check on the general validity of those responses.

The authors investigated both the incidence of lbp and sciatica, and the extent of occupational and recreational exposure to wbv.

They estimated that 7.2 million men and 1.8 million women were exposed to whole-body vibration at work in a sample one-week period, including contributions from cars, vans and motor cycles, but the numbers fell to 374,000 and 9,000 respectively for those whose average daily exposure exceeded a VDV of $15ms^{-1.75}$.

In general, they found that "the risk estimates for LBP and sciatica associated with WBV were lower than some other researchers have reported, and smaller than those associated with some other common occupational activities".

They found what they described as "modest excesses" of low back pain in men whose average daily exposure exceeded $15ms^{-1.75}$, i.e. about 13% to 17% greater than those not exposed at all, with higher risks for one or two groups such as operators of excavators, helicopter pilots and drivers of off-road and some other vehicles.

As with other researchers, they equated riding on a vehicle or machine to "vibration exposure" and appear to have made no effort to quantify, or to adjust for postural stress.

They analysed incidence of lbp and sciatica, and exposure to vibration, in several slightly different ways, which could give rise to some confusion. In particular, vibration exposure was classified according to both occupation and industry sector, whereas low back pain was classified according to the type of machine or vehicle. This leads to a potential misinterpretation in the case of those driving tractors, for whom a lower than average risk of back trouble was found. However, it is not clear whether the tractor drivers in the survey sample were from the agricultural or municipal groups, which could have had very different actual exposures.

Apart from the armed forces, no group was bigger than 157 (M), or 428 (M) if by industry sector. E.g. there were only 51 farm workers, with a possible extra 36 farm owners, managers, or horticulturists. This means that some groups became too small to be included in some parts of the analysis and presentation, e.g. farm workers did not appear on the figure showing occupational VDV, although it was estimated that 27.5% would have had a VDV greater than $15ms^{-1.75}$. Helicopter pilots were also excluded from this figure, and possibly operators of construction and earthmoving machines, although this last is not clear, as they could be included as civil engineers.

Although estimates of vibration exposure were very approximate, being based on applying averaged, median values for each class of machine, and then using questionnaire values for duration, they may be useful for providing a broad picture, if not for correlation in individual cases. Thus, certain types of machine or activity are associated with high vibration exposures, including fork lift trucks, heavy goods vehicles, buses and coaches, and (farm) tractors. Even the value for farm tractors of 27.5% with VDV $>15ms^{-1.75}$ compares closely with that found in a comprehensive survey (Lines et al, 1993) of 25% of days exceeding a VDV of $17.8ms^{-1.75}$.

This report is notable for the high incidence of low back pain in the population as a whole (one year prevalence of between 50% and 70%), and the small differences between occupational groups. However, it is difficult to distinguish between someone who rides on an industrial vehicle regularly, but for short periods, and someone who uses one for most of the working week, and consequently difficult to identify those who one would expect to be at greatest risk.

5.3 Agricultural machines, including wheeled tractors

The history of the development of farm tractors may provide some insight into the parallel history of interest in symptoms of back trouble exhibited by their drivers.

- By about 1950, steel wheels had been replaced by pneumatic tyres, causing a large increase in vibration at frequencies of around 3 Hz.
- At about the same time, at least in northern Europe, the driver's option to stand was reduced by mechanical developments, forcing a more general use of the seat under all conditions, whereas it had previously been usual to stand when traversing rougher terrains. At this time, seats did not have effective suspension mechanisms. As described by Radke (1957), cushion seats, and those with poorly designed suspensions could actually amplify the vebration transmitted to the driver.
- By about 1960, later in some countries, seat suspensions that made an effective reduction of the more severe vibrations began to be introduced, and were almost universal by about 1970.
- From the mid-1970's, a marginal number of tractors were available with some form of effective wheel suspension, but the numbers with effective wheel or cab suspension did not begin to increase until after 1990, and even now represent only a small proportion of the market, and an even smaller proportion of the whole tractor park. The earliest forms of wheel suspension were introduced to comply with road traffic legislation, and were often so stiff as to increase vibration, as had been the case with earlier seats.
- Seats with additional horizontal suspension, and with facilities for swivelling or tilting (e.g. Bottoms 1978) have been offered as options for some years, but have not sold in large numbers.
- Another change which may be relevant to back troubles among farm workers has been the more recent move away from sacks and bales which can be lifted by hand, replacing many of these with much heavier units that require machines to move them. These were introduced from about 1980, and since about 1990 could have had a significant impact on the amount of heavy lifting required of the average tractor driver.

Thus it can be seen that both vibration and postural stress increased in the 1950's, and vibration decreased between 1960 and 1970. It should be noted (Lines & Stayner 2000) that the decrease in vibration affected mostly the higher magnitude shocks and jolts. Suspended seats do not work well for vibration less than a magnitude somewhere between 0.5 and 1.0ms^{-2}. Also, suspended seats do not isolate the driver from the relatively intense horizontal motions, both lateral and longitudinal, which are encountered on off-road machines. Neither do they alleviate the additional twisted posture that characterises many farming operations.

It is therefore of little surprise that there were reports from the medical profession in the 1950's of an apparently new group of workers suffering back trouble.:

- Paulson 1949: *". . . driving a farm tractor can produce distressing symptoms. The most common was lower back ache or "tractor back*" whose cause the practitioner took on himself to conclude that a history of long hours on the tractor is the correct diagnosis, noting particularly *"the tractor lurches to and fro from side to side"* and *"long days of twelve to eighteen hours"*.
- Fishbein & Salter 1950 (quoted above)

- Haluzicky & Kubik 1957 (from the English summary): *"The authors have described pain in various muscle groups starting particularly after long shifts, occurring in summer months, so that work rather than climate factors enter in. By analysis of the low back pain, vibration myalgia, congenital anomalies, and spondylotic changes were discovered, but particularly important were those concerning the L4-5 and L5-S1 discs in 27% of the group* (which may have been 148) *The latter occurred quite frequently in young individuals up to 30 years of age"*. This report was from Hungary where the collective farming system could well have involved very long shifts.
- The work of Rosegger & Rosegger (1960) (4.3 above), gave the subject considerable impetus. In this case, and despite subsequent criticisms of their epidemiological methods, they had actually examined over 300 subjects both clinically and by X-ray.

Two aspects of the Roseggers' work are of note. First, they apparently did not consider the normal sitting position to increase the stress on the drivers' backs, but only when leaning or twisting. And secondly, and seldom mentioned since, they found no difference between drivers of wheeled and tracklaying tractors, although there are large differences in the vibration magnitudes of these two classes. [There is rather little data on vibration on tracklaying tractors. Stikeleather, 1973, compares a track-type dozer at about 0.3 ms^{-2} frequency weighted rms vertical acceleration with a wheel loader at 1.5 ms^{-2}]. The comparison could have been made only in a country with a directed economy, and would have been difficult to make at any other time, because it is unusual for operators to be restricted to only one tractor or tractor type. Taken together, these two features would now indicate that more interest should be taken in postural than vibrational stress, but at the time it was generally accepted that vibration was the cause of the health effects, even if they might have been less obvious than the authors claimed.

The most impressive study to follow up the report of Rosegger & Rosegger, was the longitudinal study of the Max-Planck Institute at Bad Kreuznach (Christ 1963, Christ & Dupuis 1968, Dupuis & Christ 1972). Although their original 211 tractor drivers eventually reduced to 106, the relatively hard X-ray and clinical evidence provided an important part of the basis for the German occupational disease classification BK2110. The main finding was that their subjects seemed to develop back trouble at an unusually early age. In relation to the subjects of the Rosegger study, the Max Planck subjects were probably using tractors with better seats, and so suffering less vibration exposure, but it was still vibration rather than posture which was regarded as the main risk factor.

With regard to what the actual vibration exposures of the subjects in these two medical studies may have been, we have very little evidence. There was certainly no direct information in the reports themselves. There have been three relatively large scale surveys of farm operator vibration exposure (in northern Europe), Stayner & Bean (1975), Graef (1979) and Lines et al (1994), all with over 100 measurements covering a wide range of field and transport tasks. One thing which these reports do show is that there was very little change between 1972 and 1991, which is consistent with the history outlined above. It can now be appreciated that the vibration exposures which can be estimated from these surveys are likely to yield lower magnitudes, or at least lower peak magnitudes, than the likely vibration exposures of drivers between 1950 and 1970.

Taking this a step further, the exposures in the surveys suggest a daily VDV range of about $6ms^{-1.75}$ to $26ms^{-1.75}$, median about $14ms^{-1.75}$, with 25% exceeding $17.8ms^{-1.75}$. In other words, the health guidance level of $15ms^{-1.75}$ was exceeded nearly half the time. If these had been the vibration levels to which the health survey subjects, e.g. of Rosegger & Rosegger or of Dupuis & Christ, had been exposed, and if vibration rather than posture had been responsible for an increase of 10% to 20% in the prevalence of back trouble, then that health guidance level of 15 $ms^{-1.75}$

might be assessed as appropriate. And indeed something very like that was the general assumption during the period 1975 to 1990. However, it now appears that the values, which would more appropriately have been associated with damage, were probably significantly higher. The German guideline of 1.25 ms^{-2} translates approximately (for an 8-hour shift) to a VDV of 22.75 $ms^{-1.75}$, and if this was supposed to provide some protection, then it may be assumed that it was thought that some field exposures prior to about 1970 could be more severe than this.

Another feature of these studies, in common with most others, is that we have no information that allows us to distinguish between the effects of vibration and those of postural stress among the groups of subjects studied.

Seidel & Troster (1970) found that back pain was the most common complaint in 60 drivers whom they examined. It is not clear that this is a particular problem of tractor drivers, nor that vibration or posture is specifically indicated as a cause. However, if this study encouraged Dr Seidel to investigate further the question of risk factors affecting the spine, it served a very useful purpose.

Other researchers, notably Köhl (1975), Schulz & Polster (1979) and Wukash (1980) claimed to find evidence of high incidence of damage to tractor drivers' backs, but without providing a direct association with vibration exposure, and without investigating the contribution of postural stress.

Thus, Hulshof and van Zanten (1987) could say of most studies of agricultural workers that they were "not very informative", only that of Dupuis & Christ being "moderately informative".

Two subsequent studies set out to address the shortcomings found by Hulshof and van Zanten.

Boshuizen et al (1990) studied workers on farmland undergoing reclamation (4.6.2 above). They found that the tractor drivers had about 10% greater prevalence of low back pain, but aimed to establish a link with vibration exposure by also measuring some vibration magnitudes. However, their measurements were very limited, and are quite insufficient to correlate with symptoms on a subject-by-subject basis, which indeed they do not claim. In fact they are inconsistent with the previously published larger surveys, and should probably be discounted for the following reasons:

- The number of actual measurements was only 24, with the longest being for a 10 minute period.
- The result of 1.1ms-2 for road use and 0.6ms-2 for field work is contrary to other studies, and reasons can be found for this,
- The several of the tractors tested were of a type with suspended axles
- The field work was done at only one season and involved operations with relatively low vibration (ploughing and drilling) and done using tractors with some form of suspension, whereas the transport work was being done with unsuspended tractors.

There was no rationale presented to show how the particular measurements were representative of the annual exposure of the operators, including the large seasonal variations in ground surface, and the machines which the operators would generally use for the different tasks in the cycle.

As a contribution to the establishment of a dose-effect between whole-body vibration and low back pain, this study falls short of the requirements set out by Hulshof and van Zanten. With regard to posture, the authors note *"sitting on the job and driving are inextricably associated and so it is not possible to adjust for sitting"*.

Bovenzi & Betta (1994) (4.6.3 above) reported a comparison between 1155 drivers of agricultural tractors and 220 office workers. They found disc protrusion in 75 (6.5%) of the tractor drivers compared with 5 (2.3%) of the control group. However, these numbers were too small to allow successful statistical comparisons. They also found that incidences of "lifetime LBP (low back pain)", "acute LBP" and "sciatic pain" increased with total driving time, presented in thousands of hours.

It is worth considering the value of the study in relation to the general "dose-effect" question. The vibration exposures were estimated by extrapolation from measurements on 53 tractors, using one-third octave band frequency spectra to obtain frequency weighted rms acceleration magnitudes. The report is mainly concerned with the analysis of the effects rather than with the "dose", and so it is difficult to discover exactly what was done. However, it appears that a driver's exposure was estimated on the basis of first calculating an average vibration magnitude for each tractor, and then summing, on an equivalent energy basis, the product of years and acceleration squared, for all the tractors used by each driver. This assumes that tractor model was an important distinguishing factor in establishing vibration magnitude, whereas field task and conditions are far more important, and need to be very carefully controlled if such measurements are to be used to distinguish between tractors. It is very likely that the reported difference between the best and worst tractor models (0.89 ms^{-2} to 1.24 ms^{-2}) is no more than the range of measurement variability. The approach of obtaining an average annual value for each tractor approaches that of obtaining a simple average annual figure. The only difference then becomes that of years of exposure, which applies equally to other stresses, notably posture. Only when enough conventional tractors are replaced by fully suspended machines, such as the JCB FastTrack, with significantly lower vibration magnitudes, will an analysis on this basis serve the purpose for which it was intended.

It has to be said that it is a far from simple exercise to distinguish the exposures of individual operators, because that depends critically on whether a particular driver has specific tasks, such as ploughing (low vibration), spraying (high vibration), combining (low vibration), carting (high vibration, etc. If these differences are not distinguished, then the exposures and the effects also cannot be distinguished, or associated.

The authors' own comment on exposure response is: *"In our study the most serious low-back symptoms leading to chronic LBP and sick leave were associated with prolonged tractor driving experience, which resulted in an excessive accumulated vibration dose. In this study duration of exposure to WBV was related to LBP more than equivalent vibration magnitude".* Which in view of the above is not surprising. But what it may show is that any contribution to a dose-effect relationship was not for vibration exposure in particular, but for driving tractors in general, with whatever stresses that brings.

In any case, if the 75 subjects who suffered from disc protrusion could not be associated with particularly high magnitudes of total vibration exposure, or with some other feature of their individual vibration histories, then there is little chance of establishing a credible dose-effect relationship between vibration and damage.

All that can be safely concluded from studies of operators of agricultural tractors is that this occupation was, and possibly still is associated with an elevated risk of “Lumbar Syndrome”. It does not, in general show us what factors in tractor driving are responsible for this, but such evidence as there is indicates posture more strongly than vibration. Furthermore, there is no information which could help identify which characteristics of vibration or shock are most closely associated with the damage effect.

5.4 Earthmoving and construction machinery

With one exception, listed by Griffin (Griffin 1990), there are no reports associating whole-body vibration on earthmoving and construction machinery with health risk earlier than 1969. This may reflect the slower spread of mechanisation compared with agriculture, or the lack of research organisations specific to this sector of industry, or even the somewhat *laissez-faire* attitude to employment and health issues with which this industry is associated (at least in the U.K.).

It should be recognised that, whereas in agriculture there was one basic type of mobile machine, the wheeled tractor, used by most farm workers, this has not been the case in the earthmoving and construction industry. There are indeed many machines with similar characteristics to farm tractors, such as small site dumpers and wheeled loaders. There are also numerous tracklaying machines, with very different vibration characteristics, and significant numbers of very heavy wheeled machines, whose vibration is characterised by motion with large displacements at frequencies as low as, or lower than 2 Hz.

Kunz and Meyer (1969) examined 52 operators of heavy equipment, 49 of them radiologically, and, according to Dupuis and Zerlett (1986) "found 8 cases of discopathy and radiologically demonstrated narrowing of the intervertebral space", for which "the correlation with driving activity was considered", so that the authors "made the requirement that drivers of heavy construction equipment undergo an initial radiological examination to determine the condition of the spinal column before taking up their duties". However, there were no control groups, it is not quite clear how the subjects were chosen, and Hulshof and van Zanten (1987) found that "the results do not permit the very strong conclusions of the authors."

Milby & Spear (1974) in a study for the American National Institute for Occupational Health (NIOSH) conducted a questionnaire study in which 1,865 operators of heavy equipment were compared with 2,071 outdoor workers who were not exposed to vibration (and presumably were not constrained to fixed sitting postures for long periods either). They found that there was no increase in back complaints with increasing "vibration exposure". The term vibration exposure is very poorly defined. These authors simply selected types of machine on a rather arbitrary basis, and equated "exposure" with years of use, having no time to waste on details such as vibration magnitude, hours of use per day or days per year. They suggested that this did not really prove that vibration is harmless, because there may have been some self-selection within the workforce to remove the more susceptible subjects voluntarily, the "healthy worker" effect. In a subsequent study, aimed at testing that particular theory (Spear et al 1976) the authors found that there was indeed some evidence of this selection effect, but also that it "could not explain the trend of the morbidity pattern entirely" (Hulshof & van Zanten). In any case, the study contains no evidence which could be used to distinguish between the effects of vibration and those of postural stress, because they made no mention of postural or any other stress.

Dupuis & Zerlett (1986) also report the study of Franke (1978) in which 222 drivers of heavy "trackless" vehicles were examined after 2 years and 4 years of exposure. This showed no changes, but the time span was rather short. The description "trackless" is taken to imply a distinction between off-road vehicles used in quarries and opencast mines and those running on temporary railway systems.

One of the most important studies of operators of this type of equipment is that involving 352 drivers of heavy earthmoving equipment in the brown-coal areas of the Rhein, in Germany, who were compared with 315 surface workers. Aspects of this work have been reported by Hilfert et al (1981), Köhne et al (1982), Zerlett (1986), and Müsch (1987) as well as forming a significant part of the review in Dupuis & Zerlett (1986). The original questionnaire study was supplemented by X-ray examination of 251 of the drivers and (some of) the control group, as well as comparison of the X-ray films of specific vertebral segments of 176 of the drivers.

The typical finding was that 70% of the drivers suffered spinal disorders compared with 54% of the control group. It was also shown that 81% of the drivers suffered from "lumbar syndrome" compared with 53% of the control group.

Dupuis & Zerlett (1986) conclude with the definitive statement "In summary, the study by Köhne et al (1982) indicates that morphological changes of the spinal column, particularly in the lumbar region, are manifested more frequently and more prematurely in drivers of earthmoving equipment and that these changes **must have been caused by stress from whole-body vibration**". At that time, there appeared to be no question but that the association between whole-body vibration and spinal damage had been proved beyond doubt. But now, with the understanding of the extent to which loads in the lumbar spine are also greatly elevated by even the normal sitting posture, it is reasonable to ask to what extent the comparison between the drivers and the particular control group used did actually allow a distinction to be drawn between the effects of vibration and those of posture. Despite the comment by Hulshof & van Zanten that "little information was provided on the occupational activities of the control group", it can be inferred that these people, who were surface workers at a coal mine, were selected as being those who were not driving machines which could vibrate. In the context of a coal mine, it is difficult to imagine any useful activities in which most of the members of the control group could have been engaged which involved any significant period sitting down. On the contrary, it is far more probable that they would have been standing and moving about. In that case, the evidence that driving the machines increases the risk of damage is good, but the assertion that stress from whole-body vibration was the cause of the damage is much less easy to prove.

A further problem is that this study does not include any information about the actual vibration exposure of the individual operators, nor even about the average exposure of the group as a whole. It would therefore contribute nothing to the establishment of a dose-effect relationship, even if the problem of separating the effect of posture could have been overcome.

Dupuis and Zerlett (1986) describe "*lumbar syndrome*" as follows: "*The clinical picture is composed of diseases of the spinal column that are directly or indirectly caused by degenerative processes in the lumbar vertebrae. Included here especially are spondylosis of the lumbar part of the spine (disc degeneration with reactive bone spurs on the vertebral borders), spondylarthrosis of the lumbar spine (degenerative changes in the vertebral joints, mostly disc degeneration), and spondylosteochondrosis of the lumbar spine (disc degeneration, with separation of the body and end plates of the vertebral bodies). These processes are only included if radiologically proven changes have occurred in the spinal column with disc-related complaints (pain or disturbances of function, arising from the lumbar area). Clinical pictures, such as sciatica (lumbar syndrome with involvement of the sciatic nerve) and lumbago (acute form of lumbar syndrome), as well as spondylolisthesis, are also included in the lumbar syndrome category*".

Griffin (1990) lists a report by Sakuma (1980) in which 30% of 60 drivers of dump trucks were found to be suffering from low back pain. This does not seem to be a particularly exceptional figure when compared with incidence in general populations, e.g. Palmer *et al* (1999).

Riihimäki et al (1989) in a questionnaire survey of drivers of bulldozers (presumably tracklaying) and lift trucks, compared these with carpenters and office workers. The 12-month prevalence for lumbago was 24% for the drivers, 25% for the carpenters and 18% for the office workers, but there was an elevated prevalence of sciatica in the driver group. They also found some evidence of elevated prevalence of non-specific low back trouble. However, the recurring problem of separating vibration from posture is present in this study. There was no indication of the types of machine used, the types of seat, or the postures involved. It is most likely that the carpenter group of controls would have been active and not sitting, and office workers, while being mainly sedentary, have far greater opportunity for changes of posture and possibilities to stand and walk about within their workspace (the office) than do machine operators. This aspect is often ignored, presumably because of the assumption that postural loads are somehow of secondary importance in comparison with vibration, and that the element of change and exercise is even less relevant.

There is some interesting, if almost anecdotal evidence from Cross & Walters (1994) that relates to an analysis of compensation claims from a database of the Joint Coal Board of New South Wales, Australia. From nearly 30,000 claims, almost 1,000 or 11% were specified as caused by vehicular "jarring". It was then found that 53% of all jarring injuries were associated with just two types of vehicle, underground transporters and shuttle cars, so that a high proportion of the operators of those particular vehicles were suffering the injuries. It was also observed that these vehicles require the operator to sit sideways to the direction of travel, so that when the jarring shocks are encountered, the twist of the spine possibly exacerbates the effect. Even with this factor, it is of interest that it is the high magnitudes of shock, and not vibration, which is the suggested cause of the elevated risk.

A particularly thorough study was published by Schwarze *et al* in 1997 (Schwarze *et al* 1997). This included operators of lift trucks and truck drivers as well as operators of earthmoving machinery. It has been reviewed in some detail elsewhere (Section 4.6.4). Although the authors conclude that they have shown a strong correlation between incidence of lumbar syndrome and vibration exposure, it is difficult from what is presented to distinguish the effect of vibration magnitude from that of duration, either hours per day or years of working life. The vibration data comes from a very comprehensive collection (HVBG database), but that also does not distinguish between rms acceleration and any other feature, and so does not help to compare rms with any alternative measure.

The conclusions about operators of earthmoving and construction machines can only be similar to those for drivers of farm tractors. There is probably more convincing evidence to show that operating the machines increases the risk of lumbar syndrome than which shows no effect, but there is nothing which actually identifies vibration as the only, or even the most important casual factor, and there is nothing which indicates what feature of vibration is an important indicator of risk. The authors who have reported studies of this occupational group appear to have paid very little attention to stresses arising from posture or manual handling.

5.5 Industrial trucks

Industrial trucks, lift trucks or fork-lift trucks, have a more recent history than either agricultural tractors or earthmoving machinery. As a machine class, they encompass a range of dynamic characteristics, controlled by the different masses and wheel sizes. The do not have wheel suspensions, because of the requirement to lift loads to heights without losing stability. For this reason they are also fitted with hard tyres which, if pneumatic, are inflated to high pressures. The smaller lift trucks, with smaller wheels, are usually operated on relatively smooth floors, but respond with large transient accelerations to small irregularities, such as joints between sections of floor, and where floors have been allowed to deteriorate, the motion can be severe. It is generally characterised by higher frequencies than those found on farm tractors, often between 4Hz and 12Hz. The larger trucks have lower frequencies, and the class known as "rough-terrain" lift trucks have similar dynamics to tractors and those earthmoving machines with smaller wheels.

In addition to the vibration or shock environment and the sometimes cramped sitting posture, drivers of lift trucks have to twist quite often for reverse travel, and bend for visibility of elevated stacking locations.

As well as being included in the recent study by Schwarze *et al*, discussed above, lift truck drivers have figured in three other studies:

Lehman (1983) published results of X-ray examinations that showed that lift truck drivers in the port of Goteborg (63) suffered larger amounts of disc compression than controls (63 stevedores, 63 office workers). However, although he suggested that vibration was the cause, he provided no evidence in support of this, nor any comparison with postural load.

Brendstrup & Biering-Sørensen (1987) conducted a questionnaire and examination medical survey of 240 operators of small lift trucks, with 399 controls in greater Copenhagen between 1979 and 1980. They showed greater incidence of low back trouble among the truck operators, but again was concerned with linking the effect only to the occupation, and does not help in the search for evidence about vibration as a cause. In fact they comment: *"The fork-lift truck drivers assume a static sedentary position while driving with their hands and feet held steady on handles and pedals. During the course of performing typical tasks, the driver assumes the following positions as well: twisting of the trunk in relation to the pelvis, stooping positions, and deep sideways trunk bendings. Finally, while driving, the driver is exposed to whole-body vibration"* and *"The most radical proposal is an entirely new construction of the fork-lift truck, giving the driver a better outlook"*. These authors are clearly putting the main emphasis on ergonomic shortcomings which cause severe postural strain.

Boshuizen *et al* (1992) used a questionnaire to compare 196 drivers of lift trucks and container trucks (transport tugs, below) with 107 controls. A higher prevalence of low back pain (e.g. 1-year prevalence increased from 41 to 51) was associated with the occupation of truck driver, but the association with vibration was rather weak because "*both the interaction between age and being a driver, and the fact that the age of the drivers was correlated with the WBV dose received made it difficult to establish a dose-response relationship"* and *"drivers and non-drivers differed in their working postures"*. It should also be noted that these authors followed the common practice of averaging vibration magnitude for groups of operators, so that differences in "dose" were largely controlled by length of service. The authors also noted that the effect was greatest for young drivers with short durations of exposure, reducing with age and length of service until there was little difference between drivers and controls. They suggested that this was due to health based selection ("healthy worker effect") even though they also noticed that *"the turnover of workers in our study population was expected to be rather low because, for harbour workers, equally well-paid jobs are hard to find"*.

Apart from the work reported by Schwarze *et al*, none of the studies of lift truck operators offers any evidence for claims that damage is caused by exposure to whole-body vibration in particular, although the evidence for an occupational effect is fairly consistent.

5.6 Helicopters

The helicopter provides one of the few working environments in which the exposure to vibration is continuous, and the vibration is sinusoidal, or made up of a combination of sinusoids. In this case, the excitation arises from forces associated with rotation of the main lifting blades or of the stabilising rotor, or with the drive mechanisms for these. The magnitudes and frequencies of the main components change with flight pattern, so that the excitation is better described as "piece-wise continuous". Griffin (1990) shows some details of a range of typical vibration frequency spectra and weighted acceleration magnitudes. The dominant frequency is usually the frequency of passage of the blades of the main lifting rotor, which may be between 5 Hz and 15 Hz. The z-axis acceleration magnitude on the pilot's seat (ISO 2631: 1974 weighting) may be between 0.2 and 0.8 ms^{-2}, but Griffin reported that one machine which was *"known to have vibration problems"* had a magnitude in excess of 1.0 ms^{-2}. Because of the continuous, periodic nature of the vibration, it is unlikely that peak accelerations exceed 3.0 ms^{-2} in normal flight.

As well as this relatively unusual vibration exposure, the working posture demanded by many types of helicopter is considered particularly stressful.

Despite being a relatively small occupational group, helicopter pilots have been studied quite extensively. Griffin (1990) lists 15 reports published between 1962 and 1987, in addition to which Bongers *et al* published their findings in 1990.

Most of the published work takes one of two forms: Either questionnaire surveys, or radiological investigations.

Although some X-ray investigations showed relatively little difference between helicopter crew and non-fliers, e.g. Beck (1981), most studies of subjective low back pain show higher incidence in helicopter pilots, when compared with both groundcrew (Fitzgerald & Crotty 1972) and with pilots of fixed wing aircraft (Fischer *et al* 1980). The authors of many of the reports present opinions about whether the effects which they have observed are the result of exposure to vibration or may be blamed on postural stress, but usually without any hard evidence, e.g. (Sliosberg 1962) *"Poor posture and vibrations are the two main causes of vertebral back ache in helicopter pilots and these effects are also combined. . . Landings are very frequenct and sometimes by no means gentle"*. Sliosberg is the only author to mention the possible contribution of heavy landings to spinal damage.

Comparisons with groundcrew must be confounded by the differences between seated and ambulatory work stations, and even aircrew in fixed wing craft have generally more healthy seating positions than helicopter pilots, as well as vibration environments of an entirely different character.

Three studies may be relevant to assigning importance to the main risk factors of vibration and posture:

First, Shanahan & Reading (1984) made a simulator study in which the conditions of flying a UH-H1 helicopter were reproduced, both with and the vibration. In both conditions, the 11 pilots who took part used the same seat and controls as the actual aircraft, and so adopted very similar postures to those in real flight. Pilots were exposed to each condition for two hours, and by the measure that was used, there was no statistical difference between the rating of low back pain. It is possibly relevant that helicopter flight is one of the few occupations in which low back pain is experienced during work. The authors concluded: *"it appears that the vibration at the frequencies and amplitudes tested plays little or no role in the etiology of the low back symptoms reported by these pilots. It is proposed that the primary etiological factor for these symptoms is the poor posture the pilots are obliged to assume for extended periods while operating the helicopters"*.

Secondly, Froom *et al* (1987) conducted an experiment using AH-1S helicopters, which were capable of being flown from both the pilot's and the gunner's seats. The posture in the gunner's seat was reported as being very much better than in the pilot's seat, although the vibration was a little more severe. 18 pilots flew 3-hour missions in each seat. They reported the onset of pain sooner in the pilot's seat (64.3% cf. 7.1%), and of greater intensity (85.7% cf. 7.1%), from which the authors suggested that: *"it is unlikely that vibrational forces were responsible for the discomfort in the gunner's seat"*. They went on to conclude that: *"one component of the etiology of low back pain discomfort in helicopter pilots is an improper seating posture"*.

Thirdly, Bongers *et al* (1990) reported, in support of their epidemiological questionnaire study, a simulator study from which they found that vibration did have an effect.

Although no reports were found in which the effect of having auto-pilot available was investigated, it is reasonable to assume that this would allow some relief of postural stress as in the case of the gunner's position tested by Froom *et al* (above).

5.7 Transport "tugs" (freight container tractors)

Transport tugs are used in ports and freight distribution "hubs" in place of the tractor units of articulated lorries, for the movement of the trailer units. Until recently, they have been fitted with very hard suspensions, and it is usual for their pneumatic tyres to be inflated to very high pressures to minimise damage. As a result, their dynamic response has been characterised by frequencies in the range 3 to 6 Hz, with a large longitudinal component arising from interaction with the trailer and experienced by the driver as "backslapping" (Nishiyami *et al* 1998). The motion is not one of continuous vibration, but is the response of the vehicle to an irregular series of shocks caused by driving over bumps in the ground, and by sudden connection with the load or trailer. The high seating position and short wheelbase of these vehicles amplifies the pitching effect. In this author's experience, this can be so severe that drivers cannot ameliorate it by avoiding contact with the backrest. More recently, improved suspensions have reduced the vibration magnitudes, particularly of the fore-and-aft component (Nishiyami *et al* 1998). This provides a possibility for comparing operators of old and new vehicles to show an effect of reducing vibration stress, after a suitable period of exposure on the new vehicles.

Transport tug drivers were included in the study of lift truck drivers by Boshuizen *et al* (1992), mentioned above. This tells us that the occupation may be associated with an elevated risk of low back problems, but little about the role of whole-body vibration.

Similar information, at least as far as concerns evidence of whole-body vibration damage, is presented by Konda *et al* (1985). Nakata *et al* (1987) reported levels of x-axis (longitudinal) vibration simply as between 93 and 98 dB as being equivalent to a 2-hour fatigue/decreased proficiency limit (ISO 2631, 1974).

The evidence from drivers of transport tugs is once more that the occupation may well present a risk of more back trouble than that for ambulatory workers, but the cause cannot be clearly distinguished. If vibration or shock is an important factor, then it may be opined that in this case it is the fore-and-aft motion of the seat backrest that is the main component.

5.8 Overhead cranes

There have been a few studies of the operators of overhead (bridge) cranes. These machines "vibrate" in response to two sources of excitation. When they are travelling, the joints between the rails on which their steel wheels run cause sharp transient shocks to be transmitted through the structure to the bridge. If the operator's cabin is close to the end of the bridge span, then this shock is transmitted almost directly into the operator's seat as a short impulse. If the cab is towards the centre of the span, the impulse may be transformed into lightly damped sinusoidal motion whose frequency is controlled by the stiffness of the beam and the combined mass of the cab plus whatever load the crane is carrying. The other type of excitation is in any jerkiness in the raising or lowering of the load, which can also create a decaying sinusoidal response towards the centre of the span.

It should be noted that the crane operator has also the postural stress which arises from having to observe the operations below the bridge, and which usually involves leaning forward at those times when the shocks occur.

Bongers *et al* (1988a,b) reported a study in which 743 crane operators were compared with 662 floor workers. As discussed above, although the crane operators showed significantly more disc disorders, but evidence on the incidence of sickness was somewhat conflicting. It may be noted that the control group of floor workers was probably mainly ambulatory, and so differed in both postural stress and any which may have arisen from the shock and vibration environment.

Burdoff & Zonderfan (1990) found that 33 crane operators had about twice the incidence of low back pain, and of sciatica than 30 controls matched for age. They commented that *"In this study it seems that the combination of twisting and bending of the body in sedentary position is of greater importance for the occupation of low back pain than the risk factors in the dynamic workload of the control group"* and *"The exposure to whole-body vibration can be considered as an important contributory factor for low back pain among crane operators. In ovcerhead travelling cranes vibrations range in frequency from 1.5 to 8 Hz (Dupuis and Zerlett). This frequency is known to have a great potential (for) damage because at the resonating frequency of 4.5 Hz the spinal system is absorbing and transmitting motion in excess of the input"*. It has been remarked elsewhere that the importance of frequency without consideration of amplitude can lead to possibly inappropriate conclusions.

Zettergren *et al* (1987) reported a study of workplace design for crane operators in a steel works commented: *"A subjective assessment of the work postures of the crane drivers in a conventional cabin resulted in the following observations: frequent and long duration of flexion in the neck and in the back, frequent and extreme postures of rotation in the neck and the upper thorax, frequent and long duration of abduction and extension in the shoulders, and continuous driving without any opportunities to use the backrest and the armrests while driving"*.

None of these studies implicates vibration other than in the opinions of their authors, and none contain any data allowing the comparison of the effects of postural and vibration stresses.

5.9 Rail and subway vehicles

Drivers of railway trains and subway (rapid-transit) vehicles have appeared in several studies. There is little information about the vibration environment These are generally heavy vehicles, which would suggest low levels of vibration and at low frequencies, but often with steel wheels running on steel rails and stiff suspensions, which would suggest high levels of vibration at high frequencies, and in particular strong transmission of transients from rail joints and crossings.

Most of the studies concentrate on radiology (Arnautova-Bulat 1979) or questionnaire (Hannunkari et al 1978) to show a higher incidence of back problems in this occupational group.

Johanning (1991, see also Johanning *et al* 1991) measured the vibration and also compared subway drivers with a control group of supervisors who, it was claimed, were also subject to prolonged sitting. However, Johanning (1997) notes about New York subway drivers that *"The primitive seat and cab design, however, which typically result in awkward body posture for the train operators has not been changed"*. Even if the group of supervisors did not have the possibility of moving about more often than the train drivers, this suggests that the drivers' postures were generally more constrained, which would confound somewhat the effect of vibration. Johanning (1998) also reports that *"the Berufsgenossenschaft which is responsible for the health and safety of the transit workers (in Germany) concludes that WBV exposure would be below the proposed action level. Data substantiating this claim has not been provided"*. The "proposed action level" is presumably 0.5ms^{-2} (8-hour equivalent rms) in a proposal for a Physical Agents Directive. If it is the case that the drivers' back troubles are associated with exposure to shock and vibration, then a measure of the exposure which is more relevant to the peak shocks rather than the equivalent continuous rms would probably be more appropriate. Johanning's own measurements (Johanning *et al* 1991) give rms accelerations for vertical and transverse directions in nine subway vehicles, for which the mean magnitudes were 0.55 ms^{-2} and 0.26 ms^{-2} respectively. The lowest likely peak values can be estimated from these as 0.8 ms^{-2} and 0.4 ms^{-2}, and it is likely that the occasional transients would have exceeded 1.5 ms^{-2} or even 2.0 ms^{-2} in the vertical direction.

Yet again, we have an occupational group whose members have to sit in constrained positions for long hours that is associated with an elevated risk of back trouble. The various studies have not provided sufficient evidence to distinguish between the effects of posture and vibration, nor between the effects of vibration, or shock, of different magnitudes.

5.10 Military vehicles

Military vehicles comprise a range of types from tracklaying tanks and armoured personnel carriers to on/off highway trucks and jeeps. The tracklaying vehicles differ from tracklayers used in earthmoving by virtue of suspensions that allow much higher speeds across country, and the trucks differ from ordinary highway trucks in having stiffer suspension to withstand the off-highway use.

There is very little reported data on the effects of whole-body vibration on military personnel. Apart from Clayberg (1949, above), who reports some personal observations on the health of drivers of military trucks, Griffin (1990) lists only two.

Beevis & Forshaw (1986) report a small, *ad-hoc* comparison of two groups of drivers, those who drove armoured personnel carriers (APCs) and those who drove battle tanks. Both the rms weighted acceleration and the crest factor were twice as high in the APCs as in the slower, heavier tanks, thus the peak accelerations were about four times as great. 88% of the APC drivers reported back pain compared with 55% of the tank drivers. The numbers were small and the driving time varied for most of the subjects between 10 and 50 hours per week. Posture may well have been an important confounder, because *"although it was not possible to treat posture systematically",* the authors noted *"that it was not possible to drive either the M113 or the Centurion with the back in* *contact with the backrest without adopting a very uncomfortable posture" and "the relative position of the driver's hatch and the seat in both vehicles made it difficult to sit upright. The resulting forward hunched posture almost certainly resulted in flattening of the lumbar lordosis and compression of the lumbar discs at their forward edge, which would exacerbate any stress on the spinal column".* Beevis & Forshaw were among the few authors to report on variations in driving speed among their subjects, in particular noting that older drivers drove more slowly, but *no significance was attached to this factor, but it could be interpreted as indicating either that older drivers learn to drive more slowly, or that they are less tolerant to shock than younger drivers"*. This is a factor to which other researchers could pay more attention, if they were to take more interest in the cause as well as the effect that they study.

Maksimovic (1987) reported an analysis of back disorders in tank drivers, which includes a small number of one-third octave band frequency analyses that all exceed the 1-minute FDP level of ISO 2631, 1974, i.e. more than 3.0 ms^{-2} frequency weighted rms. It is not clear whether there is any information on durations of exposure, or postural stress, but the dynamic stress is clearly severe.

It is possible that the data from military vehicles could show an elevated risk of spinal damage associated with what is possibly the most severe of vibration and shock environments. However, this data is not available, and it would not necessarily help in assessing dose-effect relationships for less severe exposures.

5.11 Road vehicles

Road vehicles display generally lower magnitudes of vibration and shock than most of the types of vehicle and machine discussed above. Cars, and those trucks and buses fitted with air suspension systems exhibit vertical and pitch motion with natural frequencies lower than 1 Hz, and roll frequencies even lower. Buses and trucks without air suspensions expose the driver to vibration responses to road inputs at higher frequencies, e.g. between 1Hz and 2Hz, and often with additional components arising from cab "nod" on short chassis articulated tractor units or from "beaming" of the flexible chassis rails of longer, "rigid" trucks. However, over the last 20 years trucks have been fitted with increasingly effective cab suspensions whose primary frequencies are of the order of 1Hz, and which are effective in reducing higher frequency vibrations.

Apart from the work of Kelsey and colleagues (above), which implicated driving of cars as well as trucks in the causes of back trouble, most of the studies have been restricted to drivers of trucks and buses or coaches, and most of them are historically from the period before the introduction of air or cab suspensions.

In 19 of the 20 studies found, all were concerned with medical examination (e.g. Barbaso 1958, Schmidt 1969, Cavigneaux & Laffont 1969, Schoknecht & Barich 1978) or analysis of medical records (e.g. Gruber & Ziperman 1974, Gruber 1976), or subjective reporting of low back problems. None actually involved assessment of exposure to vibration or shock, or of postural stress. More recently, Anderson (1992) reported an orthopaedic study of 195 driving and non-driving workers from an urban transit union in California of whom 85% of drivers reported back pain compared with 50% of controls. There appears to be some evidence that driving any vehicle for extended periods may be associated with an increased risk of back trouble, but none to relate this to vibration in particular. Troup (1978), after reviewing the evidence then available, concluded *inter alia* that "the backache of driving is mainly the result of postural stress".

Bovenzi & Zadini (1992) (4.6.3 above) reported a postal questionnaire survey of the back health of a sample of 234 urban bus drivers and 125 controls (maintenance workers). They measured the vibration on 6 models of bus, including three each of older and newer designs, having different vibration magnitudes (older a_{wz} about 0.6 ms^{-2}, newer about 0.2 ms^{-2}, ISO-weighted). It is not clear how many replicates contributed to each value, nor whether the routes were different, but each was based on a record of between 15 and 30 minutes duration, and so is reasonably representative of a combination of bus and route. Unless there is a large difference between routes, these rms values provide good estimates of drivers' overall exposure because there is unlikely to be much change in magnitude from day to day, and the daily hours of work are closely controlled and regular. However, the authors have assumed that the overall exposure of those who drove more than one type of bus could be obtained by means of an energy average (rms averaging). They have also assumed that this effective average could be combined with the length of service to give a dose in years-m^2/s^4, also effectively invoking the equal energy principle. Since they do then differentiate between the effects of length of service and average vibration magnitude on the back health variables, they could in principle have determined a relationship between magnitude and time based on evidence. Their method of data analysis precluded the possibility of testing any other form of vibration measure than rms.

Bovenzi & Zadini show clear differences in the prevalence figures for overall driver and control groups, e.g. lifetime LBP: drivers 36%, controls 15%; (last) 12-month sick leave due to LBP: drivers 26%, controls 21%. However, they noted that the drivers and controls had quite different experiences of posture, freedom of movement and exercise.

They then compared within the driver group, estimating the effects of individual variables, and so in each case effectively adjusting for the others. Variables tested in this way included age, awkward posture (not clear how this was evaluated) body mass index, mental load, education, smoking, sport activity, previous exposure to vibration, as well as vibration severity and length of service (and the combination of the last two as total vibration dose). Unfortunately, the results of these comparisons are presented as odds ratios. This is fine for testing for statistical significance, but needs some translating to inform simply about contributions to prevalence rates.

This study does show a significant effect of vibration magnitude as well as one for duration of exposure. Because of the data gathering, which was typical of the time, it does not allow a distinction to be made between rms vibration magnitude and amplitude distribution. And it should be noted that for bus drivers, who sit generally well forward of the front wheels of their vehicles, peak accelerations can be surprisingly high.

It is not clear whether there were any postural differences between the older and newer buses as well as the differences in suspension. If there were, then these could have confounded to some extent the effects found for vibration magnitude. If not, then this study should be of considerable significance in providing evidence of a vibration effect.

It should be noted that Bovenzi & Zadini point out that their vibration data shows higher magnitudes than other data on Italian buses. Because of the effect of the driver's position, mentioned above, it is likely that the vibration was more severe than most other forms of road transport of equivalent age.

5.12 Russian concrete industry

The study of vibration exposure of workers in the concrete industry was almost peculiar to countries of the Eastern *bloc*, and to the period 1950-1970. The type of vibration exposure was unusual for two reasons: the operators were standing on a platform which vibrated, and not sitting; and the vibration was periodic, if not purely sinusoidal, and of considerable severity. Some reports indicate a displacement of between 0.3mm and 0.75mm at a frequency of between 50Hz and 75Hz, which may be equivalent to a weighted acceleration of more than $10ms^{-2}$, although whether this is peak or rms is not clear.

Rumyantsev & Chumak (1966) reported (according to Dupuis & Zerlett) *spondylosis deformans* in 50% of a group of 78 concrete workers, compared with less than 8% in a control group of 52 persons.

Ivanchuk & Karepov (1968) reported that 58 out of a group of 80 concrete workers exhibited changes to their "osteal" and locomotor apparatus, which is sometimes taken to mean the spine rather than the legs, although in this instance that may not be the case.

There were several other studies of concrete workers, doubtless because of the particularly severe and unusual conditions, but these were concerned with a wide assortment of other possible effects, and throw no further light on the question of low back disorders.

In order to compare the vibration load on the lower backs of the concrete workers with the equivalent loads in other occupations, it is necessary to estimate the magnitude of vibration reaching the pelvis. Harazin & Grzesik (1998) report some transmission experiments with standing subjects. They used a broad-band random vertical excitation with an unweighted rms magnitude of $4ms^{-2}$, which is much lower than the conditions on the concrete making platforms, but is what is available. For transmission to the hip at frequencies around 60Hz, they measured between 0.1 and 0.3. Using this, we can estimate the acceleration at the hip to have been of the order of $2.5ms^{-2}$ (w_k weighted), or $12ms^{-2}$ unweighted, at a frequency of about 60Hz. Even though it is not known whether these values are rms or peak, they are by all comparisons very severe, and scarcely comparable with magnitudes of continuous vibration experienced by seated operators. In fact it must be said that it is scarcely credible that workers would willingly undergo such exposure continuously for extended periods, but it is difficult to check this in the literature that is available. The magnitudes are however comparable with the magnitudes of peak transient acceleration to which seated operators can be exposed briefly on many work machines, although the frequency is very much higher. The only conditions in which such high frequency components are likely to be encountered on mobile machines is when seat suspensions "bottom" at the end of travel, and then only for brief, transient shocks.

5.13 Summary

As has been observed by other reviewers (Seidel & Heide, Hulshof & van Zanten, Kjellberg *et al*), prior to 1990, no one investigating the health effects of occupations associated with whole-body vibration had even attempted to combine vibration measurements with health assessments. Up to then cause and effect had been established, if that is not too strong a word, by studying the effect but not the cause. This had occurred despite the technology having been available since 1970 to make some sort of field measurements of vibration. The result of this is that the various studies succeeded in establishing associations between various occupations, or machine classes, and an elevated risk of disorders of the lower back. And in many cases, even this may be challenged by experts in epidemiology.

With regard to those studies that did specifically set out to include vibration assessment, there are to date only four, and for only one of these (Bovenzi & Zadini) can it reasonably be claimed that it makes a distinction between different **magnitudes** of vibration.

Boshuizen *et al* (1990) studied tractor drivers, and claim to have assessed their vibration exposure. However, as discussed above, their vibration measurements do not bear scrutiny, and the work effectively adds very little in this respect.

Bovenzi & Betta (1994) also studied tractor drivers. They made more extensive measurements of vibration than Boshuizen *et al*, but their method of estimating severity of exposure could not be said to distinguish vibration from any other stressor because the distinction depended on some averaged vibration values combined with particular exposure durations. Vibration was therefore indistinguishable from simply operating the machinery. More importantly, Bovenzi & Betta did distinguish, without recourse to any duration, several levels of postural stress, which they appear to have shown to be more important in determining the risk of damage than vibration, even when the latter was combined with time.

Schwarze *et al* studied operators of three classes of machine: earthmoving equipment, lift trucks, and lorries. They assessed vibration severity using magnitude data from a comprehensive database in combination with duration from interviews with subjects and their supervisors. It should be possible to distinguish, from this data, the parts played by duration and by vibration magnitude. Unfortunately, what was published was based on an assumed dose relationship, and does not allow the components to be investigated separately. It also does not include any assessment of postural load. These points will be considered further below.

What this review has discovered thus far is that there is very limited evidence that whole-body vibration *per se* is responsible for the elevated risk of spinal disorders that may be associated with a number of occupations. Furthermore, there is clearly insufficient evidence either to support a dose-effect relationship, or to identify any particular characteristic of vibration exposure that is more important than any other.

6. OVERVIEW OF RISK AND CAUSE FOR VARIOUS OCCUPATIONS

6.1 Standing operators

It has been estimated that the operators working on concrete machinery may have been exposed to vibration whose magnitude at the base of the spine was 2.5 ms^{-2} (w_k weighted) continuously throughout their working shifts. This is equivalent to magnitudes experienced by most machine operators only during occasional transients or shocks, i.e. "high acceleration events". They were standing, and so did not have the additional postural stress of sitting, but they may have had little opportunity for exercise. If the exposure estimates are correct, it is likely that in this case it was the vibration stress that contributed most to any elevated risk of back trouble.

6.2 Helicopter crew

Helicopter crew are the only group other than concrete workers (above) whose members are exposed to continuous, periodic vibration, with no large magnitude, high acceleration events. So, although rms magnitudes can be as high as 1.0 ms^{-2}, peaks seldom reach 3.0 ms^{-2}, except during heavy landings.

The main balance of the evidence, particularly when the work of Seidel and colleagues is considered, suggests that for helicopter pilots the main risk factor is postural stress, with the relatively low peak accelerations leading to a small contribution to any accumulation of "fatigue cycles". The importance of heavy landings, mentioned by Sliosberg (1962) cannot be quantified.

6.3 Agricultural workers

Tractor drivers experience the basic postural load of sitting, often for prolonged periods, with the additional load inherent in twisting to observe rear mounted implements, and leaning to reduce the effect of the tractor's tilt when working with one wheel in the furrow. Changes in cultivation practice have made the latter situation less common now than it was when concerns about tractor drivers' backs were first reported.

They are also exposed to fairly severe whole-body vibration, which can include significant horizontal components. This is in the form of a series of high acceleration events, generally decaying sinusoids at the bounce frequency of the machine, but sometimes at higher frequencies when the seat suspension "bottoms" at the end of its travel. The vibration magnitudes, and in particular the higher acceleration events, have been reduced since back trouble was first observed among tractor drivers. The vibration severity can vary considerably between tasks, and therefore between, and even within days, for the same operator.

Members of this occupational group may also have the additional stresses of manual handling and jumping down from high workplaces. The height of these workplaces has increased greatly since the early observations.

The amount of manual handling has decreased, probably with most widespread effect since about 1985-1990. If the finding of Palmer *et al,* that tractor drivers do not suffer an elevated risk of back disorders, can reasonably be compared with earlier findings, then this would suggest that manual handling had previously played a more important part in the aetiology than has previously been considered.

It is likely that posture plays at least as great a part as vibration in any elevated risk of back trouble amongst this occupational group (Bovenzi & Betta).

It may also be noted that if vibration of the type to which tractor drivers are exposed is to be evaluated against the fatigue theory of dynamic spinal loading, then it is very poorly described by the frequency weighted rms acceleration level.

6.4 Operators of earthmoving and construction machinery

This occupational group uses a wider range of machines than farm workers, including more of the tracklaying type, and a number that operate in essentially static positions. They may be exposed to less twisting and leaning, but otherwise the combination of postural stress and vibration exposure is similar to that of tractor drivers. In particular, the vibration is essentially a series of decaying sinusoids, randomly occurring, and the overall severity is similar to that on farm tractors. However, there is a smaller range of tasks worked by each operator than in agriculture, and so there can be consistent differences between operators, because of relatively continuous use of the same type of machine by the same operator.

This group may be similar to farm workers in the relative importance of posture and vibration, and in the occasional, unplanned requirement for manual handling of heavy loads.

6.5 Operators of industrial trucks

Once again, this is an occupational group whose members are exposed to a combination of whole-body vibration and postural stress. There are some in this group who operate trucks in a standing posture, which should allow some comparisons to be made, although there are no reports of this having been done. The vehicles have hard tyres, no suspension, and seats with inadequate suspension travel (if any) to reduce the effect of the sharp shocks caused by even quite small discontinuities in the ground surface. Relatively high peak acceleration magnitudes could be transmitted to the operators' backs, but the distributions in practice are not known, and the comment about rms values (under agricultural tractors, above) also applies here.

The operators' workplaces are often cramped, and they often have to twist to operate in both forward and reverse. It is likely that posture is as important as vibration for this group too.

6.6 Drivers of transport tugs

The operators in this occupational group used in the past to experience a particular type of vibration and shock in which fore-and-aft motion of the backrest predominated. There are many machines in service for which this is still the case, although improved suspensions can greatly reduce it.

For this reason, members of this occupational group may be more affected by whole-body vibration, when compared to the postural stress, than other groups. However, they are still exposed to postural stress.

The comment about the relevance of rms evaluation of vibration severity to dynamic fatigue also applies here.

6.7 Operators of overhead cranes

It is possible that the occasional shocks transmitted to the operator's seat can increase the overall spinal load. However, this occupational group is more likely than others to suffer postural stress because of the need to lean forward for much of the time.

Because of the relatively infrequent nature of any shocks, the rms evaluation is probably of even less relevance to this group than to others.

6.8 Operators of rail and subway vehicles

Prolonged sitting in cramped conditions and on poor seats used to typify the driver's environment. More recent control cabins are designed according to better ergonomic principles, but these vehicles have very long lives, and many drivers have experienced considerable postural stress. At the same time, they are exposed to vibration that is essentially a series of jolts. Peak accelerations in both vertical and transverse directions can be estimated to be higher than 0.8 ms^{-2} and 0.4 ms^{-2} respectively. It is difficult to estimate the relative importance of the three contributing factors of posture, prolonged sitting and transient vibration from information that is presently available.

6.9 Drivers of road vehicles

Prolonged sitting with little opportunity to change position is probably more important than any vibration to which drivers are exposed in contributing to back trouble. This may be more serious for drivers of long distance coaches and heavy lorries than others. Only drivers of urban 'buses are likely to suffer any significant exposure to whole-body vibration or shock, arising from the relatively poor suspensions, and from the vehicles' relatively poor response to speed controls. This group (studied by Bovenzi & Zadini) provided one of the rare examples in which vibration magnitude was shown to contribute to the incidence of back trouble.

6.10 Summary

Although some occupations may involve the additional stresses of manual handling and jumping down from elevated work platforms, it is likely that in most cases the most important contributing factors to back disorders are postural stress and whole-body shock and vibration.

When the severity of vibration is as high as 2.5ms^{-2} for many hours a day, as has been estimated that it used to be for some workers in the concrete industry, then this may be sufficient on its own to elevate the risk of damage. (It must be said that it seems surprising that workers would have remained in such an environment continuously). However, when it is less than 1.0 ms^{-2} (rms weighted), as in the case of helicopter pilots, then the evidence presently available suggests that posture is more important than vibration. This leads to the possible conclusion that in those occupations in which "vibration" is an important factor, it is not the continuous, rms level that is important, but the peak values.

In all the other cases for which studies have been found, the "vibration" exposure is in fact more akin to a random series of shocks, with typical average rms vibration accelerations less than 1ms^{-2}**.** These are then the cases in which it is more likely that any effect of the dynamic environment is associated with the occasional peak values of acceleration, and, as suggested by Sandover (1981), poorly represented by the rms magnitude. Furthermore, in all these cases there is a significant underlying stress from the sitting posture, which may often be more the controlling factor than the shock or vibration.

It has been noted that in the case of transport tugs (container tractors) the older designs exposed their drivers to high magnitudes of longitudinal acceleration, which makes this occupation a special case, although it has seldom been treated as such.

7. HEALTH CRITERIA

7.1 Introduction

In the light of all that has been discussed above, it may be interesting to review the various contributions to criteria which have been proposed in relation to the assumption that some feature of exposure to whole-body vibration may be deleterious to health.

Each source will be examined in relation to how the exposure is assessed, and in relation to the knowledge base used to justify the chosen criterion. A more extensive review of the standards is to be found in Griffin (1998).

7.2 ISO 2631: 1974

The original development of the basic guidance standard, ISO 2631, leant heavily on some laboratory tests of the most severe vibration to which fit young men were willing to be exposed (Ziegenrucker & Magid, 1959; Magid *et al*, 1960) (4.3 above). This provided a magnitude, together with some evidence of a frequency dependency. It is tempting to assume that the short term magnitude was extended by information about magnitudes of vibration in some occupations in which it was held that whole-body vibration could have been responsible for some observed complaints, notably back trouble among tractor drivers. However, this linkage was found later, and it is to the credit of the originators of ISO 2631 that the more recent information was consistent with their proposals.

The frequency dependency was further supported by laboratory trials of human perception and comfort. The vibration type was periodic, usually sinusoidal. Thus the laboratory trials were somewhat removed from the field conditions under which most workers were actually exposed to vibration.

The development of ISO 2631 followed laboratory rather than field studies. Whereas analysis of field data was, up to the mid-1960's, more concerned with amplitude distribution than frequency decomposition, ISO 2631 directed attention to the frequency domain by requiring estimation of rms acceleration in one-third octave frequency bands. This was clearly based on comparison with data obtained in single frequency sinusoidal laboratory experiments.

The possibility that such laboratory data might not reflect human response to real world environments that contained significant high acceleration events was recognised in the advice to limit application to vibrations with "crest factors" of less than 6. In reality, this excluded most occupations apart from helicopter pilots and workers at concrete plants (above).

The range of health effects for which vibration might be responsible, and therefore against which the guidance should provide some protection, was based on informed medical opinion, for want of any firm evidence.

7.3 BS 6841: 1987

BS 6841 introduced two distinct concepts.

First, greater weight would be given to high acceleration events, by using fourth power integration instead of the second power associated with rms evaluation. This was based on the reasonable assumption that high acceleration events might be more harmful, to both health and comfort, than continuous vibration at a lower level. It was justified by laboratory investigations of subjective comfort.

Although still based on laboratory studies, these were extended to vibration with higher crest factors thus justifying application to real world exposures without the "crest factor" limitation. However, the fourth-power approach is based on subjective assessment, which Seidel *at al* (1998) did not find a very good predictor of load on the lumbar spine.

Secondly, BS6841 introduced the use of the time integral of acceleration (fourth) power to calculate a daily dose, the vibration dose value or VDV. It is the VDV which is used to estimate health risk, with a daily dose of 15 $ms^{-1.75}$ suggested as a level which if exceeded should give cause for concern.

A similar principle has since been used to calculate daily doses based on rms acceleration and exposure time. It needs to be pointed out that in relation to health effects, the justification at the time was that this seemed a reasonable thing to do. There was a lack of field (epidemiological) data with which to test it. This lack appears to remain to the present day, although data gathered by Schwarze *et al* (1997) may contain the necessary information, at least in relation to dose based on rms acceleration and time.

The possible health effects against which the guidance in BS 6841 is supposed to provide protection are broadly similar to those of ISO 2631. This somewhat general risk is sometimes used as justification for the broad-band frequency weighting used in the evaluation.

7.4 BK 2110

The German occupational disease classification BK2110, like the more recent French counterpart (below) is described as a disease caused by exposure to whole-body vibration. The classification requires three things. First is the necessary symptomatology of "Lumbar Syndrome". Thus the occupational disease classification is restricted to troubles of the lower back. All the other suggested ill-effects of whole-body vibration are excluded.

Secondly, the claimant has to have been working with machines on a specified list, which originally included the following (Dupuis 1995): off-road trucks; agricultural and forestry tractors on roads field and forest tracks; forestry machinery off-road; excavators; graders (road grader, surface grader, leveller); scrapers; dump trucks; wheeled and tracked loaders; wheeled dozers; fork-lift trucks on uneven surfaces; and military vehicles off-road. Some vehicles were considered not to pose a health risk *"because the vibration exposure is too low"*: drivers of taxis; of fork-lift trucks used on smooth surfaces; and of heavy goods vehicles with good seats.

And thirdly, it is necessary to have experienced a total vibration exposure dose evaluated as the product of magnitude (squared) with lifetime number of days exposed. Magnitude is expressed in terms of the German "k-value", and a summation for days of exposure at different levels of magnitude is defined. Only exposure for which k-values are greater than 16 are considered injurious to health, but calculation of the k-value can include a multiplier of 1.3 for either impulsive vibration or unfavourable postures.

7.5 Régime Général table 97

The French tables of classified occupational diseases include both Régime Général (table 97) and Régime Agricole (table 57). It is not immediately clear why two tables are needed, unless there is a difference between the social security provisions for agricultural workers and others, because both tables include use of agricultural and forestry tractors in the list of relevant occupations. Both require diagnosis of disability arising from *"hernie discale"*, and both require 5 years exposure to the occupational hazard. The list of hazardous occupations may differ slightly from that in Bk 2110, in that it includes, *inter alia*, lorries (*tracteur routier* asd *camion monobloc*). However, the main difference is that there is no requirement to show a lifetime vibration exposure dose. Thus the French tables define an **occupational** disease rather than a **vibration** disease.

7.6 ISO 2631-1: 1997

ISO 2631 was amended slightly after its first publication, such that an approximation to the time-dependency was introduced. But a major revision was published in 1997. With regard to health effects, this provided two alternative time-dependencies, one following the relationship of the earlier edition, and the other following a relationship that approximates to the Vibration Dose Value criterion of BS 6841. These coincide for a daily exposure duration of 4 - 8 hours, but otherwise diverge considerably.

The tentative nature of the health guidance is shown by the inclusion of pairs of lines for each time-dependency. It is advised that vibration exposure whose combination of magnitude and duration falls below the lower curve, health effects "have not been clearly documented", whereas above the upper line "health risks are likely". Between each pair of lines is a "caution zone" in which "caution with respect to potential health risks is indicated". However, what may be a clear health risk according to one criterion may appear relatively safe according to the other.

As neither of the alternative health caution zones is based on a combination of observations of both health and vibration exposure, this dichotomy is scarcely surprising. What is surprising is that one form of the time-dependency has survived almost unchanged for 30 years (see Guignard, 1967), when at its inception the knowledge base was limited in the extreme.

The 1997 edition of ISO 2631-1 includes the suggestion that the health effects of vibration (repeated shocks) with high crest factors can be evaluated with either of two quite different measures, namely the VDV of BS 6841 and the MTVV developed from the study of Spång and Arnberg. However, no guidance is given on how either of these measures might be associated with a health risk.

This edition of ISO 2631 specifically identifies the lumbar spine and connected nervous system as the likely seat of any impairment due to long term exposure to high intensity whole-body vibration.

7.7 ISO/TC 108/SC 4/WG 10

Although ISO 2631:1997 includes two alternative methods for evaluating vibration with high crest factors (above),.no guidance is given as to how these methods may be used for the evaluation of health risks. It was in order to provide better founded guidance on this that Working Group 10 was set up, with the particular remit of recommending possible methods for evaluating the health effects of repeated shocks, and in particular the effect on the lumbar spine.

There have been no field studies from which health data can be analysed in any way which could help to define a function linking damage to some feature of shock history. Therefore the Working Group has had to use the approach developed by Seidel *et al* (1997), using data such as that provided by Brinckmann *et al* (1988). As indicated above, this requires two stages of evaluation. First, the intervertebral load has to be estimated from measurement at the seat surface. And then the load history has to be analysed in a way that allows comparison with fatigue life data.

As presently under discussion, the intervertebral load is substituted by the acceleration at the lumbar spine, and the acceleration history used for comparison with fatigue criteria. Furthermore, three axes of seat acceleration are included. The two horizontal axes are assumed to have linear response functions between the seat and the lumbar spine, modelled as single-degree-of-freedom systems. The vertical axis has a non-linear response, as observed by several authors (e.g. Dupuis *et al*, 1991). It is proposed to model this using a development of the neural network model of Nicol *et al* (1996, 1997), although it should be possible to develop a function which is both simpler and more easily understood.

As presently proposed, an acceleration "dose" would be calculated by summing the acceleration peaks according to a 6th power law. This would include both positive and negative peaks in the horizontal directions, but only compressive peaks in the z direction. A total equivalent static compressive stress would be obtained by summing the daily acceleration dose in all three directions, using different conversion factors (MPa/ms^{-2}) for each axis.

The daily equivalent static stress would then be compared with an "ultimate" stress to assess the health risk. The magnitude of the ultimate stress could vary according to the age of the exposed person, to reflect the measured data linking bone strength and age. And the calculation could also include a parameter which reflected the static stress due to posture.

Presumably the justification for the sixth power summation of acceleration peaks is to be found in data on S/N fatigue curves for spinal compressive failure. However, information on failure of spinal segments is based only on *in vitro* tests, and at levels which lead to failure in less than 5,000 cycles, as discussed in Seidel *et al* (1998).

The identification of acceleration peaks and the subsequent summation of some derived values is a relatively unusual process in relation to the technology of noise and vibration instruments. There is a strong possibility that the more familiar time integration method, based on a sixth power of acceleration, could produce similar ratings of vibration and shock exposures to summing the peak values. However, this needs to be tested.

7.8 Comments

The health guidance in standards (ISO 2631, BS 6841) was based on a consensus of informed opinion, in advance of any studies in which epidemiological evidence and vibration exposure data could be directly associated. This is in complete contrast to the case of noise and hearing loss. However, the vibration magnitudes that were first proposed were not inconsistent with those later found to be associated with occupations, such as tractor driving, for which elevated risk of low back trouble was indicated. As suggested above (section 5.3), by the time representative measurements of vibration exposure were practicable, it is possible that peak accelerations, if not rms averages, had actually been reduced by improvements in seat suspensions. For this reason, and because the importance of other factors such as posture and manual handling has probably been underestimated, it is likely that the guidance on vibration is somewhat conservative.

For most occupations for which vibration has been suggested as the most important risk factor, the association between incidence of low back problems and occupation has been shown, but the distribution of risk between likely causes has not. This appears to be recognized in the French tables for occupational diseases, but not in the German classification Bk 2110.

One generalisation can be made, however, and it is this. None of the standards or occupational disease criteria is based on anything more comprehensive than a test of whether an exposure to vibration would be expected to damage health or not. The degree of severity of the damage has been thought to be too difficult to assess. Any correspondence between severity of vibration and incidence rate has likewise been ignored, presumably for similar reasons. Instead, it has been seen as perfectly reasonable to be concerned with eliminating entirely any vibration component from the prevalence of lumbar syndrome, even though this would have a relatively small effect on the overall incidence of the disease. This too is in contrast with requirements for noise control. In that case, complete eradication of noise-induced hearing loss is not attempted, but rather a balance is struck between the efforts needed to control the cause, and the extent to which these can reduce the effect.

8. WHOLE-BODY VIBRATION AND SHOCK, HEALTH EFFECTS - APPROPRIATE MEASUREMENTS

8.1 Trade-off between magnitude and time

By 1967 the people who were developing what was to become ISO 2631 had selected rms acceleration as the basic measurement for evaluating the human effects of vibration. This was based on nothing else but the familiarity of rms averaging in measurements of electrical signals. Its use implies a particular form of time weighting, a particular relationship between acceleration magnitude and time. There was not then, nor is it clear that there is yet, evidence on which to found such a relationship if it is to be used to evaluate the possible health risk of exposure to vibration. It was chosen because it was familiar, and it seemed a reasonable thing to do.

Others have since suggested that a fourth power relationship between acceleration magnitude and time is more reasonable, but most of the evidence in support of this comes from subjective comparisons, e.g. Griffin & Whitham, Griffin (1984).

The difficulty is that the epidemiological evidence does not allow us to test measurements such as these. Very little of the epidemiological evidence, when examined dispassionately, even proves that the most common health effect of occupations involving vibration exposure is actually caused by the vibration. If vibration is a cause, then it is not shown how much of the damage is due to that and how much is caused by other factors such as postural stress. If the evidence is as weak as this, then how can it be used to compare different aspects of the vibration, or different methods of evaluating vibration?

Clearly, it cannot. If epidemiological evidence is to be used to justify one or another measurement method for whole-body vibration, then the studies must be constructed so as to gather data which can distinguish between duration and magnitude of exposure, and in particular to allow alternative methods for assessing magnitude.

If epidemiological evidence is not available, then we must seek other means, as has been done by Working Group 10 of ISO sub-committee 108/4. As outlined above, the members of that Working Group have suggested an approach based on methods for estimating loads in the lumbar spine, both static and dynamic, and comparing these with known damage criteria. As long as damage to the lumbar spine is seen as the only likely health effect of whole-body vibration, this is a reasonable approach. In fact it seems to be more reasonable than the justifications for using rms or VDV. And despite investigations into numerous other possible ill effects, damage to the lumbar spine is now the only widely recognised health effect of exposure to whole-body vibration and shock.

Although Working Group 10 of ISO/TC108/SC4 was set up to address the case of repeated shocks, it will be very difficult to ignore the possibility that the techniques which may be suitable for shocks might also be suitable for vibration. Clearly, this is something which should not be ignored, but rather something which should be tested. The possibility is that the main contribution to the fatigue damage comes from the higher acceleration events, whether or not low level continuous vibration is present. Thus the effect of the low level, continuous vibration on lumbar damage may be insignificant.

This is not a possibility that has been addressed in studies in which rms acceleration has been used to assess vibration severity. That is so because, by definition, the rms measure ensures that an average value is used, with a particular trade-off between magnitude and time, and peak values are lost.

If it should be the case that continuous vibration at a relatively low level is not important, then it would provide an explanation for the difficulty which researchers to date have had in associating the health "effect" with the vibration "cause". This is because the rms evaluations will have given overriding weight to long term, low level vibration, at the expense of infrequent high acceleration events.

There are two obvious conclusions from this line of reasoning:

- First, the use of rms acceleration to assess severity of vibration exposure should be treated with the utmost caution unless and until research has been published which demonstrates that the inherent time-dependency is indeed appropriate, and that vibration at a low magnitude for a long time is equivalent in its effect to vibration at a high level for a short time.
- Second, the methods for evaluating repeated shocks should be tested also on epidemiological studies which involve exposures to vibration with lower "crest factors".

8.2 Frequency weighting

It will be recalled that the frequency weightings originally proposed for ISO 2631, together with those used in BS 6841 and in the 1997 version of ISO 2631, are intended to reflect a compendium of responses, including health, comfort and interference with activities. There was some justification for using a generalised set of weightings to assess whole-body vibration as a health hazard when it was thought that there could be several symptoms and mechanisms involved. However, if the only health effect of any significance can be related to loading on the lumbar spine, then frequency weighting should be exchanged for a representative transfer function between the point of entry (seat cushion or feet) and the lumbar spine. This is essentially the approach presently under consideration by Working Group 10 of ISO/TC108/SC4. As discussed above with regard to time and magnitude, there would seem to be good reason to apply the same process to any dynamic input, whether it be shock or vibration. However, as also discussed, vibration, unless at a high intensity, could well be of little interest.

If we reflect for a moment on the case of noise-induced hearing loss, we may recall that the A-weighting has become the favoured measure in terms both of magnitude-time trade-off and frequency weighting, not because it is the absolute best fit with the epidemiological data, but because it is the simplest approximation which gives an acceptable fit.

In the present case, we appear to be concerned with an alternative to frequency weighting which models the dynamic response of the human spine. We are at the stage of having an apparently precise model that is rather complex and abstruse. Although this can be defined very precisely, there would seem to be scope for developing a simpler, more familiar approximation which would be quite adequate for assessing risk.

9. DISCUSSION

9.1 GENERAL COMMENTS

There are some general criticisms of the present state of “received wisdom” of the effects of whole-body vibration which flow from the above historical review. First, it is quite clear that there are indeed certain occupations which are associated with a risk of back problems that is greater than in the population as a whole. The degree of elevation of risk varies from 10% (i.e. from 50% to 60%) to 50% (i.e. from 30% to 80%), and tends to be greater for younger people. There can surely be no doubt about this, and the German occupational disease classification Bk2110 clearly requires that injuries, in the form defined in some detail as “lumbar syndrome”, must have been sustained during the operation of one of a defined set of machines which fall into this category.

In this, Bk 2110 is relying on hard research evidence. However, in describing the disease as “vibration disease”, the classification is relying more on the informed opinion of respected scientists than on hard evidence. There has been a widespread acceptance of the suggestion (e.g. Rosegger & Rosegger) that exposure to whole-body vibration is the aspect of these occupations which is of particular significance in elevating the risk. However, the degree of association has been difficult to assess.

There has been a plethora of research studies whose aims have included providing evidence to confirm this suggestion, most of which have fallen short of achieving this particular aim (see reviews by Hulshof & van Zanten, Seidel & Heide and Kjellberg et al). These reviewers found earlier studies wanting for many reasons, e.g. from Huslhof and van Zanten: *“The quality and quantity of exposure data constitute the weakest part of most studies” “Because most disorders are non-specific, the lack of clear and specific diagnostic criteria is an important problem” “The majority of the studies provided too little information about study design and treatment and analysis of the data” “Only a few studies examined a control group” “There exist many confounding or contributing factors . . most studies failed to control for confounding variables”*

They also mentioned other possible confounding factors, of which posture is particularly singled out, but only Seidel, with his co-workers, and Bovenzi & Betta, then went on to incorporate postural stress in their studies.

Hulshof and colleagues at the Coronel Laboratory attempted to improve on the techniques of earlier researchers, and their studies (see above) were doubtless sound from the point of view of selection of exposed and control subjects, examination, and related aspects. However, the consideration that they gave to evaluating the occupational exposure of the subjects in their exposed groups was somewhat restricted. Having identified a shortfall in exposure data as a major limitation of earlier studies, it is unfortunate that there own were not better funded to improve more on this aspect. The limitations of the exposure data in their study of farm tractor drivers have been discussed above.

It is only the studies of Schwarze et al and of Bovenzi and Zadini which have the benefit of adequate sources of vibration data.

It is a common feature of many of the research reports and reviews that they refer to occupational groups as “exposed” groups, using “WBV exposure” as a synonym for working on a machine, and thereby implying that they are concerned only with vibration exposure. This is even the case in Kjellberg *et al*, although they clearly identify posture as one of several other factors important in causing the elevated occupational risk. This seemingly innocuous mistake carries with it the assumption that the researchers are not trying to discover the cause of the disease or effect, but that they have already decided what it is and are intent only on finding evidence in support of their decision. This is perhaps an inappropriate basis on which to conduct scientific research.

In addition to the use of generalised group exposure data, which, it has been argued, may conceal differences in the exposure between different subjects, there is the question of what aspect of vibration (or shock) is really responsible for the damage. ISO 2631, despite announcing an intention to the contrary (see above), has actually stifled research into the possibility that anything other than frequency weighted rms acceleration is necessary to evaluate health risk.

Until the proposal of an alternative hypothesis, by Seidel and colleagues, few people thought of gathering any other data but frequency weighted rms acceleration (or, in the UK, VDV). Even though Sandover (1981) had pointed out that *"if tissue fatigue is important as regards degeneration in the lumbar spine, then current methods of assessment of the effects of vibration are deficient. The exponential relationship between tissue stress and the number of load applications to failure emphasises that the actual stress involved is a critical parameter. Thus small numbers of large transient loads assume greater importance, and estimates based on rms measures alone may underestimate their effect. Also, reduction in exposure time must be regarded as an ineffective way of reducing risk compared with reducing the magnitude of the vibration stress"*.

The other element that is missing from data on factors in occupations with risk of excess back trouble is an evaluation or quantification of postural stress. This was attempted, perhaps somewhat approximately, by Bovenzi & Betta, and found to be at least as important as vibration (4.6.3). This bears out to some extent the Seidel hypothesis, but quantifying postural stress in field situations does not yet have a strong basis, and some extension of the work of Seidel's team may be needed to provide a relevant assessment method.

For most occupations in which vibration has been suggested as an important factor if the aetiology of low back disorders, there is little evidence to show whether or not it is the most important factor. Hence it is possible to associate occupations that have relatively low vibration magnitudes with elevated risk of low back problems, because of the effects of posture or heavy lifting. It is thus conceivable that evidence of this type leads to very conservative guidance on vibration exposure. It can therefore be seen that reducing vibration is likely to have relatively little benefit unless it makes a significant reduction in the total load, including that from posture.

The level of dynamic load (vibration) at which it makes a significant contribution is estimated to be between 1.0 ms^{-2} and 10 ms^{-2}, peak. If this is applied to the exposure histories of the subjects in any of the epidemiological studies, it would lead to the elimination of large amounts of the exposure time from all but the most severe histories, because for many, if not all relevant work situations the vibration history consists of long periods of relatively low vibration, interspersed with a relatively few larger shocks or transient oscillations.

It can also be argued that the development of a dose-effect function would require a more specific correlation between vibration (and shock) history and the physiological effects. This argument arises because of the increased importance of the relatively few events in any history which exceed the level at which the loads begin to have a significant effect. A few high acceleration events have a small influence on the rms magnitude calculated for a long time history. Thus the features of vibration exposure which this model presents as being most important can be all but lost in any comparison of exposures based on rms magnitudes. Furthermore, the relative rarity of the important events can vary between operators of the same equipment, or between sites where the same task is carried out. If this information is lost by the use of generalised rms vibration magnitudes, then the different exposures of different subjects cannot be estimated, at least not in a way which is relevant to the risk of physiological damage.

9.2 COMMENTS ON FUTURE RESEARCH NEEDS

If the outcome of the many years of research into the possible effects of human exposure to whole-body vibration has been to show that some occupations in which vibration exposure is involved are associated with an elevated risk of lumbar syndrome, then it must be of interest to consider what further information could be useful.

If the measure used for evaluating vibration exposure does not correlate strongly with the physiological damage, e.g. providing a clear dose-effect relationship, this is likely to be for one of two reasons. Either the exposure to vibration is a small contributor to the damage risk in relation to other contributory causes, or else the wrong feature of the vibration exposure is being used for the evaluation.

9.2.1 Evaluation of vibration magnitude

As indicated in the introduction to this report, there is now a need to choose between two conceptually different ways of evaluating the magnitude of vibration and shock. One is the established device of frequency weighted rms acceleration, chosen because of familiarity and ease of use. The other is some way of estimating fatigue life, based on a credible damage mechanism.

In order to distinguish and compare these, it will be necessary to put rather more effort into analysing field vibration (and shock) data than has been done in the past in association with health risk studies. Lines *et al* (1994, 1995) compared VDV, also rmq and rms measures in a survey of tractor ride vibration. This approach should be extended, particularly to allow comparison of the different measures for a range of different environments. The developments presently going forward in ISO/TC108/SC4/WG10 probably need to be more complete before it is practical to define the alternatives which should best be compared, but then it will be important to define how vibration and shock should be measured in at least some future studies.

It may eventually be possible to replace a complex evaluation of exposure with something relatively simple, as was found with noise and its association with hearing damage. However, the case for this should be made on the basis of good evidence, not simple convenience.

9.2.2 Effect of reducing vibration on incidence of back ailments

The other question asked in the introduction was whether or not there is enough information to correlate the incidence of lumbar syndrome with the severity of vibration (or shock), however that is evaluated. In other words, how much will this incidence be reduced by reducing vibration magnitudes by a given amount? At present, the only information that we have would enable us to estimate the effect on the incidence of lumbar syndrome of removing the vibration element in the aetiology entirely. At least, that seems to be implicit in discussions about threshold levels, although no authors have actually provided estimates of the benefit of eliminating the vibration component of injury. Clearly (Palmer *et al*, Schwarze *et al*) even with no vibration exposure, there would remain a significant incidence of all forms of back trouble.

It may be possible to re-analyse data from some of the more recent studies reviewed here in order to provide the information necessary to associate any change in the incidence of the health problem with a reduction in the vibration or shock exposure. This would preferably allow comparison between the correlations obtained relating different measures of exposure to prevalence of the health effect. It would be of particular interest to distinguish magnitude and time effects with the simple rms measure. It would also be important to compare different measures of cumulative exposure, including the methods proposed by ISO/TC108/SC4/WG10, and application of Miner’s Rule.

Alternatively, it may be necessary to design some future study of the incidence of the occupational disease (lumbar syndrome) so that enough detail is gathered to make this association. Magnusson *et al* (1998) have set out a comprehensive basis for future research in this area, which is clearly aimed at collecting suitable data for this objective. However, although this reference provides valuable guidance with regard to the selection of groups to be studied and assessment of the health effect, it retains the assumption that energy equivalent magnitude and dose are appropriate for assessing the exposure. It is greatly to be preferred that vibration exposure is recorded so that alternative measures of both magnitude and dose can be calculated.

Furthermore, researchers should take great care to ensure that they appreciate the factors which can affect the variation of exposure between subjects who are engaged in apparently similar operations. In some instances, e.g. urban 'bus driving, global average values for particular types of vehicle may be adequately representative. In others, such as operating farm tractors or earthmoving equipment, the effects of operational variables can change rms magnitudes by 100%, and peak shock magnitudes by even more. This leads to the conclusion that the effort to be put in to assessing exposure needs to be as great as that which is applied to assessing the health effect.

9.2.3 Confounding factors

As suggested by Magnusson *et al* (1998), it will clearly be necessary to evaluate both postural stress and the possible contribution of lifting heavy or awkward loads. It is surely a prerequisite that methods are agreed for these evaluations before any further attempts are made to gather information.

If the objective of research is to reduce the incidence of low back problems, then research into the three subjects of postural load, manual handling and shock and vibration should be co-ordinated with the aim of developing a common measure of stress. It is possible that a measure of "equivalent fatigue cycles" could provide this where e.g. a 6^{th} power acceleration value would clearly not be appropriate for a lifting load.

9.2.4 Usefulness of questionnaire surveys

It is first noted that the association between noise exposure and hearing loss was defined only after detailed field assessments of both cause and effect, and that this was for an occupational health issue where both could be defined in relatively simple terms.

The likelihood that some similar degree of association might be found for lumbar syndrome and vibration (and shock) exposure, when both the cause and the effect are much less clearly defined, is naturally rather lower than it was for noise-induced hearing loss.

If all the restrictions of questionnaire studies are to be added to the difficulties of such a project, it seems remarkably optimistic to expect a clear outcome, with the obvious possibility that resources will be wasted.

However this may seem to add to the difficulties of such a study, it is likely that the only way in which useful data can be obtained is by direct examination of each subject, coupled with detailed knowledge of their actual exposure histories.

10. CONCLUSIONS AND RECOMMENDATIONS

Despite many years of research, we do not have definitive answers to the two questions posed in the introduction, namely:

1. To what extent will controlling vibration exposure lead to a lower incidence of back problems?

2. Are the presently defined measured values of vibration magnitude relevant to the risk of back problems?

We can also say that it has not yet been shown by any study reviewed here that reducing the stress of whole-body vibration has actually reduced the incidence of back trouble in a working population.

Much of what has been presented as evidence of the effect of whole-body vibration on human health has demonstrated only the associations between certain occupations and health.

The German and French occupational disease classifications, Bk2110 and Table 97, are probably correct in associating lumbar symptoms with particular occupations or machines. They exceed the bounds set by published scientific evidence in assuming that whole-body vibration is the particular cause of the symptoms.

In nearly all the published research, the effects of confounding factors, in particular of postural stress, have neither been quantified, nor compared with any claimed effect of vibration.

Very few studies of the health effects of whole-body vibration have included both cause and effect. Instead, there has been a preponderance of health studies with little or no evaluation of the exposure of the subjects to dynamic stresses. In other words, the effect has been given more attention than the cause.

The few studies that have included any evaluation of exposure to dynamic stresses have two shortcomings. First, exposures have been quantified as generalised vibration magnitudes measured on different machines or vehicles to those used by the actual subjects, and often averaged over a range of machines and conditions whose relationship to the subjects working conditions has not been verified. It is not therefore possible to distinguish subjects according to their vibration histories, nor to associate those subjects who have particular symptoms with their personal vibration (or shock) histories.

And secondly, the quantification of vibration exposure has assumed that the trade-off between magnitude and duration is already known. Frequency weighted rms values have been adjusted to equivalent 8-hour days to evaluate severity, without the essential preliminary of a justification.

The development of an assessment method for the effect of repeated shocks on the lumbar spine has led to an appreciation of the importance of peak loads, and therefore of peak accelerations. It is suggested that acceleration magnitudes are better compared using a sixth power relationship, and that the number of occurrences is of interest, not the duration.

This is quite inconsistent with the accepted hypothesis that frequency weighted rms acceleration of long term vibration provides an appropriate assessment of risk of damage to the lumbar spine.

It also is inconsistent with the idea that vibration at a low level makes a significant contribution to any fatigue damage.

The research study described by Schwarze *et al* may contain data which could be used to answer some of the above criticisms. If so, it would be useful if this could be presented in a way which allows direct comparison between groups of subjects who were exposed to high magnitude vibration for short daily periods with others who were exposed to lower magnitudes of vibration for long daily exposures.

If this cannot be done with existing data, then future epidemiological studies should be conducted in such a way that it can.

Vibration measurements used in future epidemiological studies should also allow the method for quantifying repeated shocks proposed by ISO/TC108/SC4/WG10 to be tested, including those environments which involve only continuous vibration.

Present proposals for evaluating the health effects of repeated shocks involve computations which are both complex and opaque. Methods for quantifying repeated shocks should be developed to find one which combines a simple approach with acceptable correlation with loads in the lumbar spine.

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