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DOSE–RESPONSE RELATIONSHIPS BETWEEN WHOLE-BODY VIBRATION AND LUMBAR DISK DISEASE—A FIELD STUDY ON 388 DRIVERS OF DIFFERENT VEHICLES

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In a longitudinal study, the dose–response relationships between long term occupational exposure to whole-body vibration and degenerative processes in the lumbar spine caused by the lumbar disks were examined. From 1990 to 1992, 388 vibration-exposed workers from different driving jobs were examined medically and by lumbar X-ray. For each individual, a history of all exposure conditions was recorded, and a cumulative vibration dose was calculated allowing comparisons between groups of low, middle, and high intensity of exposure. 310 subjects were selected for a follow-up four years later, of whom 90·6% ($n = 281$) agreed to participate. In comparing the exposure groups, the results indicate that the limit value of $a_{zw(8h)} = 0{\cdot}8$ m/s^2 should be reviewed. The best fit between the lifelong vibration dose and the occurence of a lumbar syndrome was obtained by applying a daily reference exposure of $a_{zw(8h)} = 0{\cdot}6$ m/s^2 as a limit value. The results became more distinct still when only those subjects were included in the statistical analysis who had had no lumbar symptoms up to the end of the first year of exposure. The prevalence of lumbar syndrome is 1·55 times higher in the highly exposed group when compared to the reference group with low exposure ($CI_{95\%} = 1{\cdot}24/1{\cdot}95$). Calculating the cumulative incidence of new cases of lumbar syndrome in the follow-up period yields a relative risk of $RR_{MH} = 1{\cdot}37$ ($CI_{95\%} = 0{\cdot}86/2{\cdot}17$) for the highly exposed group. It is concluded that the limit value for the calculation of an individual lifelong vibration dose should be based on a daily reference exposure of $a_{zw(8h)} = 0{\cdot}6$ m/s^2. With increasing dose it is more and more probable that cases of lumbar syndrome are caused by exposure to vibration.

1. INTRODUCTION

A relationship between occupational exposure to whole-body vibration and degenerative processes in the lumbar spine caused by the lumbar disks has been ascertained in numerous epidemiological studies during the last decades (cf., previous reviews in references [1–3]). Most studies are restricted to one of the typical occupations associated with exposure to

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whole-body vibration, mainly drivers of tractors, earth-moving equipment, and trucks. Measuring of outcome is mostly limited to the occurrence of low-back pain based on questionnaire or interview data. Due to various methodological shortcomings, e.g., insufficient details on exposure data, lack of adequate reference groups, etc., only a few studies give information about dose–response relationships (e.g., references [4, 5]). In particular, there are few *longitudinal* studies concerned with the degeneration of the lumbar spine caused by exposure to vibration (e.g., reference [6]).

Several awkward problems have to be faced in epidemiological research on the relationship between back disorders and occupational exposure to vibration (as discussed in reference [7]): the variety of back symptoms on a subjective, clinical, and radiographic level which causes difficulties to agree on a classification of back diseases and to make a precise diagnosis; the high prevalence of spinal problems in the general population culminating in a lifetime incidence of low-back pain from 50% to 70% and of sciatica from 13% to 40% [8]; the biological changes in the intervertebral disks due to age which are difficult to differentiate from pathological degeneration and which make age a major confounder in any analysis of degenerative processes in the lumbar spine; the multifactorial origin of non-specific low-back pain which has been related to a multitude of individual risk factors such as physical fitness, relative muscle strength, smoking, and a number of psychosocial factors [9]; the concurrence of work-related risk factors such as heavy lifting and carrying, twisting and bending of the trunk, prolonged sitting or heavy physical work in general. These factors might act in combination with vibration on the one hand or make it difficult to define a control group of blue collar workers free from strain on the back on the other hand.

While scientific research still deals with urgent methodological issues, the practice of occupational safety demands for support in the prevention of health hazards due to occupational exposure to vibration. Therefore, in 1989, the Central Federation of the Industrial Professional Associations (HVBG) initiated a longitudinal study to examine the dose–response relationship between whole-body vibration and spinal disorders more thoroughly, especially with regard to the present German guidelines which consider a daily reference exposure of $a_{zw(8h)} = 0{\cdot}8\ \mathrm{m/s^2}$ respectively $0{\cdot}6\ \mathrm{m/s^2}$ (in case of shock type vibration or poor body posture) as thresholds for health risks in longtime exposure to vibration.

2. OBJECTIVES

The research was aimed at the following: quantitative descriptions of the dose–response relationship between whole-body vibration and spinal disorders; a review of the German guidelines for whole-body vibration as a health hazard (daily reference exposure); application of a calculation procedure for the cumulated dose of occupational vibration exposure; findings on the practicability of a guideline for preventive medical examination respectively of an instruction on accident prevention with regard to whole-body vibration.

3. METHODS

3.1. STUDY DESIGN AND SAMPLE

From 1990 to 1992, an initial cohort of 496 subjects who were insured of one of the participating Industrial Professional Associations was collected from more than 30 companies in different parts of Germany. 43 subjects had to be excluded from further analysis due to incomplete data or lack of meeting the criteria of classification, so that the remaining cohort consisted of 388 drivers from different driving jobs such as fork-lift truck drivers, truck drivers, and operators of earth moving machinery, and 65 controls never exposed to vibration (see Table 1).

Each of the three participating Industrial Professional Associations (for mechanical engineering and metall processing, vehicle business, and civil engineering) was obliged to provide a certain number of subjects. Contacts with companies willing to collaborate and dates for the examinations were arranged by the technical officials of the associations. Subjects were chosen by the officials at the place of work on the day of examination depending on availability and willingness to participate. Minimum requirement for participation was a regular exposure to whole-body vibration at the present workplace. Further it was desired to choose subjects between 30 and 40 years of age, as this age was considered most crucial for developing lumbar degenerations due to vibration, and with a history of at least 10 years of vibration exposure. For practical reasons, the two last criteria could not be met strictly within the time limits of the study. There was no intention to draw a representative sample from each company as the methodological emphasis was put on collecting a sample with a wide range of individual intensities of vibration load.

The controls were taken from the same companies as the exposed subjects, and the intention was to avoid any divergence between the groups in socio-economic conditions or working load besides the fact of exposure to vibration.

From 1995 to 1996, a reduced sample of 310 drivers was selected for a follow-up, in which 281 of them (90·6%) took part. This selection followed two criteria: all 65 controls were omitted (cf., section 4.1); 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.

For each subject of the follow-up, a minimum period of four years between first and second examination was kept. The collection of data of the medical examination and of the vibration exposure followed the same schedule as will be described for the initial examination.

3.2. ASSESSMENT OF VIBRATION LOAD

For each exposed person, a history of all periods and conditions of occupational exposure to vibration was recorded, and a cumulative vibration dose D_V for the whole working life was calculated according to the equation proposed by Dupuis [10], i.e.,

$$D_V = \sum_{i=1}^{n} a^2_{zw,i(8h)} \cdot d_i, \qquad (1)$$

TABLE 1

Size and mean age of the cohort and the different professional groups

Type of job	n	Age in years: mean	Age in years: $s.d.$
Controls	65	38·3	10·3
fork-lift truck drivers	159	39·8	10·0
truck drivers	64	39·8	10·1
operators of heavy machinery	165	42·0	9·6
Total	453	40·4	10·0

TABLE 2

Arithmetic means (AM) of vibration intensity and duration of exposure of the cohort and the different professional groups

Job title	frequency-weighted energy-equivalent acceleration (8h) in present job $a_{zw(8h)}$ AM	s.d.	min.	max.	total duration of exposure to vibration (in years) AM	s.d.	min.	max.
Fork-lift truck drivers	0·45	0·18	0·13	1·12	12·8	7·7	0·5	31·8
Truck drivers	0·47	0·22	0·30	1·02	18·4	9·3	2·3	36·4
Operators of heavy machinery	0·67	0·30	0·18	1·90	20·1	9·8	2·0	42·0
Total	0·55	0·26	0·13	1·90	16·8	9·5	0·5	42·0

with $a_{zw,i(8h)}$ = frequency-weighted energy equivalent acceleration (8h) for homogenous exposure periods and d_i = number of days of homogeneous exposure periods.

The assessment of the history of exposure included several steps: First the worker was interviewed by the technical officials with regard to his job history. For each job period, the duration of vibration was recorded in terms of hours per day, days per week and weeks per year, and the type of vehicle used was noted as precisely as possible including special conditions of use such as driving on rough ground. Technical details on each vehicle, its suspension and tyres, and the driver's seat were recorded on the basis of inspection by the technical officials, whenever possible, or from the statements of the employees.

The Institute of Occupational Safety of the HVBG (BIA) which maintains an extensive database on vibrations of machinery (VIBEX) with more than 4000 records processed all these data in a calculation of the individual frequency-weighted energy equivalent acceleration for each homogeneous period of exposure which was the basis for any further calculation of vibration doses.

Table 2 gives some information about the actual average vibration load at the time of the examination for the whole cohort and the three professional groups. Vibration dose calculations cannot be given for the professional groups as in most cases the lifetime vibration load is based on different periods of employment often implying different types of job.

In interviewing the subjects, the technical officials also recorded additional work loads to the spine such as heavy lifting and carrying, twisted body posture, etc. During the follow-up, a detailed questionnaire was used assessing all aspects of lifting and carrying at the workplace in order to quantify the load, but the subjects' statements proved too vague to allow any quantification.

3.3. ASSESSMENT OF MEDICAL DATA

For each individual, a large quantity of medical data was assessed: a detailed standardized case history focussing on back pain including accidents or traumas of the spine and possible confounders not related to work (sports, building of a house, etc.); a standardized clinical examination of the spine; lumbar X-rays in two planes; data of the health insurance on inability to work due to lumbar disorders.

The medical diagnosis of "lumbar syndrome" was considered to be the most important outcome variable combining the variety of data from very different and divergent levels of observation to only one medical category. In accordance with the official information leaflet for the medical examination referring to occupational disease no. 2110, "Diseases of the lumbar spine from disc degeneration caused by long-term (mainly vertical) whole body vibration...'' [11], a ''lumbar syndrome'' was defined as any kind of symptoms (like lumbago or sciatica) in the lumbar region and in the sacral area for which a vertebral cause could be assumed after differential diagnosis [10, 12]. Two forms of clinical manifestation were distinguished: ''lumbar radicular syndrome'' in case of any symptom of affection of the spinal nerves and ''local lumbar syndrome'' when such signs were missing. The diagnosis was made by the same medical practitioner specialised in occupational medicine and radiology who was responsible for all medical examinations of the study. The entire anamnestic and clinical data served as a basis for the medical diagnosis, and competing non-degenerative causes of disease (i.e., spondylolisthesis) were excluded by evaluation of X-rays. As a lumbar syndrome is considered to be a degenerative process and as all participants of the study were fit for work at the time of the examination, this diagnosis includes also the reporting of plausible and serious complaints in the past without actual clinical concomitants.

3.4. DATA ANALYSIS

For both periods of the study, the detailed recording of the professional vibration exposure allowed to differentiate a wide range of intensities of vibration load and to determine internal reference groups. In order to examine the current German guidelines for protection from health hazards caused by occupational whole-body vibration [13], the cumulative vibration dose D_V was calculated using various limit values of daily reference exposure: Either $a_{zw(8h)} = 0{\cdot}4\ \mathrm{m/s^2}$ or $a_{zw(8h)} = 0{\cdot}6\ \mathrm{m/s^2}$ or $a_{zw(8h)} = 0{\cdot}8\ \mathrm{m/s^2}$ was considered a threshold for hazardous exposure to vibration. From the individual dose D_V resulting on the base of the respective limit value, groups of low, medium, and high vibration dose were set up.

The ''low exposure'' group I was defined as ''never being exposed above the respective limit value'', e.g., $a_{zw(8h)} = 0{\cdot}6\ \mathrm{m/s^2}$. In most of the statistical analyses, the distinction between ''medium'' and ''high'' exposure (groups II and III) was made relating to a cumulative reference dose (vibration guideline dose) $D_{VG} = 1414\ \mathrm{m^2/s^4} \times \mathrm{days}$ which corresponds to a full-time occupational exposure of $a_{zw(8h)} = 0{\cdot}8\ \mathrm{m/s^2}$ during ten years or exposure $a_{zw(8h)} = 0{\cdot}6\ \mathrm{m/s^2}$ during 17·8 years. In some analyses, subjects with ''very high'' exposure were treated as a separate group (group IV with $D_{VG} > 2828\ \mathrm{m^2/s^4} \times \mathrm{days}$).

Additionally, comparisons between exposure groups were calculated by using criteria for exposure unrelated to age, such as maximum daily exposure value, average lifelong daily exposure, or divergence of the individual dose D_V from the dose–age regression in the sample.

Possible confounders such as body-mass index, former spine injuries, heavy lifting, load to the spine by leisure activities were examined statistically with regard to their impact on the main outcome variables. As only age and prevalence of lumbar complaints prior to the onset of exposure proved to be of importance, these two confounders are dealt with in the following presentation of results which concentrates on a choice of analyses of the most interesting variables of vibration load and health responses.

4. RESULTS

4.1. EFFECT OF VIBRATION LOAD IN RELATION TO PROFESSION

Subjects had been recruited from rather different industrial jobs to assure a wide range of occupational exposure to vibration, from the relatively low vibration load of drivers of fork-lift trucks on asphalt tracks up to the presumably high intensities of vibration frequently found with operators of earth moving machinery in construction sites. Professional groups are often used as an indicator of exposure to vibration. But sometimes the actual profession is biased by the healthy worker effect and by selective survival. In order to demonstrate the low validity of professional groups as an indicator of exposure, the lifetime prevalence of the diagnosis "lumbar syndrome" was calculated (see Figure 1). The percentage of diagnoses differs only slightly between the groups: from 58·5% in the controls to 64·8% in the drivers of fork-lift trucks. As these two groups have the lowest mean age, the possible confounding effect of age is not systematical.

In addition, there was evidence from self-reports and from the notations of the physician that the recruiting of controls was heavily biased by selection and information bias (including individual motives for voluntary participation as well as strain to the back induced by other working conditions which had not been recorded). As a consequence, the suitability of the controls as a reference had to be questioned. Instead, the low exposure group I seemed to be a more appropriate reference group in all the following comparisons between groups of different exposure, as exposure to vibration below the limit value should not cause any harmful health effect.

4.2. PREVALENCE OF LUMBAR SYNDROME AMONG GROUPS OF DIFFERENT VIBRATION DOSE

In the cross-sectional part of the study, the epidemiological analysis was focussed on the *prevalence* of the relevant diagnoses and symptoms among the different exposure groups. Figure 2 shows the percentage of subjects with the diagnosis "lumbar syndrome" in three groups of different exposure to vibration based on the limit value of $a_{zw(8h)} = 0{\cdot}6\ \mathrm{m/s^2}$. The frequency of the diagnosis rises from 55·6% in the "low exposure" group $I_{0{\cdot}6}$ to 65·0% with "medium exposure" (group $\mathrm{II}_{0{\cdot}6}$) and to 73·2% in the highly exposed group $\mathrm{III/IV}_{0{\cdot}6}$.

The results became more distinct when the statistical analysis included only those subjects who had had absolutely no lumbar symptoms up to the end of the first year of exposure ($n = 315$). Of course, it is also important to observe the aggravation of symptoms caused by superimposing vibration exposure on existing lumbar health disorders, but as the rate of pre-existing spinal disorders is highest in the group of low exposure to vibration, there might have happened a selection of the fittest at the very beginning of employment. Therefore, it seems reasonable to carry out a separate analysis only for those subjects without any low-back symptoms till the end of the first year of exposure.

When the sample is reduced this way to 315 subjects, the percentage of subjects with the diagnosis "lumbar syndrome" now rises from 39·4% in the reference group with

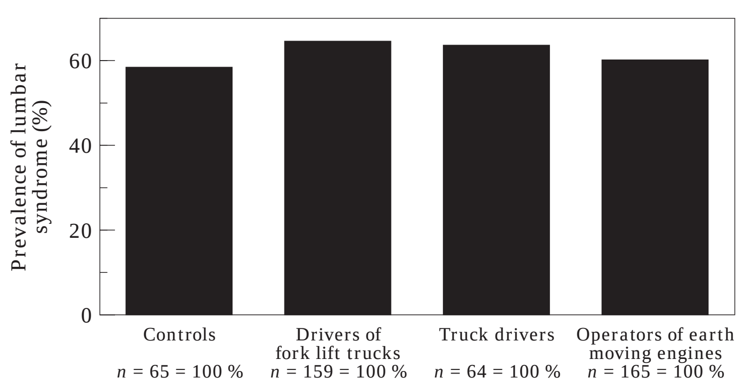

Figure 1. Prevalence of lumbar syndrome in four different professional groups.

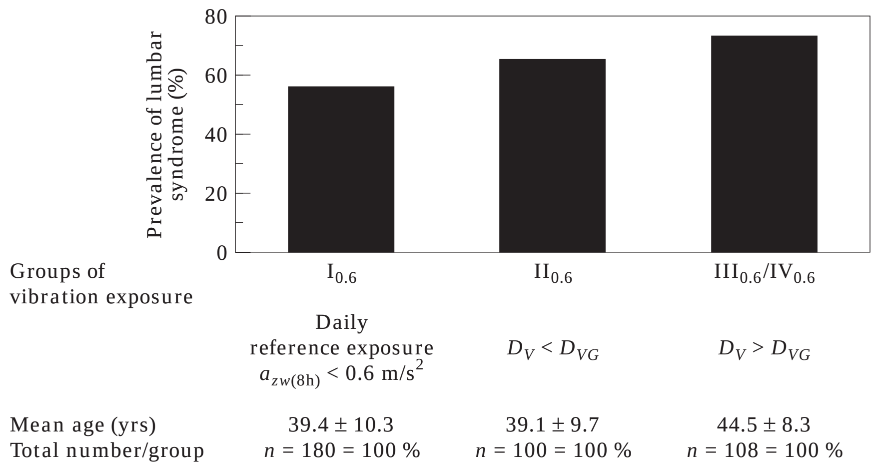

Figure 2. Prevalence of lumbar syndrome for different groups of vibration exposure based on a daily reference exposure of $a_{zw(8h)} = 0{\cdot}6$ m/s^2 ($n = 388$). $a_{zw(8h)}$ = daily reference exposure; D_V = total occupational vibration dose = $a^2_{zw(8h)} \times$ days of exposure (m^2/s^4 $\times$ days) (only days with $a_{zw(8h)} > 0{\cdot}6$ m/s^2); D_{VG} = guidance for supposed health effects = 1414.

low exposure to 59·0% in the group with medium exposure and to 72·0% in the highly exposed group (see Figure 3).

The differences in frequency of the diagnosis are statistically significant between the exposure groups, but as the cumulative vibration dose and the outcome variable are highly correlated with age, age has to be taken into account as a confounder. Therefore, the confounding by age was adjusted by means of the Mantel–Haenszel estimate. The prevalence is 1·55 times higher in the highly exposed group III/IV$_{0{\cdot}6}$ when compared to the reference group I$_{0{\cdot}6}$ (prevalence ratio adjusted for age: $PVR_{MH} = 1{\cdot}55$; $CI_{95\%} = 1{\cdot}24/1{\cdot}95$). Calculating the attributive risk (AR%) results in 35% of the cases of lumbar syndrome which can be attributed to the vibration exposure. Even for the group II$_{0{\cdot}6}$ with medium

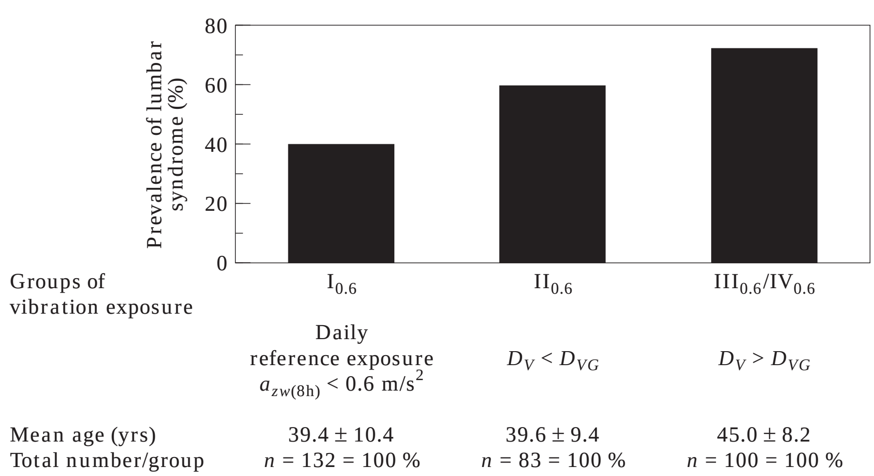

Figure 3. Prevalence of lumbar syndrome for different groups of vibration exposure based on a daily reference exposure of $a_{zw(8h)} = 0{\cdot}6$ m/s^2—only subjects without lumbar syndrome up to the end of the first year of exposure ($n = 315$). $a_{zw(8h)}$ = daily reference exposure; D_V = total occupational vibration dose = $a^2_{zw(8h)} \times$ days of exposure (m^2/s^4 $\times$ days) (only days with $a_{zw(8h)} > 0{\cdot}6$ m/s^2); D_{VG} = guidance for supposed health effects = 1414.

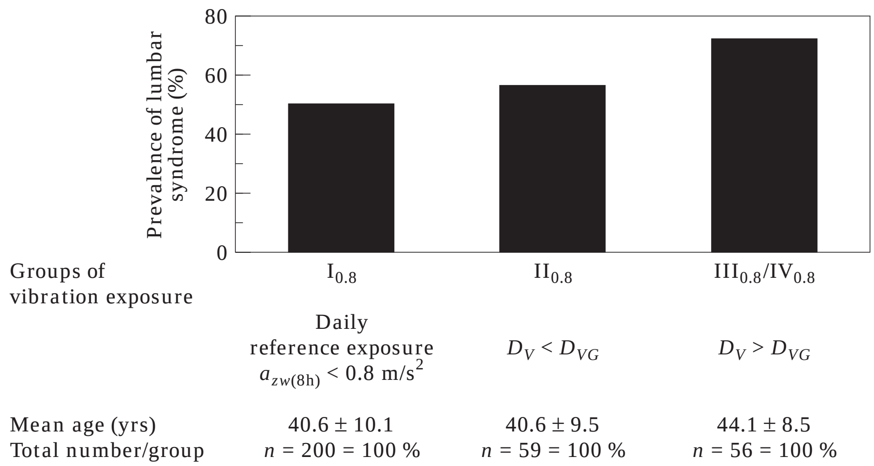

Figure 4. Prevalence of lumbar syndrome for different groups of vibration exposure based on a daily reference exposure of $a_{zw(8h)} = 0{\cdot}8$ m/s^2—only subjects without lumbar syndrome up to the end of the first year of exposure ($n = 315$). $a_{zw(8h)}$ = daily reference exposure; D_V = total occupational vibration dose = $a^2_{zw(8h)} \times$ days of exposure (m^2/s^4 × days) (only days with $a_{zw(8h)} > 0{\cdot}8$ m/s^2); D_{VG} = guidance for supposed health effects = 1414.

exposure, the PVR_{MH} still amounts to 1·49 ($CI_{95\%} = 1{\cdot}13/1{\cdot}96$); 33% of the cases of lumbar syndrome in this group can be attributed to the occupational exposure to vibration.

In general, the best fit between the lifelong vibration dose and the occurrence of a lumbar syndrome as well as the highest consistency in results for various measures of effect was obtained applying a limit value for the daily reference exposure of $a_{zw(8h)} = 0{\cdot}6$ m/s^2. As an example for the results obtained with other criteria of vibration load, figure 4 illustrates the frequency of the diagnosis "lumbar syndrome" in different exposure groups when the calculation of the vibration dose is based on a limit value of $a_{zw(8h)} = 0{\cdot}8$ m/s^2, again for the reduced sample of 315 subjects without any lumbar problem up to the end of the first year of exposure.

The most striking result is the rise of the prevalence in the low exposure group $I_{0{\cdot}8}$ up to 50% which means a higher background risk for those workers who should not be in danger of damage to their health by definition. In addition, the difference between the groups of medium and low exposure has been nearly levelled off. These changes in frequencies suggest the conclusion that a limit value for daily reference exposure of $a_{zw(8h)} = 0{\cdot}8$ m/s^2 does not represent the threshold of hazard for health.

In addition, applying $a_{zw(8h)} = 0{\cdot}4$ m/s^2 as daily reference exposure did not lead to a lower prevalence of lumbar syndrome in the group with low vibration so that the background risk seems to be represented best by a daily reference exposure of $a_{zw(8h)} = 0{\cdot}6$ m/s^2. Therefore the best distinction between groups of different vibration doses is made by introducing a threshold value of $a_{zw(8h)} = 0{\cdot}6$ m/s^2 in the calculation of the cumulative dose D_V.

4.3. RELATIONSHIPS BETWEEN ANAMNESTIC ITEMS AND VIBRATION DOSE

Besides the main outcome variable "lumbar syndrome", a variety of items of the medical examination, predominantly anamnestic items, reflect the same dose–response relationship between the proportion of back disorders and exposure groups. Figure 5 illustrates the percentage of positive responses among the exposure groups (based on a daily reference exposure of $a_{zw(8h)} = 0{\cdot}6$ m/s^2) for some basic anamnestic items: Have you ever had low-back pain?; Have you been medically treated for these complaints?; Have you ever been unfit for work because of these complaints?; Do you have low-back pain today?. In Figure 5, the results which were obtained for the reduced sample ($n = 315$) are shown. The results for the whole cohort ($n = 388$) were similar.

For each item there is a more or less pronounced distinction between the three exposure groups, and a stairwise increase can be observed. For the lifetime prevalence of low-back pain as well as for the medical treatment and the temporary disability to work, the increase of positive responses among the exposure groups is statistically significant (chi^2 test, $p < 0{\cdot}01$).

The relative risk for each anamnestic symptom was calculated adjusting for age by means of the Mantel–Haenszel estimate. There is a higher risk for each level of anamnestic complaints about low-back pain when the high resp. medium exposure groups are compared with the low exposure group:

lifetime prevalence of low-back pain
group III/IV$_{0{\cdot}6}$ versus group I$_{0{\cdot}6}$: $PVR_{MH} = 1{\cdot}50$ (CI_{95} 1·19/1·88),
group II$_{0{\cdot}6}$ versus group I$_{0{\cdot}6}$: $PVR_{MH} = 1{\cdot}35$ (CI_{95} 1·04/1·76);

medical treatment for low-back pain
group III/IV$_{0{\cdot}6}$ versus group I$_{0{\cdot}6}$: $PVR_{MH} = 1{\cdot}54$ (CI_{95} 1·15/2·06),
group II$_{0{\cdot}6}$ versus group I$_{0{\cdot}6}$: $PVR_{MH} = 1{\cdot}43$ (CI_{95} 1·03/1·98);

temporary disability to work
group III/IV$_{0{\cdot}6}$ versus group I$_{0{\cdot}6}$: $PVR_{MH} = 1{\cdot}45$ (CI_{95} 1·06/2·00),
group II$_{0{\cdot}6}$ versus group I$_{0{\cdot}6}$: $PVR_{MH} = 1{\cdot}44$ (CI_{95} 1·02/2·04).

This recurring pattern of increasing frequency of positive answers to anamnestic items among the exposure groups confirms the consistency of the results reported for the main outcome variable.

4.4. INCIDENCE OF LUMBAR SYNDROME IN THE FOLLOW-UP PERIOD

4.4.1. *Effects of the total occupational vibration dose*

The main interest in analyzing the follow-up period was directed towards the *incidence* of lumbar syndrome, i.e., the proportion of new cases in this period of time. 111 subjects

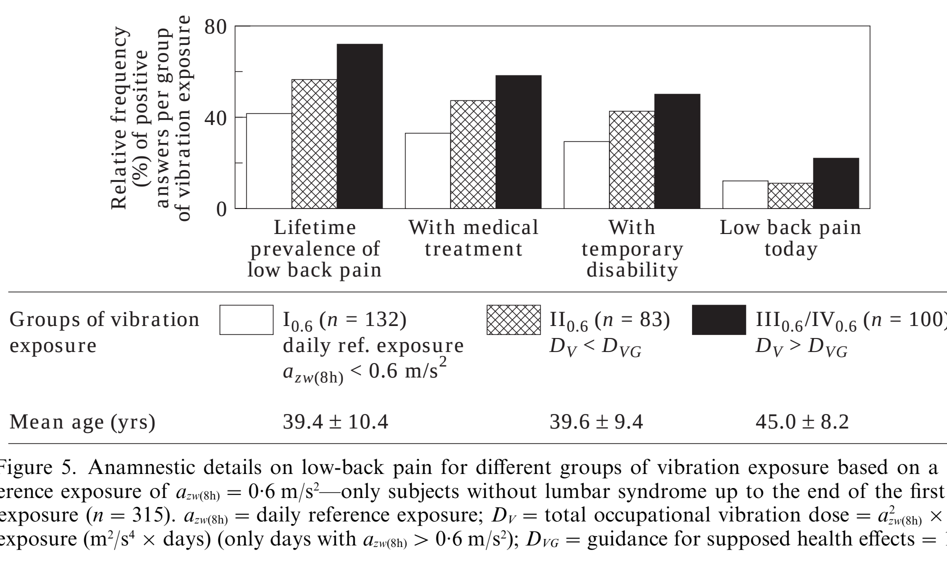

Figure 5. Anamnestic details on low-back pain for different groups of vibration exposure based on a daily reference exposure of $a_{zw(8h)} = 0{\cdot}6$ m/s^2—only subjects without lumbar syndrome up to the end of the first year of exposure ($n = 315$). $a_{zw(8h)}$ = daily reference exposure; D_V = total occupational vibration dose = $a^2_{zw(8h)} \times$ days of exposure (m^2/s^4 × days) (only days with $a_{zw(8h)} > 0{\cdot}6$ m/s^2); D_{VG} = guidance for supposed health effects = 1414.

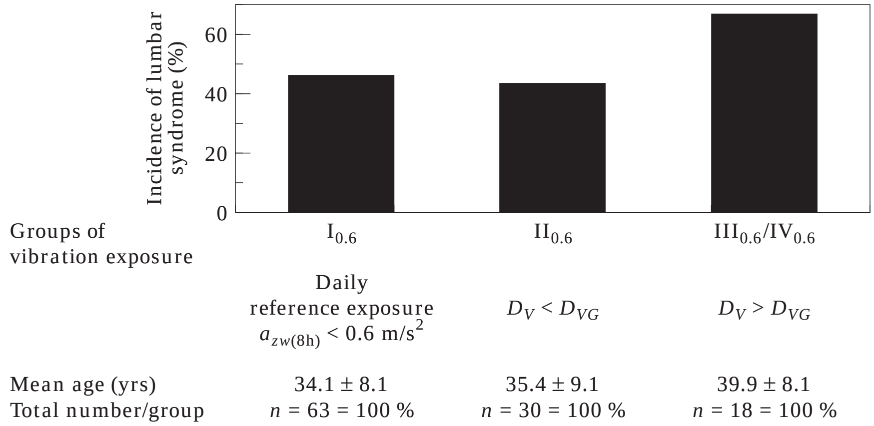

Figure 6. Incidence of lumbar syndrome among subjects without this disease prior to the follow-up ($n = 111$)—groups based on a daily reference exposure of $a_{zw(8h)} = 0{\cdot}6$ m/s^2. $a_{zw(8h)}$ = daily reference exposure; D_V = total occupational vibration dose $= a^2_{zw(8h)} \times$ days of exposure (m^2/s^4 × days) (only days with $a_{zw(8h)} > 0{\cdot}6$ m/s^2); D_{VG} = guidance for supposed health effects = 1414.

out of the sample of 281 subjects taking part in the follow-up had had no lumbar syndrome at the initial examination four years earlier. 54 of these 111 subjects (49%) got this diagnosis for the first time during the follow-up. As Figure 6 shows the highest incidence occurs in the "high exposure" group III/IV$_{0{\cdot}6}$ whereas the incidence in the other groups is about the same (46 and 43%, respectively).

Upon calculating the incidence during the follow-up period, the relative risk is $RR_{MH} = 1{\cdot}37$ ($CI_{95\%} = 0{\cdot}86/2{\cdot}17$) for the highly exposed group as compared to the reference group I$_{0{\cdot}6}$. 27% of the new cases of lumbar syndrome in this group can be attributed to the cumulative vibration dose. Due to the reduced size of the sample, the confidence interval is rather large moderating the validity of the result.

During the follow-up period, two subjects had developed such a severe state of lumbar syndrome leading to very long-lasting working disability respectively the need to leave the job. For these cases, an occupational disease according to no. 2110 (official list of occupational diseases in German law) might be assumed.

4.4.2. *Effects of the daily reference exposure*

At the time of the first investigation, 147 of the 281 subjects taking part in the follow-up had reported a vibration load of $a_{zw(8h)} > 0{\cdot}6$ m/s^2 for some period of time during their working life. During the period of the follow-up, only 76 subjects were exposed to vibration of this intensity, 13 of them for the first time. Several reasons may account for this general reduction in daily exposure: better equipment involving technical improvements in the attenuation of the vibration, changes of the workplace or the tasks in the company, reductions of daily exposure time due to organizational, economical or even medical reasons, etc.

From the 111 subjects without the diagnosis "lumbar syndrome" at the initial examination, 32 were exposed to a daily reference exposure of $a_{zw(8h)} > 0{\cdot}6$ m/s^2 in the period till the follow-up. When this group was compared with the lower exposed one, those subjects who had been exposed to vibration $> 0{\cdot}6$ m/s^2 showed a relative risk of $RR_{MH} = 1{\cdot}32$ ($CI_{95\%} = 0{\cdot}90/1{\cdot}92$) to be given the diagnosis "lumbar syndrome". Even without taking the cumulated doses into account, a higher risk of low back disorders seems to be associated with a continous exposure to vibration with a daily reference exposure of $a_{zw(8h)} > 0{\cdot}6$ m/s^2.

4.5. LOCAL LUMBAR SYNDROME VERSUS LUMBAR RADICULAR SYNDROME

The two forms of manifestation of a lumbar syndrome, with and without affection of the radicular nerves, might be influenced by vibration exposure to a different degree. Hence the two diagnoses were analyzed separately. For the cross-sectional study, Figure 7 shows the percentage of both diagnoses in each of the three exposure groups based on a daily reference exposure of $a_{zw(8h)} > 0{\cdot}6$ m/s^2 (reduced sample of 315 subjects without lumbar disorders up to the end of the first year of exposure). There is a clear stairwise relationship between the proportion of diagnoses and the exposure groups which is more distinct for the diagnosis "local lumbar syndrome". Further analysis by stratifying for age provides evidence that the frequency of the diagnosis "local lumbar syndrome" is closely related to the total vibration dose in each age stratum, whereas the lumbar radicular syndrome is associated stronger with age only. Thus, the calculation of age-adjusted prevalence ratios for the two diagnoses yields quite different risks for the exposure groups:

local lumbar syndrome
group III/IV$_{0{\cdot}6}$ versus group I$_{0{\cdot}6}$: $PVR_{MH} = 2{\cdot}38$ (CI_{95} 1·52/3·74),
group II$_{0{\cdot}6}$ versus group I$_{0{\cdot}6}$: $PVR_{MH} = 2{\cdot}00$ (CI_{95} 1·21/3·28),
group III/IV$_{0{\cdot}6}$ versus group II$_{0{\cdot}6}$: $PVR_{MH} = 1{\cdot}29$ (CI_{95} 0·87/1·90);

lumbar radicular syndrome
group III/IV$_{0{\cdot}6}$ versus group I$_{0{\cdot}6}$: $PVR_{MH} = 1{\cdot}52$ (CI_{95} 1·07/2·15),
group II$_{0{\cdot}6}$ versus group I$_{0{\cdot}6}$: $PVR_{MH} = 1{\cdot}53$ (CI_{95} 1·04/2·24),
group III/IV$_{0{\cdot}6}$ versus group II$_{0{\cdot}6}$: $PVR_{MH} = 1{\cdot}06$ (CI_{95} 0·75/1·48).

From the data of the separate age strata one can conclude that a profound "selection of the fittest" is effective among workers with a high total vibration dose resulting in prematurely leaving a job when low back disorders are accompanied by severe radicular

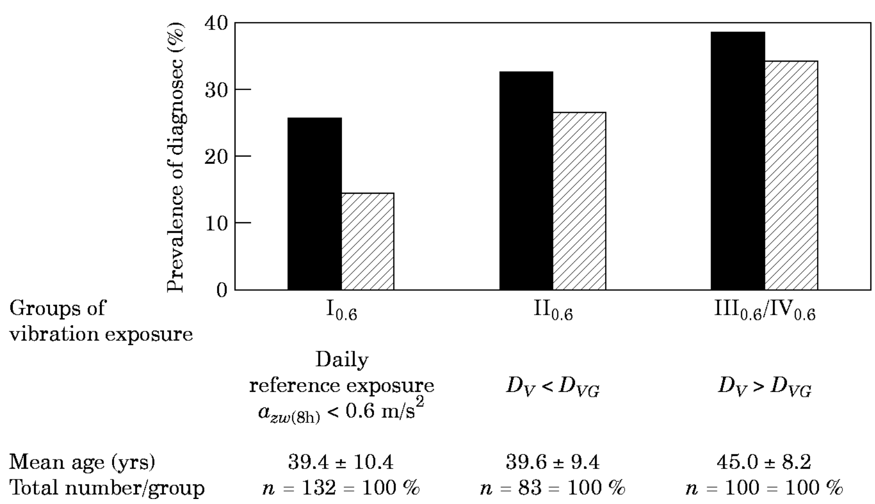

Figure 7. Prevalence of local lumbar syndrome *vs*. lumbar radicular syndrome for different groups of vibration exposure based on daily reference exposure of $a_{zw(8h)} = 0{\cdot}6$ m/s^2—only subjects without lumbar syndrome up to the end of the first year of exposure ($n = 315$). Black columns: lumbar radicular syndrome; patterned columns: local lumbar syndrome. $a_{zw(8h)}$ = daily reference exposure; D_V = total occupational vibration dose = $a^2_{zw(8h)}$ × days of exposure (m^2/s^4 × days) (only days with $a_{zw(8h)} > 0{\cdot}6$ m/s^2); D_{VG} = guidance for supposed health effects = 1414.

symptoms. This conclusion is supported by the calculation of *incidence* for the follow-up period which shows an opposite trend regarding the two diagnoses:

When the incidence of diagnoses is split into "local lumbar syndrome" and "lumbar radicular syndrome", there is very clear evidence that the incidence of radicular symptoms is strongly related to exposure to vibration ($RR = 2{\cdot}27$; $CI_{95\%} = 1{\cdot}25/4{\cdot}14$) whereas the relative risk for a local lumbar syndrome associated with a daily exposure reference $a_{zw(8h)} > 0{\cdot}6\ \mathrm{m/s^2}$ during the follow-up period amounts to $RR = 0{\cdot}8$ ($CI_{95\%} = 0{\cdot}37/1{\cdot}89$) only. Thus, the calculation of the prevalence of the lumbar radicular syndrome in the cross-sectional part of the study seems to underestimate the true risk of developing back disorders with radicular affection caused by exposure to vibration.

5. DISCUSSION

The design of this longitudinal study had some special features which have to be discussed with regard to their implications, as follows.

5.1. OUTCOME VARIABLES

The pathogenic model underlying the research on whole-body vibration and spinal disorders is mainly based on the hypothesis that whole-body vibration causes or accelerates degenerative processes in the lower part of the vertebral column. This degeneration starts at the intervertebral disks and gradually affects the adjoining structures or tissues. Therefore, epidemiological studies dealing with the long term effect of whole-body vibration should try to relate the outcome variable to diagnostic criteria which represent some equivalent of this degenerative process.

Of course, subjective complaints of suffering from low-back pain are strongly related to a relevant degeneration of the spine and are easily recorded by questionnaire. But low-back pain itself may be caused by a bundle of other factors and may not always reflect the presence of a degenerative process of the intervertebral disk.

In order to increase the probability of really detecting degeneration of the vertebral column, the outcome variable in this study was defined as a result of the evaluation of informations gained from three different levels of observation: an extensive set of data—anamnestic, clinical, and radiological—was collected and combined in a *medical diagnosis* made by a specialist. This also opened up the chance to look for special patterns of symptoms related to vibration exposure.

But as the analysis showed the study was not successful in identifying items or sets of items which can be considered as typical effects of exposure to vibration. Only the more general anamnestic items showed a relation to the total vibration dose as shown in Figure 5. These basic anamestic items can be compared to similar questions of the frequently used low-back pain questionnaires (see, e.g., references [4, 5, 14–17]) and strengthen the evidence of an increase of low back disorders in subjects exposed to whole-body vibration. The clinical items, of course, are strongly related to actual complaints which do not depend significantly on vibration exposure for their part. The radiological items proved to be highly correlated with age. A more detailed analysis of the radiological part of the study will be published later.

The main outcome variable "diagnosis of a lumbar syndrome" showed a very clear statistical relation to the groups of different exposure level. The lifetime prevalence of the diagnosis which amounts to 62·3% in the whole cohort of 453 subjects is in accordance with the lifetime prevalence of low-back pain as reported in the literature [7, 8, 18]. In view of the fact that the subjects of the study were industrial workers recruited at the workplace and no patients with acute complaints, there is only a slight divergence between the medical diagnosis and the self-reported back problems as assessed in the anamnesis: The main advantage of the medical examination consists in the differentiation of radicular involvement in some cases when clinical tests (neural reflexes or Lasègue) turned to be positive, and in the correction of the diagnosis in only a few cases when the radiographs proved a non-degenerative cause of complaints.

Concerning improvements in defining an outcome variable for future research, experience of this study indicates that there is an imbalance between the precise quantification of vibration load as suggested in the present study in terms of total vibration dose and the evaluation of low-back disorders. Besides divergences in terms and definitions, there is a considerable lack of knowledge in classifying different forms of manifestation and accompanying symptoms with regard to the severity of the disorders. For future research, it is desirable to work on a ranking scale including not only self-reported items, but also clinical and radiological signs which allows one to relate the outcome variables to the exposure data in a more quantitative dimension.

5.2. TYPES OF OCCUPATION

Most epidemiological studies on low-back pain and occupational risk factors focus on one specific type of occupational exposure and one non-exposed reference group (see, e.g., references [4, 5, 6, 19, 20]). Typically, the workers under risk are exposed to combined factors such as vibration, prolonged sitting, heavy lifting or carrying and/or twisting of the trunk. Often it is difficult to isolate and evaluate the effect of a single strain like vibration. In this study, subjects came from quite different occupations regarding the intensity of daily exposure to vibration. Thus, the cohort provided a wide range of daily exposure levels, and presumably the lifetime vibration dose would correlate less with age than in any homogeneous cohort.

As shown in Figure 1, the four groups of different profession did not differ significantly in their lifetime prevalence of lumbar syndrome, whereas a regrouping of the same subjects according to the total vibration dose produces pronounced differences. Obviously, the type of occupation is a factor which includes other individual or job-specific influences besides vibration load. One of them which represents a methodological problem may be deduced from comparing Figures 2 and 3: When all subjects who had reported low-back problems before the onset of exposure are excluded from analysis the decrease of prevalence of lumbar syndrome is greater among the subjects with relatively low exposure levels, i.e., mainly fork-lift truck drivers. From personal notes of the research team one can conclude that superiors sometimes consider a working place like driving of fork-lift trucks to be a kind of protective job for workers with a history of back problems. The type of occupation seems to imply a preselection which is difficult to detect retrospectively.

5.3. TOTAL VIBRATION DOSE

Undisputably equivalent vibration magnitude and duration of exposure are two main components determining the hazard to health caused by whole-body vibration. Up to now, only few attempts are reported in literature to combine these two dimensions in the calculation of a total vibration dose: Boshuizen *et al*. [15] and Bovenzi and Zadini [16] applied a calculation model very similar to the one used in this study. Only Boshuizen *et al*. gave some details about the dose values obtained but as they included the frequency weighted accelerations in all three body-axes, their exposure groups cannot be related directly to the exposure data found in the present study.

Although the results of the study just indicate a higher risk of lumbar back disease when subjects are exposed to vibration with a daily reference exposure of $a_{zw(8h)} > 0{\cdot}6$ m/s^2, there is another increase of risk for those who exceed the vibration guidance D_{VG} as defined above. This guidance which corresponds roughly to 10 full-time working years with a daily reference exposure of $a_{zw(8h)} = 0{\cdot}8\ \mathrm{m/s^2}$ (or to nearly 18 years with a daily reference exposure of $a_{zw(8h)} = 0{\cdot}6\ \mathrm{m/s^2}$), was derived from former epidemiological studies [10] and represents an orientation, but not a strict and invariable limit. In the present study, several modifications of the proposed vibration guidance D_{VG} with higher and lower values were tested, but none of them resulted in better discrimination between exposure groups. Thus it is recommended to use the vibration guidance $D_{VG} = 1414\ \mathrm{m^2/s^4} \times$ days as a reasonable basis for further research. It has to be noted that this pragmatic guidance does not imply any determination of a limit value for daily reference exposure.

5.4. LONGITUDINAL STUDY

Only few longitudinal studies are found in the epidemiological research on low-back disorders due to vibration exposure, although they provide the best solutions to methodological problems like confounding, selection bias, temporality, etc. The present study was designed as longitudinal with a follow-up after four to five years. The main advantage of the follow-up was the chance to study the *incidence* of the relevant diagnoses in the years under observation. There was a distinct increase of risk related to exposure groups for the diagnosis "lumbar syndrome" in general and "lumbar radicular syndrome" in particular. The latter points to a possible specific risk related to vibration exposure which might remain undiscovered in cross-sectional studies as workers with lasting radicular symptoms are more likely to change their job.

It has to be mentioned that there were still methodological shortcomings in the design of the study. Firstly, many subjects were already quite old at the beginning of the study (89 subjects (19·6%) age 50 or above). Of course, on the one hand it has to be supposed that the harmful effects of vibration on the spine have a long induction period, but on the other hand there is a strong influence of age on the vertebral column which leads to the same effects. In general, the prevalence of lumbar syndrome is very high, not only among workers, but in the total population so that the excess risk induced by vibration can only be small. In terms of risk quantification it has to be realized that, assuming for example a prevalence about 50%, a twofold increase in risk would lead to 100% of subjects affected. Thus, mathematically the relative risk cannot be higher than two in this example.

Further, some data suggest that a "selection of the fittest" might have happened already among the middle-aged workers exposed to higher vibration magnitudes so that the true effect of vibration might have been underestimated in the cross-sectional part of the study. As a consequence of this preselection, the follow-up period of four years might have been too short and too late with reference to the temporal development of back disorders in the cohort to detect the harmful effects of vibration with higher statistical power.

Especially, the temporal onset of the individual low-back problems and possible changes in symptoms with time had to be reconstructed retrospectively. Thus, a major problem in research on occupational risks of low-back disorders, the differentiation between individual and occupational causes of the complaints, could only be handled somewhat arbitrarily by excluding subjects from further analysis who had reported low-back pain before exposure or up to the end of the first year of exposure. Also the question remains unsolved to what extent the different forms of back disorder, namely lumbar syndrome with and without radicular affection, might represent stages of an individual course of disease influenced by the amount of vibration load. In summary, there is still a need for longitudinal research in which the subjects under exposure are escorted from a starting point in their working life as early as possible.

5.5. CONCLUSIONS

Altogether the results of this study confirm that vibration exposure has to be considered as a health hazard to the lumbar spine, and it is shown that the probability of lumbar syndromes caused by occupational vibration exposure rises with increasing vibration dose. The calculation of a total vibration dose proved to be a valuable predictor for degenerative processes of the lumbar spine caused by vibration exposure. The observation which had been made in other studies, that the current limit value for daily reference exposure $a_{zw(8h)} = 0{\cdot}8\ \mathrm{m/s^2}$ is too high can be supported by this study [21]. The harmful effect of whole-body vibration yields a significant increase of cases of lumbar syndrome already with vibration exposure values of $a_{zw(8h)} > 0{\cdot}6\ \mathrm{m/s^2}$ (daily reference exposure). Therefore, the national and international regulations and standards in question should be reconsidered.

In the follow-up, the incidence rates of lumbar radicular syndromes were higher than those of local lumbar syndromes, whereas the respective prevalence rates of the first phase showed just the inverse proportion. Presumably, subjects with radicular symptoms have a higher probability of leaving their job than those with more general symptoms, because radicular symptoms usually are regarded as being more serious. This leads to a differential selection of the population exposed, so that the workers remaining at the working place represent a selection of individuals with better constitution.

The present study was able to confirm that a considerable number of cases of lumbar syndrome (about 27 to 35%) can be attributed to whole-body vibration. As spinal disorders are a very common cause of working inability (in Germany about 10% of *cases* of temporary disability, about 30% of the total *number of days* regarding temporary disability, and about 50% of cases of permanent disability [22]), preventive action programs are of high importance.

Prevention should not only be based on better medical surveillance with the intention to detect those subjects who are at higher risk. As there are no specific signs which might help to distinguish age-related from vibration-related effects, too many subjects would need protection, e.g., a change of job or extra periods of recreation. The technical aspects of prevention must take priority by reducing the impact of vibration so that the threshold for the risk of health effects will not be exceeded for longer periods of time.

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