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An overview of low back pain and occupational exposures to whole-body vibration and mechanical shocks

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Parole chiave: Rachide lombare; vibrazioni meccaniche; epidemiologia; biodinamica

Summary

This paper offers an overview of the relation of low back pain (LBP) to occupational exposures to whole-body vibration (WBV) and mechanical shocks. LBP is a condition of multifactorial origin and is a very common health problem in the general population. Among occupational risk factors, epidemiological studies of driving occupations have provided evidence for strong associations between LBP and occupational exposures to WBV and mechanical shocks. Since it is hard to separate the contribution of WBV exposure to disorders in the lower back from that of other individual, ergonomic or psychosocial risk factors, a quantitative exposure-response relationship for WBV cannot be outlined precisely. Experimental research has provided biodynamic support to the findings of epidemiological studies, showing that in controlled laboratory conditions exposure to WBV can cause mechanical overload to the human spine. The EU Directive on mechanical vibration has established daily exposure action and limit values to protect the workers against the risk from WBV. There is some evidence that the EU exposure limit values are excessive, so much so that an elevated risk of LBP has been found for WBV exposures beneath the EU limit values. In the Italian arm of the EU VIBRISKS prospective cohort study of professional drivers, measures of internal lumbar load (compressive and shear peak forces), calculated by means of anatomy-based finite-element models, were found better predictors of the occurrence over time of low back disorders than the metrics of external exposure suggested by the EU Directive on mechanical vibration. Further biodynamic and epidemiological studies are needed to validate the findings of the VIBRISKS study.

Riassunto

***«Lombalgia ed esposizione occupazionale a vibrazioni trasmesse al corpo intero e a shock meccanici: considerazioni sullo stato dell'arte»**. Questo studio riporta una revisione della letteratura sulla relazione tra lombalgia (low back pain, LBP) ed esposizione occupazionale a vibrazioni trasmesse al corpo intero (whole-body vibration, WBV) e a shock meccanici. LBP è un sintomo di origine multifattoriale molto frequente nella popolazione generale. Tra i fattori di rischio occupazionali, gli studi epidemiologici hanno evidenziato significative associazioni tra LBP e esposizione a WBV e shock meccanici negli autisti di macchine industriali o agricole e di veicoli di pubblica utilità. Poiché è*

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arduo separare il contributo indipendente di WBV nell'occorrenza di LBP da quello di altri fattori avversi di origine individuale, ergonomica o psicosociale, una precisa relazione esposizione-risposta per WBV è di difficile definizione. Le ricerche sperimentali hanno fornito supporto biodinamico ai risultati degli studi epidemiologici, evidenziando che in laboratorio l'esposizione controllata a WBV provoca sovraccarico meccanico del rachide lombare. La Direttiva Europea 2002/44/CE sulle vibrazioni meccaniche ha stabilito valori giornalieri di azione e valori limite giornalieri di esposizione contro il rischio da WBV. Vi è evidenza sperimentale e epidemiologica che i valori limite di esposizione della Direttiva EU sono eccessivamente elevati, tant'è che un significativo rischio di LBP è stato osservato per esposizioni a WBV inferiori ai valori limiti EU. In uno studio prospettico di coorte realizzato nell'ambito del progetto europeo VIBRISKS, misure delle forze spinali (di compressione e di taglio) generate dall'esposizione a WBV (dose interna) si sono rivelate migliori predittori dell'occorrenza di LBP rispetto alle metriche di esposizione esterna della Direttiva EU sulle vibrazioni meccaniche. Questi risultati necessitano, tuttavia, di ulteriori validazioni da parte sia della sperimentazione biodinamica sia dell'osservazione epidemiologica.

Introduction

Low back pain (LBP) is a symptom frequently experienced by people over their lifetime. Epidemiological surveys of LBP in the general population have found that the point prevalence of LBP ranges from 1.0% to 58.1% (mean: 18.1%) and 1-year prevalence from 0.8% to 82.5% (mean: 38.1%), (31). Estimates of 1-year incidence of any episosode of LBP range between 1.5 to 36%, and recurrence at 1 year vary from 24 to 80% (31). LBP is associated with activity limitation, work absenteeism, and disability. The Global Burden of Disease 2010 Study has reported that LBP causes more disability, expressed as years lived with disability (YLDs), than any other condition: it has been estimated that YLDs from LBP has increased from 58.2 millions in 1990 to 83.0 millions in 2010 worldwide (32, 40). Prevalence and burden of LBP tend to increase with age and are greater in males than in females.

LBP is a condition of multifactorial origin and several individual-, social-, and work-related risk factors have been found to be associated with the occurrence of this symptom, e.g. age, gender, anthropometric characteristics, previous back traumas, educational level, physical work load, whole-body vibration (WBV), and psychosocial and psychological risk factors. Focusing on labour force in Europe, data from the Fifth European Working Condition Survey (EWCS 2010) showed that among 35476 subjects who had been at work (as an employee or employer/self-employed) during the past week, the overall 1-year prevalence of (low) back pain was 46.1% (95% CI 45.5-46.6), (26, 27). Prevalence estimates by occupation varied from 32.7% (armed forces) to 62.3% (agricultural, fishery and related labourers).

In the EWCS 2010 investigation, prolonged working time ("almost all of the time" or "all of the time") entailing carrying or moving heavy loads, lifting or moving people, or exposure to vibration was associated with the highest prevalences of (low) back pain (66.2%, 61.3%, and 61.2%, respectively, among workers aged ≥15 yr and resident in 34 European countries), (27). These findings are in accordance with the results of systematic reviews and meta-analyses which concluded for an epidemiological evidence for a causal relationship between (low) back disorders and work-related lifting/forceful movements, awkward posture, heavy physical work, or exposure to WBV, (table 1) (19, 39, 41).

Table 1 - Epidemiological evidence for occupational risk factors associated with (lower) back disorders according to NIOSH, 1997 (41)

Risk factors	Strong evidence	Evidence	Insufficient evidence
Lifting/forceful movements	✓		
Awkward posture		✓	
Heavy physical work		✓	
Static work posture			✓
Whole-body vibration	✓		

LBP and occupational exposure to WBV

According to EWCS 2010 by Eurofound (26), about 23-25% of all workers interviewed during the survey reported being exposed to mechanical vibration in the workplaces of the European Union (EU). Among vibration exposed men (35% of the male workforce), about 20% were exposed to mechanical vibration all or nearly all of the time during a workshift, and about 15% around ¼ or more of the time. Among vibration exposed women (10% of the female workforce), about 5% were exposed to mechanical vibration all or nearly all of the time during a workshift, and about 5% around ¼ or more of the time.

In epidemiological studies of working populations and occupational groups, disorders of the lumbar spine and the connected nervous system have been found to be related to long-term exposures to WBV, (8, 9, 19). In the EWCS 2010 investigation, drivers and mobile-plant operators (n=825) showed the highest prevalence ratio, adjusted for individual-level risk factors, for (low) back pain when compared with the reference category of teaching professionals (aPR 1.36; 95% CI 1.18 – 1.58), (27). Driving tasks entail exposure to WBV, and in several European Countries, (low) back disorders occurring in professional drivers or machinery operators are, under certain conditions regarding intensity and duration of exposure to WBV, considered to be an occupational disease which may be compensated according to the regulations adopted by the national legislations (38).

The role of WBV in the etiopathogenesis of low back disorders is not yet fully clarified since driving vehicles involves not only exposure to harmful WBV but also to postural load, which is known to strain the lower part of the back (16). Individual characteristics (e.g. age, anthropometry, smoking habit, constitutional susceptibility), and previous back traumas are also recognised as important predictors for low back disorders, while the influence of psychosocial risk factors is still uncertain (29). Since disorders of the lower back are conditions of multifactorial origin, it is hard to separate the contribution of WBV exposure to the onset and the development of low back troubles from that of other individual, ergonomic or psychosocial risk factors. Nevertheless, epidemiological investigations of specific driving occupations (e.g. operators of agricultural, forestry or industrial machinery, drivers of public utilities vehicles) have consistently shown significant associations between lower back disorders and exposure to WBV when this latter has been measured and evaluated with appropriate metrics of intensity and duration of vibration (5, 9).

Epidemiological reviews have suggested that there is strong evidence for an association between occupational exposure to WBV and an increased risk of (low) back pain, sciatic pain, and degenerative changes in the spinal system, including lumbar intervertebral disc disorders (8, 19, 20). In a personal updated meta-analysis of cross-sectional studies published between 1986 and 2014 (9), the combined prevalence odds ratio (POR) for 12-month prevalence of LBP, adjusted at least for age, was estimated to be 1.87 (95% CI 1.52-2.30) in 28 driver groups with occupational exposure to WBV when compared with unexposed groups (figure 1). The combined POR for 12-month prevalence of sciatic pain in 12 driving occupations with exposure to WBV was 1.67 (95% CI 1.25-2.23) compared to controls groups, (figure 2). These findings are consistent with the results of a recent meta-analysis of 20 epidemiological studies which concluded for scientific evidence that occupational exposure to WBV increases significantly the risk of LBP and sciatica with pooled estimates showing approximately a double risk for both outcomes (19). It should be reminded, however, that meta-analyses of cross-sectional studies may suffer from several drawbacks such as the heterogeneity between studies, the effects of "healthy worker" selection or survival, the lack of control of potential confounders, or possible publication bias.

Owing to the cross-sectional design of most studies of LBP in WBV-exposed workers, it is hard to outline a clear quantitative exposure-response relationship for WBV. Nevertheless, recent prospective cohort studies and meta-analytic reviews have provided some elements of positive exposure-response relationship revealing a trend of increasing LBP occurrence with increasing WBV exposure in workers with high vibration levels compared to those with low vibration levels (5, 8, 19).

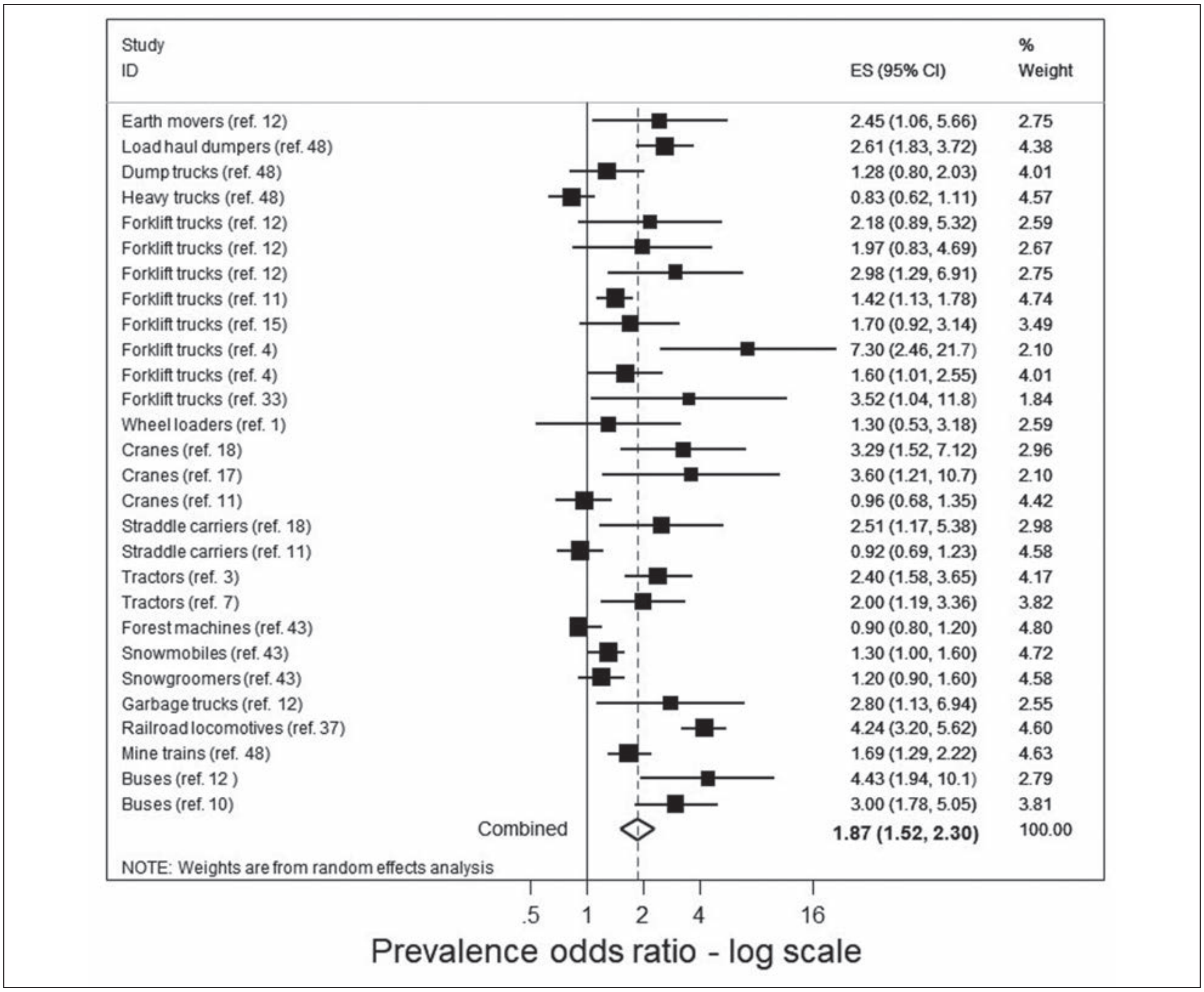

Figure 1 - Effect size (ES) in terms of prevalence odds ratios (POR) and 95% confidence intervals (95% CI) for 12-month prevalence of low back pain in 28 driving occupations with exposure to whole-body vibration (WBV) compared to control groups. The area of each box is inversely proportional to the estimated variance in each study. Random effects estimation of the combined POR and 95% CI is shown [adapted from (9)]

Some studies have tried to control for confounding by known causes of (low) back disorders. For instance, in an epidemiological survey of 1155 tractor drivers and 220 controls unexposed to WBV (7), cumulative vibration exposure and postural load were found to be independently associated with "chronic" low back pain defined as daily experience of low back pain or several episodes of low back pain lasting more than 30 days in the previous 12 months (table 2). A significant trend was found with higher levels of both vibration dose and postural load, such that tractor drivers with high exposure to both factors had a more than threefold elevated risk of chronic low back pain relative to controls exposed to mild postural load and unexposed to vibration (table 3).

There is experimental evidence that concomitant exposure to WBV and awkward posture can give rise to an excess of compressive load and shear stress on the soft and bone tissues of the spine (24, 28). Frequency analysis of the vibration recorded on the seats of most industrial machines and vehicles has shown acceleration peaks at the frequencies of 1.25-

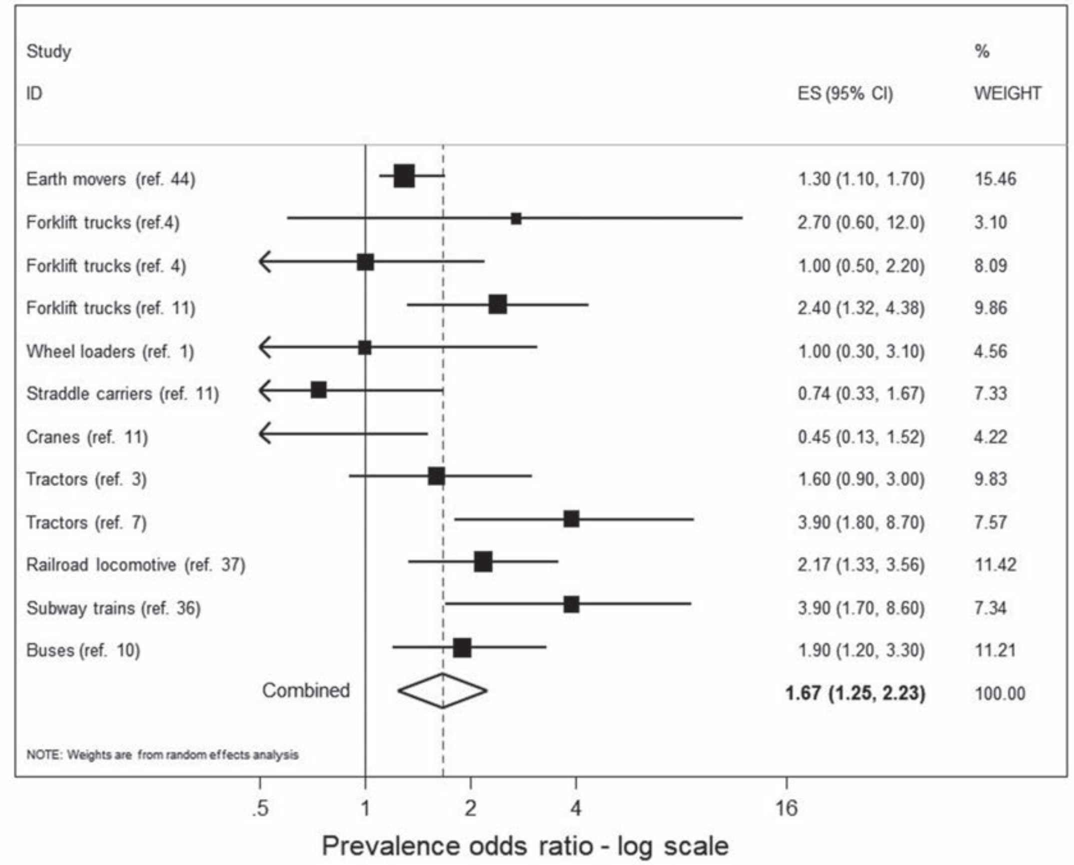

Figure 2 - Effect size (ES) in terms of prevalence odds ratios (POR) and 95% confidence intervals (95% CI) for 12-month prevalence of sciatic pain in 12 driving occupations with exposure to whole-body vibration (WBV) compared to control groups. The area of each box is inversely proportional to the estimated variance in each study. Random effects estimation of the combined POR and 95% CI is shown

5 Hz (24, 28). Biodynamic experiments have shown that in a seated subject exposed to vertical vibration the lumbar tract of the spine has a resonance in the frequency range between 2 and 6 Hz (28). Since under resonance large relative displacements between the lumbar vertebrae take place, it is likely that the lumbar spine of professional drivers is overloaded by mechanical vibration during operating conditions.

Overall, biodynamic and physiological experiments have shown that seated vibration exposure can affect the spine by mechanical overloading and excessive muscular fatigue, supporting the epidemiological findings of a possible causal role of WBV in the development of (low) back troubles (28).

LBP and measures of external exposure to WBV

The EU Directive on mechanical vibration provides qualitative and quantitative guidance to protect workers against the risks arising from exposure to vibration at work. In the EU Directive, WBV is defined as '*the mechanical vibration that, when transmitted to the whole body, entails risks to the health and safety of workers, in particular lower-back morbidity and trauma of the spine*' (23).

The human response to vibration depends on the physical characteristics (magnitude, frequency, direction) and the duration of the vibration (28). To

Table 2 - Effects of cumulative vibration exposure and postural load on chronic low back pain in a population of 1155 tractor drivers and 220 controls unexposed to whole-body vibration (WBV). Adjusted odds ratios (aOR) and 95% confidence intervals (95% CI) were estimated by multivariable logistic regression analysis (7)

Cumulative WBV exposure (years m^2s^{-4})[a]	aOR (95% CI)	Postural load (grade)	aOR (95% CI)
0 (n=220)	1.0 (–)	Mild (n=96)	1.0 (–)
<15 (n=335)	1.48 (0.87-2.50)	Moderate (n=231)	1.20 (0.60-2.40)
15-30 (n=374)	1.90 (1.13-3.20)	Hard (n=450)	1.61 (0.82-3.16)
>30 (n= 446)	2.00 (1.17-3.40)	Very hard (n=598)	2.30 (1.17-4.54)

aORs adjusted by age, body mass index, smoking, education, sporting activity, car driving, marital status, mental stress, climatic conditions, and previous back trauma.

[a]Cumulative vibration exposure was estimated as $\sum a_{vi}^2 t_i$, where a_{vi} is the vibration total value (or vector sum) of the frequency-weighted r.m.s. acceleration magnitudes of tractor *i* and t_i is the number of full-time working years driven on tractor *i* (year m^2s^{-4}).

Table 3 - Odds ratio estimates for the combined effect of selected values of cumulative whole-body vibration (WBV) exposure and postural load on the occurrence of chronic low back pain in tractor drivers [7, with reference to controls exposed to mild postural load and unexposed to WBV]

Cumulative WBV exposure (years m^2s^{-4})	Postural load (grade)			
	Mild	Moderate	Hard	Very hard
5	1.29	1.79	2.50	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

Table 4 - Daily exposure action values and daily exposure limit values for whole-body vibration (WBV) according to the European Directive 2002/44/EC on mechanical vibration and the Italian Law for safety and health at the workplace (Decree No. 81-2008). *A*(8) is the daily vibration exposure value normalised to an eight-hour reference period, and VDV is the Vibration Dose Value

Vibration exposure values	WBV
Daily exposure action value	*A*(8)=0.5 ms^{-2} r.m.s. VDV=9.1 $ms^{-1.75}$
Daily exposure limit value	*A*(8)=1.15 ms^{-2} r.m.s.(EU) 1.0 ms^{-2} r.m.s. (Italy) VDV=21 $ms^{-1.75}$
Exposure for a short period	1.5 ms^{-2} r.m.s. (Italy)

account for the differences in the response of the body (and the lumbar spine) to vibration frequency, current standards for human vibration recommend to weight the frequencies of the measured vibration according to the possible deleterious effects associated with each frequency. Frequency weightings are required for three orthogonal directions (*x*-, *y*- and *z*-axes) at the interfaces between the body and the vibration, in accordance with the international standard ISO 2631-1 (34).

The EU Directive 2002/44/EC has established "daily exposure action values" (EAV_d) and "daily exposure limit values" (ELV_d) for WBV (table 4), (23). Workers shall not be exposed above the ELV_d. If the EAV_d are exceeded, the employers shall implement administrative, technical and medical measures with the aim to protect workers against the risks from excessive exposure to WBV. According to the EU Directive, workers exposed to mechanical vibration in excess of the EAV_d are entitled to appropriate health surveillance.

In the EU Directive, two different metrics are suggested to evaluate daily vibration exposure. The metric *A*(8) is the eight-hour energy-equivalent frequency-weighted root-mean-square (r.m.s.) acceleration (ms^{-2}), and for WBV exposure is calculated as:

$$A(8)_{max} = \left(\sum_i a^2_{wi(max)} \times \frac{t_{di}}{T_{(8)}}\right)^{1/2} \quad (ms^{-2}\, r.m.s.) \quad (eqn. 1)$$

where $a^2_{wi(max)}$ is the greatest weighted r.m.s. acceleration for exposure condition i determined on three orthogonal axes (1.4 a_{wx}, 1.4 a_{wy}, or a_{wz} for a seated worker), t_{di} is the duration of daily exposure to condition i, and $T_{(8)}$ is a reference duration of 8 h.

Moreover, the EU Directive suggests the Vibration Dose Value (VDV) of the frequency-weighted accelerations as an alternative measure of daily WBV exposure. The VDV is a cumulative dose, based on the fourth power averaging of the acceleration time history (root-mean-quad (r.m.q.) method) and is expressed in $ms^{-1.75}$. VDV is considered a better indicator of the risks arising from exposures to vibration containing peaks or shocks. VDV is calculated as follows:

$$VDV_{\max} = \left[\int_{t=0}^{t=T} a^4_{w(\max)}(t)\,\mathrm{d}t \right]^{\frac{1}{4}} \quad (ms^{-1.75}) \qquad (eqn.\ 2)$$

where $a^4_{w(max)}$ is the greatest weighted r.m.q. acceleration determined on three orthogonal axes (1.4 a_{wx}, 1.4 a_{wy}, or a_{wz} for a seated worker), and T is the duration of the vibration exposure in seconds.

For exposure to WBV, the EU EAV_d is set at either $A(8)_{max}$ 0.5 ms^{-2} r.m.s. or VDV_{max} 9.1 $ms^{-1.75}$ (table 4). The EU ELV_d, that is the exposure value which shall never be exceeded, is set at either $A(8)_{max}$ 1.15 ms^{-2} r.m.s. or VDV_{max} 21 $ms^{-1.75}$. These figures are higher than those recommended in an annex to international standard ISO 2631-1 dedicated to the effects of WBV on health (table 5), (25, 34). Whilst there is some evidence, based on experimental observations and experience of fatigue-related work interference, for the EAV_d $A(8)_{max}$ 0.5 ms^{-2} r.m.s., in opposite there is neither biomechanical nor epidemiological validation for the ELV_d $A(8)_{max}$ 1.15 ms^{-2} r.m.s., so much so that an elevated risk of LBP has been found for WBV exposures beneath this limit value. Wisely, the Italian law has lowered the ELV_d $A(8)_{max}$ to 1 ms^{-2} r.m.s., and a limit of 1.5 ms^{-2} r.m.s. has been introduced for exposures of short period to prevent WBV-related acute health effects (table 4), (21). The German law has lowered the ELV_d $A(8)$ in the vertical axis to 0.8 ms^{-2} r.m.s. (51).

The national laws of European countries have, in general, adopted $A(8)_{max}$ as the preferred measure of daily exposure to WBV. It has been argued that $A(8)_{max}$, compared with VDV_{max}, may underestimate the adverse health effects of WBV in presence of vibration peaks, shocks, or repetitive shocks. Moreover, the choice of a single (highest) vibration axis to calculate $A(8)$ or VDV has been debated, since multi-axis vibration, calculated as the root-sums-of-squares of the r.m.s. acceleration values, also known as vector sum $a_{wsum} = [(1.4\ a_{wx})^2 + (1.4\ a_{wy})^2 + (a_{wz})^2]^{0.5}$, might be more appropriate for certain types of machines or vehicles with comparable vibration in two or more axes.

In a four-year research project entitled "*Risks of Occupational Vibration Injuries*" (VIBRISKS) and funded by the EU Commission (52), we have measured WBV in a representative sample of mobile-plant machinery and transport vehicles (n=68) used by three groups of professional drivers of earth-moving machines, fork-lift trucks, or public utilities vehicles (n=202), who were free of LBP at the cross-sectional survey (6). Paired data comparison showed that the difference between multi-axis vibration acceleration and the most severe axis acceleration was highly significant ($p<0.001$). In each driver group, $A(8)_{sum}$ and VDV_{sum} were significantly greater than

Table 5 - Health guidance caution zones: exposure boundaries for whole-body vibration (WBV) suggested in Annex B to international standard ISO 2361-1 (34). $A(8)$ is the daily vibration exposure value normalised to an eight-hour reference period, and VDV is the Vibration Dose Value

Health risks	Level of risk	ISO standard 2631-1	
		$A(8)$ (ms^{-2} r.m.s.)	VDV ($ms^{-1.75}$)
Not clearly documented and/or objectively observed health effects	Low	<0.45	<8.5
Potential health effects	Moderate	0.45-0.90	8.5-17
Likely health effects	High	>0.90	>17

$A(8)_{max}$ and VDV_{max}, respectively ($p<0.001$). In this study, 23 drivers (11.4%) were exposed to $A(8)_{max}$ greater than the EAV_d of 0.5 ms^{-2} r.m.s., while this figure increased to 48 drivers (23.8%) when the EAV_d was expressed in terms of $A(8)_{sum}$, and to 65 drivers (32.2%) when the EAV_d was expressed as VDV_{max} (table 6). As a result, in this study about 21% of the drivers would be excluded from prevention programmes if $A(8)_{max}$, instead of VDV_{max}, was chosen as the preferred measure of daily vibration exposure. A greater number of drivers (n=80, 39.6%) would be eligible for compulsory health surveillance if VDV was estimated on the basis of summation over axes (VDV_{sum}). To support the opinion that health surveillance should not be limited to workers exposed to $A(8)_{max}$ > 0.5 ms^{-2} r.m.s., figure 3 shows that the cumulative incidence of 12-month LBP, high pain intensity and disability in the lower back of the professional drivers tended to increase progressively from $A(8)_{max}$ to VDV_{sum} for daily vibration exposure greater than the action values established by the EU Directive. Since most of the European countries have adopted $A(8)_{max}$ as the basic metric for the assessment of daily vibration exposure, this fact is a matter of concern for the protection of the health of people occupationally exposed to WBV.

LBP AND MEASURES OF INTERNAL SPINAL LOAD

The metrics $A(8)$ and VDV are measures of "external" vibration exposure and it may be assumed that they reflect only partially the internal forces acting on the anatomical structures of the lumbar spine. Moreover, it is unlikely that measures of daily vibration exposure are suitable for the assessment of the risk of long-term adverse health effects such as disorders of the lumbar spine. Since disorders of the lower back and the connected nervous system are of multifactorial origin in driving occupations, it has been argued that the measures of daily vibration exposure established by ISO 2631-1 (34) and the EU Directive (23) do not sufficiently consider the influence of other co-factors on the risk of low back disorders such as age, anthropometric characteristics, postures, and lifetime duration of WBV exposure which are additional risk factors for the development of adverse health effects in the spine of the exposed workers (47). On the basis of these considerations, dynamic finite-element (FE) models have been suggested to predict internal spinal forces acting on the lumbar spine during occupational exposures to WBV (42, 46, 47). FE-modelling of the spinal response to WBV has been validated by

Table 6 - Distribution of the drivers according to the daily exposure action values established by the EU Directive on mechanical vibration. Data are given as numbers (%) [6]. $A(8)$ is the daily vibration exposure value normalised to an eight-hour reference period, and VDV is the Vibration Dose Value

Measures of daily vibration exposure	Drivers			
	Earth movers (n=49)	Fork lift trucks (n=67)	Utility vehicles (n=86)	Total sample (n=202)
$A(8)_{max}$ (ms^{-2} r.m.s.)				
<0.5	39 (79.6)	54 (80.6)	86 (100)	179 (88.6)
>0.5	10 (20.4)	13 (19.4)	0 (0)	23 (11.4)
$A(8)_{sum}$ (ms^{-2} r.m.s.)				
<0.5	20 (40.8)	48 (71.4)	86 (100)	154 (76.2)
>0.5	29 (59.2)	19 (28.4)	0 (0)	48 (23.8)
VDV_{max} ($ms^{-1.75}$)				
<9.1	19 (38.8)	32 (47.8)	86 (100)	137 (67.8)
>9.1	30 (61.2)	35 (52.2)	0 (0)	65 (32.2)
VDV_{sum} ($ms^{-1.75}$)				
<9.1	14 (28.6)	31 (46.3)	77 (89.5)	122 (60.4)
>9.1	35 (71.4)	36 (53.7)	9 (10.5)	80 (39.6)

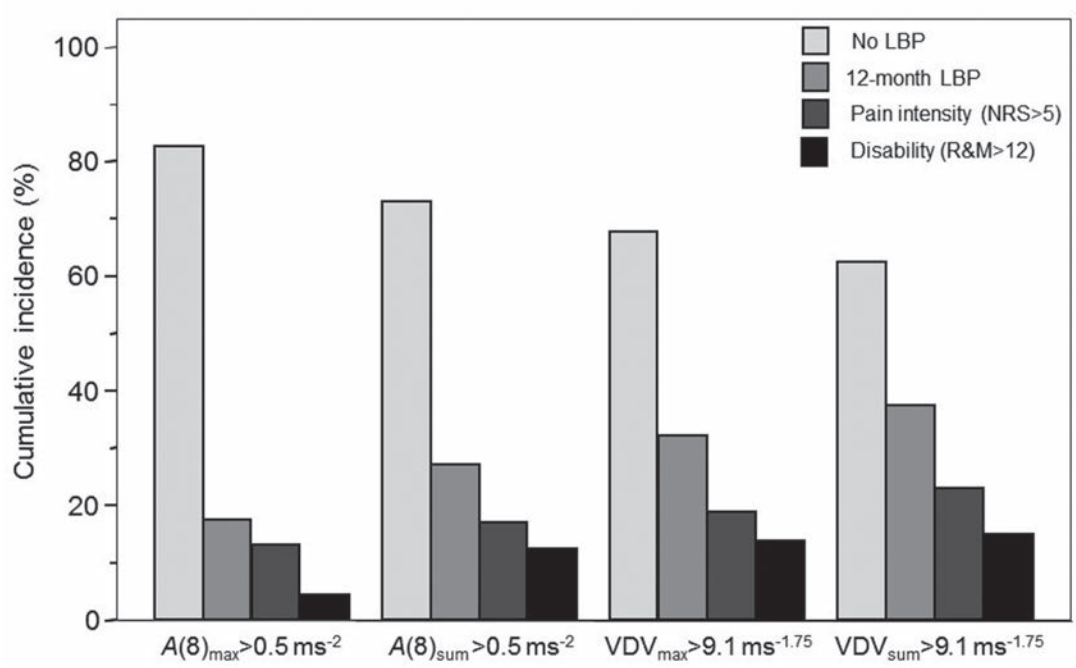

Figure 3 - Cumulative incidence of 12-month low back pain (LBP), high pain intensity (Numerical Rating Scale (NRS) score > 5), and disability due to the last episode of LBP in the previous 12 months (Roland and Morris (R&M) disability scale score > 12) in the professional drivers according to measures of daily vibration exposure dichotomised at the daily exposure action values established by the Directive of the European Union on mechanical vibration. $A(8)_{max}$ (highest axis) and $A(8)_{sum}$ (root-sum-of-squares) are the 8-h energy-equivalent frequency-weighted acceleration magnitude in ms^{-2} r.m.s., respectively. VDV_{max} (highest axis) and VDV_{sum} (root-sum-of-quads) in $ms^{-1.75}$ are the Vibration Dose Value, respectively (6)

experimental laboratory research on human biodynamics (42, 47). Compared with other biodynamic models, dynamic FE-models are closely related to the anatomy of the lumbar spine region and have been adapted to different sitting postures and individual anthropometric data of representative groups of European drivers (30).

Recently, a method for the evaluation of occupational exposures to WBV containing multiple shocks has been proposed in a Committee Draft of International Standard ISO/CD 2631-5 (35). The spinal response to vibration is predicted by means of the calculation of internal vertebral forces on the basis of transfer functions between unweighted vibration accelerations and vertebral forces determined by anatomy-based FE models. The derived metrics for the assessment of the risk to the lumbar spine are expressed in terms of daily compressive dose S_{ed} (MPa) and risk factor R (non-dimensional units) calculated from the static gravitational force acting on the vertebral endplates, the vibration-related peaks of the dynamic compressive vertebral forces, and other factors such as the individual characteristics (age, body mass, body mass index, size of the bony vertebral endplates), the duration of vibration exposures and the postures of the drivers.

The daily compressive dose S_{ed} (MPa) is calculated according to the following equation (35):

$$S_{ed} = \left(\sum_i S_i^6 \times \frac{t_{di}}{t_{mi}} \right)^{1/6} \quad (MPa) \qquad (eqn. 3)$$

where, S_i is the dynamic compressive stress due to vibration for the exposure to condition (vehicle) i defined as the sum of peak compressive forces acting on the area of a vertebra endplate (cm^2), t_{di} is the duration of the daily exposure to condition (vehicle) i, t_{mi} is the period over which S_i has been calculated based on measurement, and i is the counter of exposure conditions (vehicles).

The 6th power method to calculate S_{ed} is based on the Palmgren-Miner model with reference to fatigue fractures caused by repeated compressive loading of the human spine (35).

The risk factor R (non-dimensional units) is a metric for the assessment of adverse health effects related to the compressive dose. For constant exposure pattern per day, the risk factor R is calculated as follows (35):

$$R = \left[\sum_{j=1}^{n}\left(\frac{S_{ed} \times N_j^{1/6}}{S_{uj} - C_{stat}}\right)^6\right]^{1/6} \qquad (eqn. 4)$$

where, S_{ed} is the daily compressive dose (MPa), S_{uj} is the ultimate strength of lumbar spine endplates (MPa) for a person of age (age_{init} + j) where age_{init} is the age at which the exposure started and j is the year counter, C_{stat} is the static compressive stress due to gravitational force as a function of body mass, body mass index (BMI), and posture, N is the number of exposure days per year, and n is the number of exposure years. For variable exposure patterns during a year, the compressive dose per year can be calculated in analogy to the compressive dose per day, and the risk factor R relies on the compressive dose per year.

For practical use, a software tool has been developed to simplify the calculations of the internal forces and the derived daily compressive dose S_{ed} and risk factor R. The tool, including an user guide, has been published in DIN SPEC 45697 (22).

In the Italian arm of the above-mentioned EU VIBRISKS study (13, 14, 52), we carried out a prospective cohort study of professional drivers with the aims (i) to validate from an epidemiological viewpoint the measures of internal spinal load for the assessment of the adverse health effects of vibration, and (ii) to compare the relative performance of measures of external dose ($A(8)_{max}$ and VDV_{max} according to the EU Directive) with those of internal spinal load (S_{ed} and R factor according to ISO/CD 2631-5) for the prediction of low back symptoms (13, 14, 23).

The occurrence of low back symptoms were investigated in a cohort of 537 drivers at baseline and over a two-year follow up period. Low back outcomes (low back pain, sciatic pain), individual characteristics (age, anthropometry), and work-related risk factors (physical work load, psychosocial work environment) were investigated with a structured questionnaire.

LBP was defined as pain or discomfort in the low back area between the twelfth ribs and the gluteal folds (showed in a body map), lasting at least 7 days in the previous 12 months. Sciatic pain was defined as radiating pain in one or both legs (below the knee) in the previous 12 months. The two forms of low back outcomes were treated as mutually exclusive in data analysis.

Exposures to WBV was evaluated by means of measures of external dose ($A(8)$ and VDV) and measures of internal lumbar load (S_{ed} and risk factor R), according to *eqn. 1 – 4*.

At the cross-sectional survey the prevalences of LBP and sciatic pain in the 537 professional drivers were 12.7 and 23.1%, respectively. Over the follow up period, there were 79 new cases of low back pain and 90 new cases of sciatic pain, giving rise to cumulative incidences of 16.8 and 21.8%, respectively.

Multivariable longitudinal logistic regression analysis by means of the generalised estimating equations method for repeatead measures over time showed significant positive associations between 12-month low back outcomes and the measures of internal lumbar load (S_{ed} and mainly R factor) expressed as continuous variables (table 7). For a change of 0.1 units for the R factor, the adjusted risk estimates increased by 28% for low back pain and 32% for sciatic pain. No associations were found for the measures of external dose ($A(8)_{max}$ and VDV_{max}). When occupational risk factors were included as quartile-based design variables in the longitudinal logistic models, internal lumbar load (R factor) and physical work load, but not psychosocial work environment, were significatly associated with low back outcomes (table 8).

To assess the risk of fatigue fractures of the vertebral endplates caused by mechanical loading, in ISO/CD 2361-5 only the predicted compressive (vertical) forces are considered, while shear (lateral and anterior-posterior) forces are not taken into account (35). In the EU VIBRISKS study, WBV exposures gave rise to shear forces of quite high magnitudes and comparable to those in the compressive direction (45). In the professional drivers, the meas-

Table 7 - Relationships of 12-month low back outcomes to measures of external whole-body vibration (WBV) exposure according to the EU Directive ($A(8)_{max}$, VDV_{max}) and measures of internal lumbar load according to ISO/CD 2631-5 (S_{ed}, *R* factor). Odds ratios, crude (cOR) and adjusted by confounders (aOR), and robust 95% confidence intervals (95% CI) are estimated by means of longitudinal logistic regression models [14]. *A*(8) is the daily vibration exposure value normalised to an eight-hour reference period; VDV is the Vibration Dose Value; S_{ed} is the daily compressive dose; R is the Risk factor

12-month low back outcomes	Measures of WBV exposure	cOR (95% CI)	aOR (95% CI)
Low back pain	$A(8)_{max}$ ($ms^{-2}\times10^{-1}$)	0.99 (0.87–1.13)	0.94 (0.83–1.08)
	VDV_{max} ($ms^{-1.75}$)	0.98 (0.93–1.04)	0.95 (0.90–1.01)
	S_{ed} (MPa × 10^{-1})	1.17 (0.95–1.44)	1.09 (0.86–1.38)
	R factor (units × 10^{-1})	1.26 (1.08–1.47)	1.28 (1.08–1.51)
Sciatic pain	$A(8)_{max}$ ($ms^{-2}\times10^{-1}$)	1.08 (0.96–1.22)	1.06 (0.94–1.18)
	VDV_{max} ($ms^{-1.75}$)	1.01 (0.96–1.06)	1.00 (0.95–1.04)
	S_{ed} (MPa × 10^{-1})	1.35 (1.13–1.61)	1.30 (1.07–1.58)
	R factor (units × 10^{-1})	1.33 (1.17–1.52)	1.32 (1.15–1.52)

$A(8)_{max}$ - VDV_{max}: OR adjusted by age at entry, body mass index, full-time driving years, physical work load, psychosocial work environment, herniated lumbar disc, lumbar trauma, and follow up time.
S_{ed}: OR adjusted by age at entry, full-time driving years, physical work load, psychosocial work environment, herniated lumbar disc, lumbar trauma, and follow up time.
R factor: OR adjusted by physical work load, psychosocial work environment, herniated lumbar disc, lumbar trauma, and follow up time.

Table 8 - Relationships of 12-month low back outcomes to measures of internal lumbar load according to ISO/CD 2631-5 (*R* factor), physical work load, and psychosocial work environment. Odds ratios adjusted by confounders (aOR), and robust 95% confidence intervals (95% CI) are estimated by means of longitudinal logistic regression models (14)

Factors	12-month low back pain aOR (95% CI)	12-month sciatic pain aOR (95% CI)
R factor (units)		
0.07-0.19	1.0 (-)	1.0 (-)
0.20-0.27	0.73 (0.43-1.27)	1.09 (0.72-1.65)
0.28-0.40	1.09 (0.65-1.84)	1.57 (0.99-2.48)
0.41-0.72	1.83 (1.07-3.13)	2.13 (1.36-3.36)
Physical work load		
mild	1.0 (-)	1.0 (-)
moderate	1.34 (0.85-2.11)	1.46 (1.04-2.06)
hard	1.59 (1.01-2.50)	1.72 (1.23-2.41)
very hard	2.09 (1.35-3.24)	2.03 (1.46-2.83)
Psychosocial work environment		
good	1.0 (-)	1.0 (-)
reasonable	0.68 (0.43-1.09)	0.87 (0.58-1.29)
a little poor	0.71 (0.45-1.10)	0.86 (0.60-1.24)
poor	1.05 (0.64-1.71)	1.39 (0.91-2.13)

aOR adjusted by herniated lumbar disc, lumbar trauma, and follow up time

ures of shear forces in the anterior-posterior directions were found to be significantly related to the occurrence of LBP and sciatic pain (table 9). These epidemiological findings seem consistent with those of in-vitro experiments reporting fatigue-induced injuries in the soft and hard tissues of human lumbar spine specimens exposed to anterior-posterior shear loads (49, 50).

Table 9 - Relationships of 12-month low back outcomes to internal lumbar shear peak forces expressed as equivalent daily dose* measured in the anterior ($S_{ed,F}$(a)), posterior ($S_{ed,F}$(p)), and lateral ($S_{ed,F}$(l)) directions. Odds ratios, crude (cOR) or adjusted by confounders (aOR), and robust 95% confidence intervals (95% CI) are estimated by means of longitudinal logistic models

12-month low back outcomes	Measures of internal lumbar shear stress	cOR (95% CI)	aOR (95% CI)
Low back pain	$S_{ed,F}$(a) (× 100 N)	1.36 (1.11-1.67)	1.25 (1.01-1.54)
	$S_{ed,F}$(p) (× 100 N)	1.38 (1.11-1.73)	1.28 (1.01-1.62)
	$S_{ed,F}$(l) (× 100 N)	1.28 (0.91-1.79)	1.22 (0.84-1.78)
Sciatic pain	$S_{ed,F}$(a) (× 100 N)	1.34 (1.13-1.58)	1.25 (1.05-1.50)
	$S_{ed,F}$(p) (× 100 N)	1.46 (1.20-1.76)	1.38 (1.13-1.69)
	$S_{ed,F}$(l) (× 100 N)	1.23 (0.92-1.64)	1.25 (0.92-1.69)

$$* \, S_{ed,F}(a,p,l) = \left(\sum_i S^6_{(a,p,l),i} \times \frac{t_{d,i}}{t_{m,i}}\right)^{\frac{1}{6}}$$

where $S_{(a,p,l),i} = \left(\sum_i \left(F_{(a,p,l),i}\right)^6\right)^{\frac{1}{6}}$, $F_{(a,p,l)i}$ is the dynamic internal peak force at timepoint i in the horizontal (a,p,l) directions,

$t_{d,i}$ is the time period of the daily vibration exposure to condition i, and $t_{m,i}$ is the time period over which $S_{(a,p,l),i}$ has been measured.

aOR adjusted by age at entry, full-time driving years, physical work load, psychosocial work environment, herniated lumbar disc, lumbar trauma, and follow up time.

In annex E to ISO/CD 2361-5, it is said that R factor <0.8 indicates a low probability of an adverse health effect, and R factor >1.2 indicates a high probability of an adverse health effect (35). These R factor boundary values are based on 45 working years with 240 days per year of equal exposure to daily compression doses (S_{ed}) of 0.5 and 0.8 MPa, respectively. However, at present there are no epidemiological validation for these R factor boundary values. In the VIBRISKS study, longitudinal logistic analysis revealed about a two-fold increase in the adjusted risk estimates for 12-month low back outcomes (aOR: 1.83-2.13) in the upper quartile of the R factor (0.41-0.72 units) compared to the lower one (0.07-0.19 units), (table 8). It should be noted that in this study the boundaries of the R factor upper quartile are lower than the R factor value suggested by ISO/CD 2631-5 as predictive of a low probability of lumbar spine disorders (R <0.8 units). Thus, the epidemiological findings of this study seem to indicate that the current boundary values for the risk factor R proposed by ISO/CD 2631-5 are not protective for the lumbar spine of the exposed workers. However, it is encouraging that a note included in the ISO document states that "*….existing experience of adverse effects of long-term exposure might justify a re-evaluation of the values*" (35). We recognised, however, that further biodynamic and epidemiological studies are needed to validate the findings of the VIBRISKS study.

Conclusions

The following conclusions may be drawn from this overview of WBV-related low back disorders:

1. LBP is a condition of multifactorial origin and is a very common health problem in the general population. Among occupational risk factors, epidemiological studies of driving occupations have provided evidence for significant associations between low back disorders and occupational exposures to WBV and mechanical shocks;
2. Since it is hard to separate the contribution of WBV exposure to disorders of the lower back from that of other individual, ergonomic or psychosocial risk factors, a quantitative exposure-response relationship for WBV cannot be outlined precisely;
3. The daily exposure limit values for WBV established by the EU Directive, ($A(8)_{max}$ =1.15 ms^{-2} r.m.s. or VDV_{max} = 21 $ms^{-1.75}$), are excessive, so

much so that an elevated risk of LBP has been found for WBV exposures beneath these limit values;

4. In the Italian arm of the EU VIBRISKS prospective cohort study of professional drivers, measures of internal lumbar load (compressive and shear peak forces) calculated by means of anatomy-based FE models, were found better predictors of the occurrence over time of low back disorders than the metrics of external exposure ($A(8)_{max}$ or VDV_{max}) suggested by the EU Directive on mechanical vibration;
5. The exposure boundary values of internal lumbar load (risk factor *R*) for the probability of adverse health effects recommended by ISO/CD 2631-5 are not epidemiologically validated; the findings of the EU VIBRISKS prospective cohort study suggest that the ISO boundary values tend to underestimate the risk of low back disorders in professional drivers.

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