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ORIGINAL ARTICLE

Relationships of low back outcomes to internal spinal load: a prospective cohort study of professional drivers

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Abstract
Purpose To investigate the relationships between low back symptoms and alternative measures of external dose and internal spinal dose in professional drivers exposed to whole body vibration (WBV).
Methods The occurrence of low back symptoms was investigated in a cohort of 537 drivers over a 2-year follow-up period. Low back pain (LBP), individual characteristics, and work-related risk factors were investigated with a structured questionnaire. Exposure to WBV was evaluated by means of measures of external dose (daily vibration exposure in terms of either equivalent continuous acceleration over an 8-h period ($A(8)$) or vibration dose value according to the EU Directive on mechanical vibration) and measures of internal lumbar load (daily compressive dose S_{ed} and risk factor R according to ISO/CD 2631-5 2014).
Results In the drivers' cohort, the cumulative incidence of 12-month low back outcomes was 16.8 % for LBP, 9.3 % for chronic LBP, and 21.8 % for sciatic pain. The measures of internal spinal load were better predictors of the occurrence of low back symptoms than the measures of daily vibration exposure. A twofold increase in the risk estimates for low back outcomes was found in the upper quartile of the R factor (0.41–0.72 units) compared to the lower one (0.07–0.19 units).
Conclusions In this prospective cohort study, measures of internal spinal dose performed better than measures of daily vibration exposure (external dose) for the prediction of low back outcomes in professional drivers. The ISO boundary values of the risk factor R for low and high probabilities of adverse health effects on the lumbar spine tend to underestimate the health risk in professional drivers.

Keywords Driving · Exposure–response relationships · External dose · Internal spinal dose · Low back disorders · Whole body vibration

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Introduction

Musculoskeletal symptoms in the lower back are frequently reported by professional drivers. It is believed that disorders of the lumbar spine in driving occupations are of multifactorial origin. Individual characteristics, exposure to whole body vibration (WBV) and awkward postures while driving, and poor psychosocial work environment are considered the main risk factors for the onset and development of low back pain (LBP) in professional drivers (Bongers and Boshuizen 1990; Bovenzi and Hulshof 1999; Bovenzi and Palmer 2010; Burdorf and Sorock 1997; Tiemessen et al. 2008).

To prevent, or at least to reduce, the occurrence of low back disorders caused by WBV, the EU Directive 2002/44/EC on mechanical vibration (2002) has established daily exposure action values (EAV) and exposure limit values (ELV) for WBV generated by machinery at the workplace. The EAV and ELV are based on the calculation of the equivalent continuous acceleration over an 8-h period ($A(8)$ in ms^{-2} r.m.s.) or the vibration dose value (VDV in $ms^{-1.75}$), calculated from the highest value of the

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weighted accelerations ($A(8)_{max}$, VDV_{max}) determined on three orthogonal axes ($1.4a_{wx}$, $1.4a_{wy}$, or a_{wz} for a seated or standing worker).

A more complex method for the evaluation of occupational exposures to WBV containing shocks has been proposed in a Committee Draft of International Standard ISO/CD 2631-5 (2014). The method suggested in the ISO document uses finite element (FE) models to predict internal spinal forces based on time series of unweighted accelerations. To estimate the lumbar spine response to vibration, recent biodynamic studies have developed FE models anatomically adapted to the anthropometry and the sitting postures of the exposed workers (Seidel et al. 2001, 2008; Hinz et al. 2008). 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 (nondimensional 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 aims of this prospective cohort study of professional drivers were (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.

Subjects and methods

The biodynamic and epidemiological data of this investigation were collected within the VIBRISKS study (2007), a European research project, funded by the EU Commission, which seeks to improve understanding of the risk of injury from occupational exposures to mechanical vibration by means of epidemiological studies supported by fundamental laboratory research.

Study population

The Italian arm of the VIBRISKS study included a cohort of male professional drivers ($n = 628$) employed in several industries (marble quarries, marble laboratories, dockyards, paper mills) and public utilities (garbage services, public transport) located in various provinces of Italy. The cohort was followed up annually over the calendar periods 2003–2006. The study design and the response rate of the participants have been described in previous papers (Bovenzi 2009, 2010). Briefly, 598 drivers (95.2 %) were enrolled at the initial cross-sectional survey. Of these, 537 responders participated in one or two follow-up surveys (89.8 %). Owing to either organisational problems due to time schedules at the workplace or opposition by the employers, 220 workers could participate in only the 1-year follow-up survey. Sixty-one subjects were lost at the follow-up; of these, 15 had changed their place of residence, 36 refused to participate in the follow-up, and 10 could not be identified. At baseline, the lost subjects did not differ significantly from the participants in the study with respect to age, anthropometric characteristics, smoking and drinking habits, measures of vibration exposure, and prevalence of LBP.

Written informed consent to the study was obtained from employers and employees at each company.

A minimum of 1 year of professional driving in the current job was established as the basic criterion for the inclusion of drivers in the study population.

Drivers were divided into three groups according to the machines and/or vehicles more frequently used in their work activities: earth-moving machines in marble quarries and laboratories for Group A ($n = 124$), forklift trucks in marble laboratories, dockyards and paper mills for Group B ($n = 169$), buses in public transport, and garbage machines in public services for Group C ($n = 244$).

Questionnaire and LBP outcomes

A structured questionnaire developed within the VIBRISKS project (2007) was administered to the drivers by certified occupational health personnel.

The questionnaire consisted of various sections which have been described in detail in our previous papers (Bovenzi 2009, 2010). In short, the questionnaire requested information about: (i) the subject's personal characteristics (age, height, weight, smoking and drinking habits, education, marital status, physical activity, and annual car driving); (ii) the occupational history in the current and previous companies with details about job titles, duration of employment, types of machines or vehicles driven, daily and cumulative duration of driving on specific machine or vehicle; (iii) physical load other than while driving during a typical working day (e.g. lifting, awkward postures); and (iv) aspects related to psychosocial factors at work. Traumatic injuries to the lower back requiring medical care in the past were also considered.

Perceived physical work demands were evaluated by a combined approach of both direct observation of working conditions (photographs and video) and the subject's self-assessment during the interview. A perceived physical work load index was calculated from eleven questions including standing and walking at work, prolonged sitting other than

Table 1 Low back outcomes as defined in the questionnaire

Outcomes	Definitions
Low back pain (LBP)	Pain or discomfort in the low back area between the twelfth ribs and the gluteal folds (showed in a body map), lasting 1 day or longer during the last 7 days, or lasting at least 7 days but less than 30 days in the previous 12 months
Chronic LBP	Daily experience of LBP or several episodes of LBP lasting more than 30 days in the previous 12 months
Sciatic pain	Radiating pain in one or both legs (below the knee) in the last 7 days or the previous 12 months
Treated LBP	LBP treated with anti-inflammatory drugs or physical therapy in the last 7 days or the previous 12 months

when driving, bending forward, twisting, digging and shovelling, working with arms raised and hand above shoulder, lifting loads >15 kg, and lifting with trunk bent or twisted. Heavy physical work was graded by rating the frequency of manual activities on a 3-point response scale (e.g. lifting loads >15 kg with trunk bent and twisted: "not at all", "1–10 times", "more than 10 times"). Awkward postures were graded by rating the duration of each posture on a 4-point time scale ("never", "less than 1 h", "1–2 h", "more than 2 h"). A mean value of physical load variables over a typical working day was calculated for each subject. In the total sample, the average measure of perceived physical work demands was categorised into four grades of increasing physical load: mild, moderate, hard, and very hard physical load grade.

A measure of the perceived psychosocial work environment was derived from five questions concerning job decision (three questions), job support (one question), and job satisfaction (one question) (Karasek 1979). Job decision and job support were measured on a 4-point scale (a: "often", b: "sometimes", c: "seldom", d: "never/almost never"), as well as job satisfaction (e: "very satisfied", f: "satisfied", g: "dissatisfied", h: "very dissatisfied"). By combining the responses to the above questions, perceived psychosocial work environment was divided into categories of increasing psychosocial load: good (items a + e), reasonable (items b + f), a little poor (items c + g), and poor (items d + h) psychosocial work environment.

Low back symptoms were investigated by means of a modified version of the Nordic questionnaire on musculoskeletal symptoms (Kuorinka et al. 1987). The drivers were questioned on several types of low back symptoms as defined in Table 1. Low back complaints were asked with reference to the last 7 days and the previous 12 months. In data analysis, the various forms of low back outcomes were treated as mutually exclusive. A history of herniated lumbar disc was considered positive only if supported by computed axial tomography or magnetic resonance imaging reports exhibited by the driver.

Measures of daily vibration exposure (external dose)

Vibration was measured on representative, randomly selected, samples of industrial machines and vehicles ($n = 68$) used by the professional drivers according to the recommendations of the International Standard ISO 2631-1 (1997) and the VIBRISKS protocol (2007). Details of vibration measurements, sampling procedures, and methods to estimate the duration of daily and lifetime vibration exposures are reported elsewhere (Bovenzi 2009, 2010).

Briefly, vibration was measured at the driver–seat interface with a semi-rigid mounting disc containing three uniaxial accelerometers. The signals from the accelerometers were simultaneously acquired to a digital tape recorder and downloaded to a PC for post-analysis. The stored acceleration time histories were then analysed in the laboratory by a digital frequency analyser. Vibration signals were averaged by using the root-mean-square (r.m.s.) method and the root-mean-quad (r.m.q.) method. Frequency-weighted accelerations from anteroposterior (x), lateral (y), and longitudinal (z) directions (a_{wx}, a_{wy}, a_{wz}) were obtained by using the weighting factors suggested in ISO 2631-1 (1997).

Daily vibration exposure was expressed in terms of $A(8)_{max}$ according to the EU Directive on mechanical vibration (2002):

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

where $a_{\text{wsi(max)}}$ is the greatest weighted r.m.s. acceleration for exposure condition (vehicle) 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 (vehicle) i, and $T_{(8)}$ is a reference duration of 8 h.

Daily vibration exposure was also expressed in terms of VDV_{max}:

$$VDV\text{max} = a_{wqi(\text{max})} \times (t_{di} \times 60 \times 60)^{1/4} \quad \left(\text{ms}^{-1.75}\right) \tag{2}$$

where $a_{\text{wqi(max)}}$ is the greatest weighted r.m.q. acceleration for exposure condition (vehicle) i determined on three orthogonal axes (1.4 a_{wx}, 1.4 a_{wy}, or a_{wz} for a seated worker), and t_{di} is the duration of daily exposure to condition (vehicle) i in hours.

Measures of internal spinal load

Representative acceleration time histories for various machines/vehicles and working tasks measured within the VIBRISKS project were selected. The measuring time was in the range 300–1100 s. Impacts due to sitting down or losing the contact to the seat were eliminated. Finally, 19 checked time histories were available, each with a duration of 200 s in accord with the ISO standard which recommends a minimal duration of measurement of 120 s to ensure that multiple vibration-related shocks are recorded and are typical of the drivers' exposures (ISO/CD 2631-5 2014).

All time histories contained shocks in at least one direction according to several shock containment criteria (Mohr 2004; Schust et al. 2012).

The internal forces were predicted by anatomically based FE models (Seidel et al. 2001, 2008; Hinz et al. 2008). The basic model family is based on 32400 acceleration to spine force transfer functions (4 acceleration inputs (buttock, back, hands, feet) in the three directions *x*, *y*, and *z* within 3 ranges of magnitude, 5 sitting postures, 2 body mass index categories each with 5 body mass classes, 6 spine levels, 3 spinal force directions). In the present study, the model was adapted to 2 ranges of external vibration magnitudes measured on the seat (unweighted r.m.s. $a_z < 0.65\ \text{ms}^{-2}$, $0.65\ \text{ms}^{-2} \le a_z \le 1.35\ \text{ms}^{-2}$), 4 typical driving postures, and 10 classes of anthropometric characteristics of the drivers. In total, 80 models were used which delivered time histories of internal forces on six levels of the lumbar spine from T12/L1 to L5/S1 (Schust et al. 2013).

The daily compressive dose S_{ed} (MPa) was calculated according to the following equation (ISO/CD 2631-5 2014):

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

where S_i is the dynamic compressive stress due to vibration for the exposure (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 risk factor *R* (non-dimensional units) can be defined for the assessment of adverse health effects related to the compressive dose. For constant exposure pattern per day, the risk factor *R* was calculated according to the following equation (ISO/CD 2631-5 2014):

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

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 ($\text{age}_{\text{init}} + j$) 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. However, in the present investigation the yearly exposure patterns remained constant.

The dynamic compressive stress, and consequently S_{ed} and *R* factor, are different on each of the six lumbar spine levels. In this study, data analysis was carried out on the basis of the lumbar spine level with the highest values of S_{ed} and *R* factor.

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 a user guide, has been published in DIN SPEC 45697 (2012).

Statistical methods

The statistical analysis of data was made with the Stata software®, version 13.1 (StataCorp, College Station, Texas).

Continuous variables were summarised with the mean as a measure of central tendency and the standard deviation as a measure of dispersion.

Comparisons between independent groups were made with one-way analysis of variance. Differences between categorical data cross-tabulated into contingency tables were tested by the χ^2 statistic.

Prevalence and cumulative incidence of low back symptoms were calculated according to traditional epidemiological methods. Prevalence was defined as the proportion of drivers affected with low back symptoms at baseline. Cumulative incidence was calculated as the number of new cases reporting low back symptoms over the follow-up period divided by the number of drivers at risk.

The associations between LBP (binary) outcomes and individual- and work-related explanatory variables were assessed by means of the generalised estimating equations (GEE) method to account for the within-subject dependency of the observations over time (Twisk 2003). Odds ratios (ORs) and robust 95 % confidence intervals (95 % CI) were estimated from the GEE logistic regression coefficients and their standard errors. Measures of either external dose ($A(8)_{\text{max}}$, VDV_{max}) or internal spinal load (S_{ed}, *R* factor) entered the logistic model as time-dependent categorical or continuous variables, while other individual- or work-related covariates were included as time-dependent categorical variables, except for age which was treated as a time independent continuous variable (age-at-entry). Interactions between independent variables were assessed by adding appropriate product terms to the GEE logistic models. All models included a linear term for time effect.

The relationship between LBP (binary) outcomes and measures of external or internal spinal dose, while controlling for potential confounders, was assessed by means of two analytic models (Twisk 2003):

- *standard model*: the binary outcome variable for subject i at time point t (Y_{it}) was related to independent variable(s) k for subject i at time point t (X_{ikt}). In this model, repeated measures of LBP outcomes on the same subject are regressed on independent variables repeatedly measured on the same subject at the same time point. As a result, odds ratios from the GEE standard model are pooled risk estimates of cross-sectional and longitudinal relationships. An advantage of the standard model is that all available exposure and health data collected over time can be used in the analysis, resulting in an increased power of the study.
- *transition model*: to investigate the temporal sequence of cause and effect and to "capture" the longitudinal part of the relationship, the binary outcome variable for subject i at time point t (Y_{it}) was related to both the independent variable(s) k for subject i at time point $t-1$ (X_{ikt-1}) and the outcome variable for subject i at time point $t-1$ (Y_{it-1}), i.e. the values of the independent variable(s) and the outcome at one time point earlier. The transition model (also called autoregressive model) assumes that the value of an outcome variable at each time point is strongly related to the value of the outcome at the previous study time.

A p value <0.05 was established as the limit of statistical significance.

Results

Characteristics of the study population

At baseline, the three driver groups were similar for individual characteristics, although some differences were observed for smoking and drinking habits, marital status, and regular physical activity (Table 2).

Perceived physical work load was more prevalent in the drivers of Group A and B than in those of Group C ($p < 0.001$), while the drivers in the latter group experienced poor psychosocial work environment more frequently than the other two driver groups ($p < 0.001$).

Daily vibration exposures in terms of $A(8)_{max}$ and VDV_{max} were greater in Group A than in Groups B and C ($p < 0.001$). In the entire driver population, the daily compressive dose S_{ed} averaged 0.28 (0.09) MPa and the risk factor R 0.29 (0.12) units. A multiple comparison test showed that S_{ed} and R factor were significantly greater in Groups A and C than in Group B ($p < 0.001$).

Prevalence and incidence of low back outcomes

At the cross-sectional survey, LBP and sciatic pain in the previous 7 days were more prevalent in the drivers of public utility vehicles than in the other driver groups (Table 3). The cumulative incidence of 12-month low back outcomes over the follow-up period was greater in the drivers of earth-moving machines than in the other two groups, with significant differences for chronic LBP and LBP treated with anti-inflammatory drugs or physical therapy. At baseline, herniated lumbar disc, diagnosed by imaging techniques, was reported by 10 % of the drivers with no significant difference between groups. There were 25 new cases of lumbar herniated discs over the follow-up period, giving rise to a cumulative incidence of 5.2 %. The incidence of lumbar hernia was greater in the drivers of earth movers (9.6 %) than in the other two driver groups (2.3–6.0 %) ($p = 0.012$).

Traumatic injuries to the lower back requiring medical care were reported by 6 % of the drivers with no difference between groups ($p = 0.63$).

Low back outcomes and measures of external dose and internal lumbar load

Crude GEE logistic analysis showed significant positive associations between most of the 7-day and 12-month low back outcomes and the measures of internal lumbar load expressed as continuous variables and processed with either standard or transition models (Tables 4, 5). No associations were found for the measures of external dose, with the exception for the transition model relating 7-day treated LBP to $A(8)_{max}$ ($p < 0.05$).

After adjustment for several individual- and work-related covariates, the pooled cross-sectional and longitudinal risk estimates produced by the GEE standard model showed significant positive relations of 7-day and 12-month low back outcomes to the measures of internal lumbar load, mainly the R factor (Tables 4, 5). The measures of external dose were not related to any of the low back outcomes. It should be pointed out that the adjustment for potential confounders differed between the various models since some explanatory variables included in the models with $A(8)_{max}$

Table 2 Characteristics of the study populations at baseline

Characteristics	Professional drivers							
	Group A		Group B		Group C		Total	
	($n = 124$)		($n = 169$)		($n = 244$)		($n = 537$)	
Age (year)	41	8.3	40.3	8.4	41.5	7.8	41	8.1
Body mass index (kg/m^2)	26.5	3.5	25.9	4	26.7	3.6	26.4	3.7
Smoking (n)								
Never	**50**	**40.3**	**66**	**39.1**	**130**	**53.3**	246	45.8
Ex-smokers	**30**	**24.2**	**33**	**19.5**	**49**	**20.1**	112	20.9
Current smokers	**44**	**35.5**	**70**	**41.4**	**65**	**26.4**[a]	179	33.3
Drinking (n)	**85**	**68.6**	**120**	**71**	**140**	**57.4**[a]	345	64.3
Married (n)	**102**	**82.3**	**116**	**68.6**	**169**	**69.3**[a]	387	72.1
Education (year)								
≤6	10	8	16	9.5	9	3.7	35	6.5
7–12	87	70.2	105	62.1	163	66.8	355	66.1
>12	27	21.8	48	28.4	72	29.5	147	27.4
Physical activity								
Never	**69**	**57.7**	**86**	**50.9**	**82**	**33.6**	237	44.1
<1 per week	**9**	**7.3**	**17**	**10**	**38**	**15.6**	64	11.9
1–3 per week	**40**	**32.2**	**63**	**37.3**	**107**	**43.9**	210	39.1
Every day	**6**	**4.8**	**3**	**1.8**	**17**	**7.0**[a]	26	4.8
Car driving (km/year)								
<8,000	36	29	38	22.5	71	29.1	145	27
8–24,000	81	65.3	117	69.2	149	61.1	347	64.6
>24,000	7	5.7	14	8.3	24	9.8	45	8.4
Daily driving time (h)	**5.7**	**2.4**	**5.4**	**2.1**	**6**	**0.7**[b]	5.7	1.7
Seniority in current job (year)	**14.6**	**9.7**	**12**	**8.7**	**11.9**	**8.8**[b]	12.6	9
Seniority in driving occupations (year)	**19.2**	**10**	**15.9**	**9.1**	**18.5**	**9.4**[b]	17.8	9.5
$A(8)_{max}$ (ms^{-2} r.m.s.)	**0.5**	**0.15**	**0.35**	**0.14**	**0.34**	**0.07**[b]	0.38	0.13
VDV_{max} (ms$^{-1.75}$)	**12.4**	**2.6**	**9.5**	**3.5**	**7.6**	**1.6**[b]	9.3	3.2
S_{ed} (MPa)	**0.29**	**0.05**	**0.23**	**0.08**	**0.32**	**0.10**[b]	0.28	0.09
R factor (units)	**0.29**	**0.08**	**0.22**	**0.09**	**0.33**	**0.13**[b]	0.29	0.12
Physical work load								
Mild	**47**	**37.9**	**36**	**21.3**	**102**	**41.8**	185	34.5
Moderate	**33**	**26.6**	**30**	**17.8**	**81**	**33.2**	144	26.8
Hard	**21**	**16.9**	**47**	**27.8**	**38**	**15.6**	106	19.7
Very hard	**23**	**18.6**	**56**	**33.1**	**23**	**9.4**[a]	102	19
Psychosocial work environment								
Good	**59**	**47.6**	**65**	**38.5**	**27**	**11.1**	151	28.1
Reasonable	**34**	**27.4**	**64**	**37.9**	**36**	**14.7**	134	24.9
A little poor	**27**	**21.8**	**32**	**18.9**	**105**	**43**	164	30.5
Poor	**4**	**3.2**	**8**	**4.7**	**76**	**31.2**[a]	88	16.4

Data are given as means and standard deviations or numbers and percentages (see text for the definitions of $A(8)_{max}$, VDV_{max}, S_{ed}, and R factor)

Bold indicates significant differences between groups ([a] χ^2 test; [b] one-way ANOVA)

Group A: drivers of earth-moving machines; Group B: drivers of forklift trucks; Group C: drivers of public utility vehicles

and VDV_{max} were used to calculate S_{ed} (e.g. BMI) or R factor (e.g. age, BMI, driving years) (see equations above).

The GEE transition model, which extracts the longitudinal part of the relationship, revealed significant associations between LBP and treated LBP in the previous 7 days and the measures of internal spinal load, while only the R factor, expressed as either a continuous variable (Table 5) or a quartile-based design variable (Table 6), was significantly related to all low back outcomes occurred in the past 12 months. As expected, in the transition models prior episodes of low back complaints exerted a strong influence on the occurrence of subsequent low back outcomes, with point estimates of the adjusted ORs varying from 3.6 to 13.5 ($p < 0.001$) (Table 6).

Table 3 Prevalence at baseline and cumulative incidence of 7-day and 12-month low back outcomes in the professional drivers over the follow-up period

Low back outcomes	Professional drivers															
	Group A ($n = 124$)				Group B ($n = 169$)				Group C ($n = 244$)				Total ($n = 537$)			
	Prevalence		Cumulative incidence		Prevalence		Cumulative incidence		Prevalence		Cumulative incidence		Prevalence		Cumulative incidence	
	N	%	*N*	%	*N*	%	*N*	%	*N*	%	*N*	%	*N*	%	*N*	%
7-day outcomes																
LBP	**18**	**14.5**	23	21.7	**41**	**24.3**	16	12.5	**78**	**31.9**	22	13.3	136	25.5	61	15.3
Sciatic pain	**6**	**4.8**	10	8.5	**9**	**5.3**	13	8.2	**30**	**12.3**	18	8.4	45	8.4	41	8.3
Treated LBP	3	2.4	14	11.6	8	4.7	11	6.8	17	7.0	19	8.4	28	5.5	44	8.6
12-month outcomes																
LBP	10	8.1	27	23.7	24	14.2	24	16.6	34	13.9	28	13.3	68	12.7	79	16.8
Chronic LBP	6	4.8	**18**	**15.3**	15	8.9	**13**	**8.4**	19	7.8	**15**	**6.7**	40	7.5	46	9.3
Sciatic Pain	24	19.3	27	27.0	38	22.5	28	21.4	62	25.4	35	19.2	124	23.1	90	21.8
Treated LBP	32	25.8	**34**	**37.0**	48	28.4	**41**	**33.9**	67	27.5	**37**	**20.9**	147	27.4	112	28.7

Data are given as numbers and percentages. LBP is low back pain

Bold indicates significant differences between groups (χ^2 test)

Group A: drivers of earth-moving machines; Group B: drivers of forklift trucks; Group C: drivers of public utility vehicles

Herniated lumbar disc and previous lumbar trauma, although the latter to a lesser extent, were significant predictors of low back symptoms over time. Physical work load other than driving was significantly related to 12-month low back symptoms in the GEE standard model, but it reduced substantially in the transition model after adjustment for the same outcomes at the previous study time. No significant associations between 12-month low back complaints and psychosocial work environment were observed.

There were no significant interactions between measures of external or internal dose, physical load, and psychosocial environment, and between these variables and previous low back symptoms when appropriate product terms were included in the alternative statistical models.

Discussion

Driving occupations, WBV exposure, and low back disorders

In the epidemiological literature, the independent role of WBV in the etiopathogenesis of low back disorders in the exposed workers continues to be debated. In several studies of either the general population or occupational groups, professional drivers showed an increased risk of low back symptoms compared to sedentary workers (Bovenzi and Hulshof 1999; Farioli et al. 2014). This finding has been attributed to driving-related WBV exposure by some authors, while others have more emphasised the contribution of other work-related risk factors such as excessive ergonomic demands (e.g. prolonged sitting and/or awkward postures during driving) or unfavourable psychosocial or psychological conditions (Bovenzi and Palmer 2010; Burdorf and Sorock 1997; Bongers et al. 1993; Hoogendoorn et al. 2000). In general, the multifactorial origin of low back disorders in professional drivers is recognised by most investigators.

In several epidemiological studies, occupational exposure to WBV has been merely treated in terms of job title (driving *vs* non-driving occupations) or dichotomised exposure variable (yes *vs* no). On the contrary, epidemiological investigations of specific driving occupations (e.g. operators of industrial or agricultural machinery, bus drivers) 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 (Bongers and Boshuizen 1990; Bovenzi and Hulshof 1999; Bovenzi 2009). As a result, national and international standards or directives have fixed rules to improve the safety and health protection of WBV exposed workers and have established methods for

Table 4 Relationships of 7-day low back outcomes to measures of external dose 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)

7-day outcomes	Dose measures	Standard model ($n = 537$; obs = 1,391)				Transition model ($n = 537$; obs = 854)			
		cOR	95 % CI	aOR*	95 % CI	cOR	95 % CI	aOR*	95 % CI
LBP	S_{ed} (MPa × 10^{-1})	**1.36**	**1.13–1.65**	1.19	0.97–1.45	**1.34**	**1.08–1.65**	**1.34**	**1.04–1.73**
	R factor (units × 10^{-1})	**1.34**	**1.16–1.53**	**1.26**	**1.10–1.45**	**1.26**	**1.08–1.47**	**1.24**	**1.05–1.47**
	$A(8)_{max}$ (ms^{-2}×10^{-1})	0.99	0.89–1.10	0.96	0.85–1.08	1.12	0.97–1.30	1.11	0.96–1.29
	VDV_{max} ($ms^{-1.75}$)	0.95	0.91–1.00	0.95	0.90–0.99	1.03	0.97–1.09	1.03	0.97–1.10
Sciatic pain	S_{ed} (MPa × 10^{-1})	**1.59**	**1.19–2.13**	1.31	0.98–1.76	**1.41**	**1.00–1.99**	1.34	0.95–1.89
	R factor (units × 10^{-1})	**1.49**	**1.22–1.83**	**1.36**	**1.12–1.66**	**1.36**	**1.06–1.74**	1.27	0.99–1.63
	$A(8)_{max}$ (ms^{-2}×10^{-1})	1.04	0.91–1.20	0.99	0.85–1.16	1.08	0.88–1.32	1.10	0.90–1.35
	VDV_{max} ($ms^{-1.75}$)	0.97	0.92–1.03	0.95	0.89–1.02	1.00	0.92–1.08	1.00	0.92–1.09
Treated LBP	S_{ed} (MPa × 10^{-1})	**1.65**	**1.24–2.20**	**1.51**	**1.09–2.11**	**1.66**	**1.17–2.36**	**1.72**	**1.11–2.68**
	R factor (units × 10^{-1})	**1.50**	**1.22–1.84**	**1.44**	**1.16–1.78**	**1.48**	**1.17–1.89**	**1.49**	**1.13–1.97**
	$A(8)_{max}$ (ms^{-2} × 10^{-1})	1.13	0.97–1.31	1.12	0.94–1.32	**1.23**	**1.01–1.50**	1.23	0.99–1.53
	VDV_{max} ($ms^{-1.75}$)	1.02	0.95–1.08	1.02	0.95–1.09	1.07	0.99–1.15	1.07	0.98–1.17

Odds ratios, crude (cOR) or adjusted by potential confounders (aOR*), and robust 95 % confidence intervals (95 % CI) are estimated by means of the generalised estimating equations method according to standard or transition models. The changes in OR for a change of 0.1 MPa for S_{ed}, 0.1 units for R factor, 0.1 ms^{-2} r.m.s. for $A(8)_{max}$, and 1 $ms^{-1.75}$ for VDV_{max} are shown. LBP is low back pain

Bold indicates significant positive associations between low back outcomes and dose measures

* $A(8)_{max}$ − 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, follow-up time, and low back outcome at the previous study time $t - 1$ (this latter for transition models only)

* S_{ed}: OR adjusted by age at entry, full-time driving years, physical work load, psychosocial work environment, herniated lumbar disc, lumbar trauma, follow-up time, and low back outcome at the previous study time c (this latter for transition models only)

* R factor: OR adjusted by physical work load, psychosocial work environment, herniated lumbar disc, lumbar trauma, follow-up time, and low back outcome at the previous study time $t - 1$ (this latter for transition models only)

the measurement, evaluation, and assessment of the risks arising from exposure to WBV at the workplace (EU Directive 2002; ISO/CD 2631-5 2014).

In the present study of professional drivers, the overall prevalence of low back symptoms in the previous 7 days and 12 months was around 34 and 44 %, respectively. In a systematic review of low back pain in the general population throughout the world, the 1-week prevalence of LBP ranged from 6.3 to 20.1 % (Hoy et al. 2010). In a more recent review of the global prevalence of LBP which included 165 studies from 54 countries, the median overall prevalence of LBP was estimated to be 25.9 % in males (Hoy et al. 2012). Thus, the prevalence estimates of our study, together with those of other epidemiological surveys of professional drivers, suggest an increased prevalence of low back symptoms in driving occupations compared to the general population (Bongers and Boshuizen 1990; Bovenzi and Hulshof 1999). Moreover, systematic reviews and meta-analysis of the prevalence of low back symptoms in professional drivers have consistently reported an excessive risk of LBP in driving occupations compared to control groups with overall, significant, risk estimates varying from 1.7 to 2.3 (Bovenzi and Hulshof 1999; Bovenzi and Palmer 2010; Nilsson et al. 2013). These findings seem to be confirmed by those of a population-based prevalence study of back pain in 35,476 workers from 34 EU countries recruited within the Fifth European Working Conditions Survey (Farioli et al. 2014): the prevalence ratio for back pain, adjusted by several individual and occupational risk factors, was 1.36 (95 % CI 1.18–1.58) for drivers and mobile-plant operators compared to teaching professionals. In the same study, frequent exposures to vibration at the workplace were also associated with an increased risk of back pain ("often": 1.11 (1.04–1.18); "always": 1.07 (1.01–1.13), when compared to "never").

Sciatic pain is a symptom more severe and with poorer prognosis than non-specific LBP. In a meta-analysis of 9 cross-sectional studies of professional drivers, an excess risk of sciatic pain was reported with an overall risk estimate of 1.41 (95 % CI 1.21–1.63) (Nilsson et al. 2013). Unfortunately, there are very few longitudinal studies of sciatic pain in driving occupations. In the cohort of this study, the cumulative incidence of sciatic pain was 21.8 %. This figure is widely consistent with a 3-year cumulative incidence of 22 % reported in a sample of 387 Finnish

Table 5 Relationships of 12-month low back outcomes to measures of external dose 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)

12-month outcomes	Dose measures	Standard model ($n = 537$; obs = 1,391)				Transition model ($n = 537$; obs = 854)			
		cOR	95 % CI	aOR*	95 % CI	cOR	95 % CI	aOR*	95 % CI
LBP	S_{ed} (MPa × 10^{-1})	1.17	0.95–1.44	1.09	0.86–1.38	1.20	0.97–1.49	1.17	0.90–1.51
	R factor (units × 10^{-1})	**1.26**	**1.08–1.47**	**1.28**	**1.08–1.51**	**1.22**	**1.04–1.43**	**1.25**	**1.05–1.50**
	$A(8)_{max}$ (ms^{-2}×10^{-1})	0.99	0.87–1.13	0.94	0.83–1.08	1.06	0.92–1.21	1.03	0.89–1.19
	VDV_{max} ($ms^{-1.75}$)	0.98	0.93–1.04	0.95	0.90–1.01	1.01	0.96–1.07	1.00	0.95–1.06
Chronic LBP	S_{ed} (MPa × 10^{-1})	1.21	0.91–1.61	1.11	0.80–1.54	1.22	0.93–1.60	1.15	0.84–1.57
	R factor (units × 10^{-1})	**1.27**	**1.04–1.56**	**1.28**	**1.03–1.60**	**1.25**	**1.03–1.53**	**1.29**	**1.04–1.59**
	$A(8)_{max}$ (ms^{-2}×10^{-1})	0.96	0.80–1.15	0.91	0.75–1.10	1.03	0.86–1.23	0.99	0.81–1.20
	VDV_{max} ($ms^{-1.75}$)	0.97	0.90–1.05	0.94	0.87–1.02	1.00	0.93–1.06	0.98	0.91–1.06
Sciatic pain	S_{ed} (MPa × 10^{-1})	**1.35**	**1.13–1.61**	**1.30**	**1.07–1.58**	**1.33**	**1.10–1.60**	1.25	0.99–1.56
	R factor (units × 10^{-1})	**1.33**	**1.17–1.52**	**1.32**	**1.15–1.52**	**1.26**	**1.09–1.46**	**1.21**	**1.03–1.43**
	$A(8)_{max}$ (ms^{-2}×10^{-1})	1.08	0.96–1.22	1.06	0.94–1.18	**1.14**	**1.00–1.29**	1.13	0.99–1.29
	VDV_{max} ($ms^{-1.75}$)	1.01	0.96–1.06	1.00	0.95–1.04	1.03	0.98–1.09	1.04	0.98–1.10
Treated LBP	S_{ed} (MPa × 10^{-1})	1.05	0.90–1.24	0.96	0.79–1.16	1.15	0.96–1.38	1.15	0.92–1.43
	R factor (units × 10^{-1})	1.12	0.99–1.27	1.11	0.97–1.27	**1.16**	**1.01–1.33**	**1.17**	**1.01–1.36**
	$A(8)_{max}$ (ms^{-2} × 10^{-1})	1.05	0.94–1.18	1.04	0.92–1.16	1.11	0.98–1.25	1.09	0.96–1.25
	VDV_{max} ($ms^{-1.75}$)	1.01	0.97–1.06	1.01	0.96–1.06	1.03	0.98–1.08	1.02	0.97–1.08

Odds ratios, crude (cOR) or adjusted by potential confounders (aOR*), and robust 95 % confidence intervals (95 % CI) are estimated by means of the generalised estimating equations method for repeated measures over time, according to standard or transition models. The changes in OR for a change of 0.1 MPa for S_{ed}, 0.1 units for R factor, 0.1 ms^{-2} r.m.s. for $A(8)_{max}$ and 1 $ms^{-1.75}$ for VDV_{max} are shown. LBP is low back pain

Bold indicates significant positive associations between low back outcomes and dose measures

* $A(8)_{max}$ − 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, follow-up time, and low back outcome at the previous study time $t - 1$ (this latter for transition models only)

* S_{ed}: OR adjusted by age at entry, full-time driving years, physical work load, psychosocial work environment, herniated lumbar disc, lumbar trauma, follow-up time, and low back outcome at the previous study time $t - 1$ (this latter for transition models only)

* R factor: OR adjusted by physical work load, psychosocial work environment, herniated lumbar disc, lumbar trauma, follow-up time, and low back outcome at the previous study time $t - 1$ (this latter for transition models only)

machine operators who were free from sciatic pain at baseline (Riihimäki et al. 1994).

Lumbar spine response to vibration

The findings of this prospective cohort study suggest that the measures of internal lumbar load performed better than the measures of external vibration dose for the prediction of the occurrence of low back symptoms in professional drivers. The risk estimates for both 7-day and 12-month low back outcomes tended to increase with the increase in the daily compressive dose S_{ed} and the risk factor R. Such a trend was not observed for $A(8)_{max}$ and VDV_{max}, i.e. the measures of daily vibration exposure calculated according to the EU Directive for mechanical vibration (2002). With reference to 12-month low back outcomes, for a change of 0.1 units for the R factor, the adjusted risk estimates increased by 25 % for LBP, 29 % for chronic LBP, 21 % for sciatic pain, and 17 % for treated LBP, according to the longitudinal transition model.

A Committee Draft of International Standard ISO/CD 2631-5 (2014) offers guidance for the assessment of the adverse health effects on the lumbar spine caused by exposures to vibration containing multiple shocks. 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 acceleration and vertebral forces determined by anatomy-based FE models adapted to typical working postures and typical drivers' anthropometries (Hinz et al. 2008; ISO/CD 2631-5 2014). By combining the calculation of the internal spinal forces with other individual-level characteristics of the driver population, the metrics S_{ed} and R factor are estimated by means of appropriate software (see section Methods). Upon consideration of the risk of fatigue fractures of the vertebral endplates caused by compressive loading and the findings of biodynamic studies (Seidel et al. 2001; Liu et al. 1983; Brickmann et al. 1988, 1989), in the ISO document it is said that R factor <0.8 indicates a low probability of

Table 6 Relationships of 12-month low back outcomes to risk factor *R* (quartile-based design variable), measures of physical work load and psychosocial work environment, herniated lumbar disc, lumbar trauma and low back outcome at the previous study time $t-1$ (this latter for transition models only)

Explanatory variables	LBP				Chronic LBP				Sciatic pain			
	Standard model		Transition model		Standard model		Transition model		Standard model		Transition model	
	aOR	95 % CI	aOR	95 % CI	aOR	95 % CI	aOR	95 % CI	aOR	95 % CI	aOR	95 % CI
R factor (units)												
0.07–0.19	1	–	1	–	1	–	1	–	1	–	1	–
0.20–0.27	0.73	0.43–1.27	0.9	0.50–1.63	0.72	0.37–1.38	0.83	0.37–1.84	1.09	0.72–1.65	1.14	0.67–1.92
0.28–0.40	1.09	0.65–1.84	1.3	0.73–2.31	0.64	0.32–1.30	0.73	0.33–1.65	1.57	0.99–2.48	1.55	0.90–2.69
0.41–0.72	**1.83**	**1.07–3.13**	**1.96**	**1.07–3.61**	1.9	0.96–3.75	**2.41**	**1.17–4.97**	**2.13**	**1.36–3.36**	**2.06**	**1.18–3.62**
Physical work load												
Mild	1	–	1	–	1	–	1	–	1	–	1	–
Moderate	1.34	0.85–2.11	0.86	0.49–1.51	1.13	0.65–1.95	0.54	0.24–1.21	**1.46**	**1.04–2.06**	1.28	0.77–2.12
Hard	**1.59**	**1.01–2.50**	0.81	0.47–1.44	1.37	0.75–2.48	0.57	0.27–1.17	**1.72**	**1.23–2.41**	0.96	0.57–1.63
Very hard	**2.09**	**1.35–3.24**	1.28	0.73–2.25	**1.79**	**1.02–3.14**	1.37	0.72–2.64	**2.03**	**1.46–2.83**	1	0.59–1.69
Psychosocial work environment												
Good	1	–	1	–	1	–	1	–	1	–	1	–
Reasonable	0.68	0.43–1.09	1.07	0.62–1.84	0.47	0.25–0.90	0.81	0.39–1.68	0.87	0.58–1.29	0.99	0.59–1.67
A little poor	0.71	0.45–1.10	1.08	0.64–1.84	0.65	0.38–1.12	0.98	0.51–1.87	0.86	0.60–1.24	1.02	0.62–1.67
Poor	1.05	0.64–1.71	0.8	0.42–1.52	0.96	0.51–1.82	0.86	0.43–1.72	1.39	0.91–2.13	1.36	0.75–2.48
Herniated lumbar disc	**3.56**	**2.13–5.94**	**2.76**	**1.66–4.60**	**5.54**	**3.05–10.1**	**3.22**	**1.74–5.96**	**3.72**	**2.37–5.85**	**2.76**	**1.50–5.09**
Lumbar trauma	**3.78**	**2.15–6.64**	1.29	0.57–2.91	**5.7**	**2.94–11.1**	2.11	0.90–4.94	**1.83**	**1.06–3.14**	**2.83**	**1.26–6.40**
Low back outcome at the previous study time ($t-1$)			**3.59**	**2.16–5.97**			**4.95**	**2.57–9.52**			**13.5**	**8.93–20.4**

Adjusted odds ratios (aOR) and robust 95 % confidence intervals (95 % CI) are estimated by means of the generalised estimating equations method according to standard or transition models. LBP is low back pain

Bold indicates significant positive associations between low back outcomes and explanatory variables

an adverse health effect, and *R* factor >1.2 indicates a high probability of an adverse health effect (ISO/CD 2631-5 2014). However, to date, there has been no epidemiological validation for these *R* factor boundary values.

In this study, the GEE transition model revealed a twofold increase in the adjusted risk estimates for 12-month low back outcomes (aOR $\geq$ 2.0) in the upper quartile of the *R* factor (0.41–0.72 units) compared to the lower one (0.07–0.19 units) (Table 6). It is worth noting 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 (2014) are not protective for the health of 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*" (ISO/CD 2631-5 2014). We recognised, however, that further studies are needed to confirm the findings of the present investigation.

As mentioned above, in this study the measures of daily vibration exposure (external dose) were poor predictors of the occurrence of low back symptoms in the professional drivers. $A(8)_{max}$ and VDV_{max} are calculated on the basis of the highest axial weighted acceleration magnitude and the daily exposure time. 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. The findings of this cohort study of professional drivers suggest that measures of internal spinal load such as the *R* factor, which is calculated on the basis of individual characteristics (age, BMI), working postures and intensity and duration of vibration exposures, seem more appropriate, at least from an epidemiological point of view, to predict the probability of low back disorders.

In this study, herniated lumbar intervertebral disc, traumatic injuries to the lower back, LBP outcomes at the previous study time, and excessive physical workload, but not adverse psychosocial work environment, were important predictors of the occurrence of low back symptoms over time. The contributions of physical and psychosocial risk factors to the occurrence of low back disorders have been discussed in previous papers of the VIBRISKS study and are beyond the scope of the present paper (Bovenzi 2009, 2010). Several epidemiological studies and reviews have concluded that there is evidence for a positive relationship between (low) back disorders and physical and/or psychosocial risk factors at the workplace, but the magnitude of this evidence varies across studies because of lack of standardisation for the metrics used to quantify these variables, and differences in the study design and data modelling (Burdorf and Sorock 1997; Bongers et al. 1993; Hartvigsen et al. 2004; Hoogendoorn et al. 2002).

Limitations of the study

In this study, some uncertainties are associated with the exposure data. As reported in previous studies of the VIBRISKS project, although vibration measurements were made on currently available machines or vehicles, the weighted acceleration magnitudes of vibration measured in the vehicles of the present study are widely comparable with those reported in recent and past investigations (Bongers and Boshuizen 1990; Griffin 1990; Griffin et al. 2006). In addition, the broad variety of machines/vehicles used by the professional drivers resulted in a significant variability in vibration exposures which allowed for the assessment of exposure–response relationships (Bovenzi 2009).

In this study, the metrics S_{ed} and R factor (ISO/CD 2631-5 2014) were calculated on the basis of the internal compressive spinal forces acting on the vertebral endplates (Eqs. 3, 4) with no consideration of the shear forces. This limitation should be taken into account in the interpretation of our epidemiological findings since there is evidence that shear load in the human lumbar spine, in addition to compressive forces, may contribute to the development of adverse health effects (Norman et al. 1996; Skrzypiec et al. 2012, 2013).

Quantification of duration of exposure to WBV may be difficult because recall bias cannot be ruled out when daily driving time is estimated by means of questionnaire or direct interview of employees and employers. To reduce, at least partially, this bias, a survey was conducted in the field to compare subjective estimates of daily exposure duration with objective measurements of actual driving time during typical working days (Pinto and Stacchini 2006). Systematic observations of the variability of work tasks over a 1-week period indicated that drivers tended to overestimate the duration of their actual exposure to WBV in the range 5–13 % (mean 11 %). This finding is broadly consistent with the results of a national survey in Great Britain (Palmer et al. 2000) which showed a good agreement between reported and observed duration of exposure to WBV in a sample of drivers of industrial and agricultural machines (median ratio of reported to observed time: 1.1). It should be noted that a difference of about 10 % in daily driving time results in a negligible effect on the estimation of daily vibration exposure (e.g. $A(8)_{max}$).

Full-time driving years for the calculation of the R factor were also estimated by means of the questionnaire. Although the role of the questionnaire as an instrument to collect exposure data is still controversial (Burdorf and van der Beek 1999), questionnaire methods may offer a means for studying cumulative exposure over time, a variable which cannot be estimated by direct observations or measurements (Kilbom 1994).

The questionnaire used in this study was originally developed within the European project VINET (Vibration Network, Pope et al. 2002). The questionnaire underwent a process of improving revisions on the basis of the findings of pilot studies and epidemiological surveys conducted across some European countries (Pope et al. 2002). The drivers were interviewed by certified occupational health personnel who were trained to administer the questionnaire in a standardised way. It was assumed that, by using trained personnel, inter-observer variability would be minimised, thereby limiting the misinterpretation of exposure and health data from the questionnaire.

Longitudinal studies involving outcomes and exposure variables that vary over time may be affected by feedback bias: drivers with LBP may modify their exposures to WBV (Eisen 1999). This potential bias cannot be excluded in the present study. Information on driving activities obtained from repeated interviews of the drivers did not reveal substantial changes in exposure associated with the onset of LBP during the follow-up period. Moreover, transition modelling of data did not show significant interactions between measures of external or internal dose and previous episodes of low back symptoms, suggesting that feedback bias, if any, should not have affected the exposure–response relationships observed in this study.

Conclusions

In this prospective cohort study of professional drivers, data analysis with a transition model, which takes into account the temporal sequence between cause and effect and captures the longitudinal part of the relationship, showed that measures of internal lumbar load, such as S_{ed} and R factor, were better predictors of the occurrence of low back symptoms over time than measures of external dose expressed in terms of daily vibration exposure, $A(8)_{max}$, VDV_{max}, according to the EU Directive on mechanical vibration. The boundary values of risk factor R for low and high probabilities of adverse health effects on the lumbar spine, as proposed by ISO/CD 2631-5 (2014), tend to underestimate the health risk caused by prolonged exposure to vibration in professional drivers.

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Conflict of interest None.

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