Int Arch Occup Environ Health (1999) 72: 351–365

REVIEW

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An updated review of epidemiologic studies on the relationship between exposure to whole-body vibration and low back pain (1986–1997)

Received: 18 June 1998 / Accepted: 23 October 1998

Abstract The aim of this study is to update the information on the epidemiologic evidence of the adverse health effects of whole-body vibration (WBV) on the spinal system by means of a review of the epidemiologic studies published between 1986 and 1997. In a systematic search, using several databases, of epidemiologic studies of low back pain (LBP) disorders and occupations with exposure to WBV, 45 articles were retrieved. The quality of each study was evaluated according to criteria concerning the assessment of vibration exposure, assessment of health effects, and methodology. The epidemiologic studies reaching an adequate score on each of the above-mentioned criteria were included in the final review. A meta-analysis was also conducted in order to combine the results of independent epidemiologic studies. After applying the selection criteria, 17 articles reporting the occurrence of LBP disorders in 22 WBV-exposed occupational groups reached a sufficient score. The study design was cross-sectional for 13 occupational groups, longitudinal for four groups and of case-control type for one group. Two studies included both cross-sectional and follow-up data on the occurrence of LBP disorders in four occupational groups. The main reasons for the exclusion of studies were insufficient quantitative information on WBV exposure and the lack of control groups. The findings of the selected studies and the results of the meta-analysis of both cross-sectional and cohort studies showed that occupational exposure to WBV is associated with an increased risk for LBP, sciatic pain, and degenerative changes in the spinal system, including lumbar intervertebral disc disorders. Owing to the cross-sectional design of the majority of the reviewed studies, this epidemiologic evidence is not sufficient to outline a clear exposure-response relationship between WBV exposure and LBP disorders. Comparing the epidemiologic studies included in this review with those conducted before 1986, it is concluded that research design and the quality of exposure and health effect data in the field of WBV have improved in the last decade.

Key words Driving · Epidemiology · Low back disorders · Postural load · Whole-body vibration

Introduction

Exposure to whole-body vibration (WBV) is a widespread occupational risk factor that may cause adverse effects on health in drivers of lorries, fork-lift trucks, tractors, cranes and loaders, and in helicopter pilots. In the USA, Canada, and some European countries, it has been estimated that 4%–7% of all employees are exposed to potentially harmful WBV [23]. Experimental research has pointed out that exposure to WBV can affect the lumbar spine and the connected nervous system [29, 67]. Biodynamic experiments have shown that WBV exposure, combined with a constrained sitting posture, can put the lumbar intervertebral disc at risk of failure [68]. Epidemiologic studies have indicated that long-term exposure to occupational WBV is associated with degeneration of the spine and with low back pain (LBP) disorders [5, 60, 61, 66]. In some countries, back disorders occurring in workers exposed to WBV are considered to be an occupational disease which may be compensable [27].

A critical evaluation of the epidemiologic literature on the effects of long-term WBV exposure on the spinal system was published in 1987 [33]. This review indicated that LBP, early degeneration of the lumbar spinal

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system and herniated lumbar disc were the most frequently reported adverse effects in workers exposed to WBV. However, in the quality score system used by the authors no study reached an adequate score on criteria of evaluation based on the quality of exposure data, health effect data, study design and methodology. Since 1986, several epidemiologic studies have been conducted on occupational groups exposed to WBV. The aim of this paper is to update the information on the epidemiologic evidence of the adverse health effects of WBV on the spinal system by means of a systematic review of the epidemiologic studies published between 1986 and 1997.

Methods

Retrieval of studies

A systematic search of epidemiologic studies of LBP disorders and occupations with exposure to WBV was performed using databases such as MEDLINE (National Library of Medicine, United States of America), NIOSHTIC (National Institute for Occupational Safety and Health, United States of America), CISDOC (International Labour Organisation, Switzerland), EMBASE (Excerpta Medica Collection, The Netherlands), and the Human Response to Vibration Literature Collection at the Institute of Sound and Vibration Research of the University of Southampton, United Kingdom. The following key words were used: (low) back pain, sciatic pain, spinal disorders, herniated lumbar disc, (whole-body) vibration, postural load, epidemiology, occupation, driving. References cited in the retrieved studies were also examined. Only original epidemiologic studies published between 1986 and 1997 were accepted for inclusion in the review. The literature search was not limited to articles published in English.

Quality rating of studies

In the 1987 review [33], a score procedure was applied to support a systematic assessment of the relationship between WBV exposure and LBP disorders. In the present review, the 1987 score system was adapted according to criteria proposed by Kuiper et al. [42]. The quality of each study was evaluated according to criteria concerning the assessment of WBV exposure, assessment of health effects, and methodology (Table 1). The available epidemiologic studies were assessed by the authors independently. There was no substantial disagreement in the score for each study between the reviewers. Studies which reached at least one-third of the maximum score for each of the three evaluation categories were included in the review.

Meta-analysis

A meta-analytic approach was used in order to combine and summarise the results of independent epidemiologic studies [26]. Point estimates and 95% confidence intervals (CI) of summary prevalence odds ratio (POR) or incidence density ratio (IDR) for LBP disorders among WBV-exposed occupational groups were obtained on the basis of the point and interval estimates of POR or IDR provided by the individual cross-sectional or cohort epidemiologic studies, respectively. Since among-study variability was expected, the summary estimates of POR or IDR and their confidence intervals were calculated according to a random effects model proposed by DerSimonian and Laird [25]. This method weights studies by the inverse of a combination of within-study variance and among-study variance. The null hypothesis of homogeneity of the risk estimates across studies was assessed by a test with approximate χ^2 distribution on $k-1$ degrees of freedom, where k is the number of studies to be meta-analysed. Cross-sectional or cohort epidemiologic studies which both reached the sufficient quality score to be included in the review and provided risk estimates and confidence intervals adjusted at least for age were included in the meta-analysis.

Results

Initially, the literature search provided 45 articles which described the occurrence of LBP disorders in WBV-exposed occupational groups or driving occupations. Of these, 26 were cross-sectional studies [1, 3, 4, 9–11, 16, 18–21, 37, 40, 41, 45–50, 52–54, 56, 58, 62], five were cohort studies [6–8, 15, 57], two were case-control studies [12, 31], and eight were community-based epidemiologic studies [2, 30, 32, 34, 44, 64, 65, 69]. Four studies included both cross-sectional and follow-up data on the occurrence of LBP disorders in bus drivers, fork-lift truck drivers, truck drivers, operators of earth moving machinery and commercial travelers [17, 51, 55, 59]. One cross-sectional study reported data on the prevalence of LBP in two different groups of fork-lift truck drivers [16].

After applying the above-mentioned evaluation criteria, 28 articles were excluded from the final review. The main exclusion criterion pertained to the lack of sufficient quantitative information on exposure to WBV [1, 2, 19, 20, 30–32, 34, 40, 41, 44, 47–51, 54–57, 64, 65, 69]. Most of the excluded studies reported only occupations or job titles with or without subjective evaluation of work seniority. Serious methodological drawbacks such as the lack of external control groups [18, 45, 47, 62], incomplete description of potential confounders or other risk factors for LBP, or inadequate control for such confounders in the study design or analysis [1, 40, 45, 48, 52–54, 62], were also causes for the exclusion of studies.

Finally, 17 articles reporting the occurrence of LBP disorders in 22 WBV-exposed occupational groups, met the inclusion criteria [3, 4, 6–12, 15–17, 21, 37, 46, 58, 59]. The study design was cross-sectional for 13 occupational groups, longitudinal for four groups, and of case-control type for one group. Epidemiologic findings

Table 1 Scoring system for evaluating the quality of exposure data, health effect data, and methodology in epidemiologic studies of low back pain disorders and occupations with exposure to whole-body vibration (adapted from [42])

		Score
Assessment of vibration exposure		
Measurement according to guidelines of ISO 2631-1		10
Duration of exposure: Objective methods		10
Subjective evaluation		5
Earlier exposure data available		5
	Maximum total	25
Assessment of health effects		
Low back pain/sciatic pain		
Self-reported (questionnaire, medical interview)		10
Health statistics		5
	Maximum subtotal	10
Herniated disc		
Clear radiographic/clinical documentation		10
Self-reported (after clinical investigation)		5
	Maximum subtotal	10
(Other) degenerative spinal column disorders		
Clear radiographic/clinical documentation		10
Health statistics		5
	Maximum subtotal	10
For all categories:		
Pre-existing disorders absent or taken into account		5
	Maximum total	15
Methodology		
Study design:		
Cohort		10
Case-control		5
Cross-sectional with control group		2
Cross-sectional without control group		0
	Maximum subtotal	10
Selection of study population:		
Absence of healthy worker effect		2
Response rate $>60\%$/drop out $<30\%$		2
	Maximum subtotal	4
Description of potential confounders/other risk factors (frequency, Mean ± SD):		
Age, smoking, education		1 for each item
Manual handling, bending and twisting, heavy physical work, Job dissatisfaction, low decision latitude		1 for each item
	Maximum subtotal	8
Control for potential confounders/other risk factors in study design or analysis:		
Age, smoking, education		1 for each item
Manual handling, bending and twisting, heavy physical work, Job dissatisfaction, low decision latitude		1 for each item
	Maximum subtotal	8
	Maximum total	30

of both the prevalence and the incidence of LBP were reported in two studies which investigated four driving occupational groups [17, 59].

Table 2 summarises the epidemiologic studies selected in this review and shows the characteristics of the study populations, data sources, vibration exposure data, and the main epidemiologic findings. No attempt was made to derive risk estimates for LBP disorders from prevalence data if they were not reported in the original cross-sectional studies.

Crane operators [6–8, 21], bus drivers [3, 46], tractor drivers [4, 11, 15, 58], and fork-lift truck drivers [16, 17, 59] were the most frequently investigated occupational groups in either cross-sectional or cohort studies. The control groups included in the epidemiologic studies consisted of either sedentary workers such as administrative officers [4, 10, 21, 46] or manual workers such as maintenance operators [3, 6, 7]. Among the study groups exposed to WBV, the mean exposure duration ranged between 7 and 21 years. In the majority of the studies, vibration measurements on the vehicles were performed according to the recommendations of the international standard ISO 2631-1 [35]. In general, vibration magnitude was expressed in terms of vector sum of the frequency-weighted root mean square (r.m.s.) acceleration, with the exception of three studies in which vibration magnitude was measured only in the vertical direction [46, 58, 59]. The reported values of vibration magnitude varied from 0.25 to 0.67 ms^{-2} in cranes, 0.36 to 0.56 ms^{-2} in busses, 0.35 to 1.45 ms^{-2} in tractors, and 0.79 to 1.04 ms^{-2} in fork-lift trucks and freight-container tractors. For the drivers of these vehicles, some investigators

Table 2 Summary of epidemiologic studies of low back pain (LBP) disorders and occupations with exposure to whole-body vibration (WBV) (1986–1997)

Author(s) (year)	Study group	Control group	Vibration magnitude and/or duration of exposure (mean or range)	Study design	Data source	Results	Quality score[a]
Brendstrup and Biering-Sørensen (1987) [17]	Fork-lift truck drivers ($n=169$)	Unskilled workers ($n=66$)	7 years	Cross-sectional study; 12-month follow-up	Questionnaire	79% lifetime LBP (control group 64%) POR: 2.2 (1.3–3.7)* 65% 1-year LBP (control group 52%) POR: 1.7 (1.0–2.8)* Follow-up: 51% LBP (control group 47%) Increased occurrence of LBP with increasing length of employment as a fork-lift truck driver,	E: 10 (40%) H: 10 (67%) M: 11 (37%)
Bongers et al. (1988) [6]	Crane operators ($n = 743$)	Maintenance workers ($n = 662$)	a_v 0.25–0.67 ms^{-2} ≤4–> 20 years	Retrospective (10-year) cohort study	Social insurance medical records	IDR for disability pensioning: 1.3 (0.8–2.1)* all back disorders 1.5 (0.6–3.6)* spondylosis 2.0 (1.1–3.7)* intervertebral disc disorders Increased risk for disability due to intervertebral disc disorders with increasing years of exposure	E: 20 (80%) H: 15 (100%) M: 17 (57%)
Bongers et al. (1988) [7]	Crane operators ($n = 743$)	Maintenance workers ($n = 662$)	a_v 0.25–0.67 ms^{-2} ≤4–> 20 years	Retrospective (10-year) cohort study	Social insurance medical records	IDR for at least one spell of sickness absence of ≥28 days due to back disorders: 1.0 (0.8–1.3)* all back disorders 1.0 (0.4–2.4)* spondylarthrosis 1.2 (0.7–2.1)* intervertebral disc disorders 1.4 (0.7–2.7)* herniated disc	E: 20 (80%) H: 15 (100%) M: 17 (57%)
Bongers et al. (1990) [8]	Crane operators ($n = 341$)	Metal workers/ bench fitters ($n = 3130$)	a_v 0.3–0.5 ms^{-2} (estimated)	Retrospective (40-year) cohort study	Medical records	IDR for disability due to back disorders: 1.0 (0.6–1.7)* all back disorders 1.1 (0.5–2.5)* intervertebral disc disorders 1.4 (0.7–2.8)* unspecified back disorders	E: 15 (60%) H: 10 (67%) M: 15 (50%)
Boshuizen et al. (1990) [12]	Drivers of the transportation industry ($n = 347$)	All other occupations in transportation industry ($n = 105$)	a_v 0.45–1.0 ms^{-2} (estimated)	Case-control study	Insurance medical records	OR for disability pensioning: 1.1 (0.8–1.7)* all back disorders 0.8 (0.3–2.1)* spondylosis 2.9 (1.1–8.1)* intervertebral disc disorders 1.1 (0.7–1.9)* herniated disc Increased risk of back disorders with increasing total lifetime exposure to whole-body vibration	E: 15 (60%) H: 10 (67%) M: 11 (37%)

Boshuizen et al. (1990) [15]	Tractor drivers ($n = 423$)	Not or slightly exposed workers ($n = 375$)	a_v 0.72 ms^{-2}	Retrospective (11-year) cohort study	Medical records	IDR for long-term sick leave (≥28 days) due to back disorders: 1.5 (1.0–2.1)* all back disorders 3.1 (1.2–8.3)* intervertebral disc disorders 1.3 (0.9–1.9)* unspecified back disorders	E: 20 (80%) H: 10 (67%) M: 18 (60%)
Boshuizen et al. (1990) [11]	Tractor drivers ($n = 450$)	Non-exposed workers ($n = 110$)	a_v 0.72 ms^{-2}, 10 years	Cross-sectional study	Questionnaire	31% regular LBP (control group 19%) POR: 2.0 (1.3–3.1)* 13% lifetime acute LBP (control group 12%) POR: 1.0 (0.6–1.7)* 19% regular sciatic pain (control group 13%) POR: 1.6 (0.9–2.6)* 8% herniated disc (control group 5%) POR: 2.1 (0.9–4.7)* Increased risk for low back disorders with increasing WBV dose[d]	E: 25 (100%) H: 15 (100%) M: 16 (53%)
Bongers et al. (1990) [10]	Helicopter pilots ($n = 133$)	Non-flying air-force officers ($n = 228$)	a_v 0.48 ms^{-2}, 9.9 years	Cross-sectional study	Questionnaire	55% regular LBP (control group 11%) POR: 10 (7.0–15)* 13% lifetime acute LBP (control group 9%) POR: 2.2 (1.2–3.8)* 12% regular sciatic pain (control group 6%) POR: 2.1 (1.2–3.7)* 5% herniated disc (control group 4%) POR: 1.0 (0.4–2.5)* Increased risk for LBP with increasing WBV dose[d]	E: 25 (100%) H: 15 (100%) M: 16 (53%)
Bongers et al. (1990) [9]	Wheel loaders ($n = 47$)	Not exposed or little exposed workers ($n = 52$)	a_v 0.95 ms^{-2}, 10 years	Cross-sectional study	Questionnaire	47% regular LBP (control group 39%) POR: 1.3 (0.6–2.7)* 9% lifetime acute LBP (control group 20%) POR: 0.5 (0.2–1.4)* 15% regular sciatic pain (control group 17%) POR: 1.0 (0.4–2.6)* Increased prevalence of LBP with increasing WBV dose[d]	E: 25 (100%) H: 15 (100%) M: 16 (53%)

Table 2 (Contd.)

Author(s) (year)	Study group	Control group	Vibration magnitude and/or duration of exposure (mean or range)	Study design	Data source	Results	Quality score[a]
Boshuizen et al. 1st study (1990) [16]	Fork-lift truck drivers and freight-container tracter drivers from six harbor companies ($n = 196$)	Non-exposed workers ($n = 107$)	a_v 0.79–1.04 ms^{-2}, 13.9 years	Cross-sectional study	Questionnaire	41% regular LBP (control group 29%) POR: 1.6 (1.1–2.4)* 19% lifetime acute LBP (control group 8%) POR: 2.8 (1.4–5.4)* 12% regular sciatic pain (control group 12%) POR: 1.0 (0.5–1.9)* 4% herniated disc (control group 5%) POR: 0.8 (0.3–2.2)*	E: 25 (100%) H: 15 (100%) M: 16 (53%)
Boshuizen et al. 2nd study (1990) [16]	Fork-lift truck drivers from a chemical company ($n = 37$)	Non-exposed workers ($n = 37$)	a_v 0.82 ms^{-2}, 8.3 years	Cross-sectional study	Questionnaire	57% regular LBP (control group 16%) POR 7.3 (2.9–18)* 19% lifetime acute LBP (control group 14%) POR 1.7 (0.8–3.7)* 22% regular sciatic pain (control group 10%) POR 2.7 (0.8–9.3)* Increased prevalence of LBP with increasing WBV dose[d]	E: 25 (100%) H: 15 (100%) M: 16 (53%)
Johanning (1991) [37]	Subway train operators ($n = 492$)	Tower operators ($n = 92$)	a_v 0.55 ms^{-2}, 10.4 years	Cross-sectional study	Questionnaire	56% LBP (control group 36%) 23% sciatic pain (control group 7%) POR: 3.9 (1.7–8.6)**	E: 15 (60%) H: 15 (100%) M: 9 (30%)
Bovenzi and Zadini (1992) [5]	Bus drivers ($n = 234$)	Maintenance workers ($n = 125$)	a_v 0.43 ms^{-2}, 13.4 years	Cross-sectional study	Questionnaire	84% lifetime LBT (control group 66%) POR: 3.1 (1.8–5.3)** 83% 1-year LBT (control group 66%) POR: 3.0 (1.8–5.1)** 35% 1-year acute LBP (control group 24%) POR: 1.9 (1.1–3.1)** 33% 1-year sciatic pain (control group 22%) POR: 1.9 (1.2–3.3)** 8% herniated disc (control group 7%) POR: 1.3 (0.6–3.0)** Increased risk for low back disorders with increasing WBV dose[d]	E: 25 (100%) H: 15 (100%) M: 18 (60%)

Burdorf et al. (1993) [21]	Crane operators (n = 94) Straddle-carrier drivers (n = 95)	Office workers (n = 86)	Crane operators: a_{v} 0.31 ms^{-2}, 8.1 years Straddle-carrier drivers: a_{v} 0.40 ms^{-2}, 7.6 years	Cross-sectional study	Medical interview	1-year prevalence of newly developed cases of LBP in current job: 40% crane operators, POR: 3.3 (1.5–7.1)* 31% SC drivers, POR: 2.5 (1.2–5.4)* (control group 20%)	E: 20 (80%) H: 15 (100%) M: 14 (47%)
Bovenzi and Betta (1994) [4]	Tractor drivers (n = 1155)	Office workers (n = 220)	a_{v} 1.06 ms^{-2}, 21 years	Cross-sectional study	Questionnaire	81% lifetime LBT (control group 42%) POR: 3.2 (2.1–5.2)** 72% 1-year LBT (control group 37%) POR: 2.4 (1.6–3.7)** 36% 1-year acute LBP (control group 10%) POR: 3.0 (1.8–5.0)** 16% 1-year sciatic pain (control group 4%) POR: 3.9 (1.8–8.7)** 7% herniated disc (control group 2%) POR: 1.8 (0.7–4.7)** Increased risk for low back disorders with increasing WBV dose[d]	E: 25 (100%) H: 15 (100%) M: 18 (60%)
Sandover et al. (1994) [58]	Tractors drivers (n = 100)	Poultry workers (n = 31)	a_{wz} 0.35–1.45 ms^{-2}, 16 years	Cross-sectional study	Questionnaire	64% lifetime LBP (control group 48%) 46% 1-year LBP (control group 16%)	E: 15 (60%) H: 10 (67%) M: 12 (40%)
Magnusson et al. (1996) [46]	Bus drivers (US = 40, Sweden = 71) Truck drivers (US = 40, Sweden = 77)	Sedentary workers (US = 64, Sweden = 73)	Bus drivers: a_{wz} 0.36–0.56 ms^{-2}, 10–16 years Truck drivers: a_{wz} 0.47–0.78 ms^{-2}, 11–18 years	Cross-sectional study	Questionnaire	LBP prevalence: Bus drivers: US 81%, Sweden 49% Truck drivers: US 50%, Sweden 59% (control group: US 42%, Sweden 42%) POR[c] for being a driver: 1.8 (1.2–2.8)** POR for vibration exposure and frequent lifting: 2.1 (0.8–5.7)**	E: 15 (60%) H: 10 (67%) M: 10 (33%)

Table 2 (Contd.)

Author(s) (year)	Study group	Control group	Vibration magnitude and/or duration of exposure (mean or range)	Study design	Data source	Results	Quality score[a]
Schwarze et al. (1998) [59]	Fork-lift truck drivers ($n = 159$) Truck drivers ($n = 64$) Operators of earth moving machinery ($n = 165$)	Low exposure group	Fork-lift truck drivers: $a_{wz(8\ h)}$ 0.45 ms^{-2}, 12.8 years Truck drivers: $a_{wz(8\ h)}$ 0.47 ms^{-2}, 18.4 years Operators of earth moving machinery: $a_{wz(8\ h)}$ 0.67 ms^{-2}, 20.1 years Three exposure groups ($a_{wz(8\ h)}$ during 10 years): Low: <0.6 ms^{-2} Medium: 0.6–0.8 ms^{-2} High: >0.8 ms^{-2}	Cross-sectional study; 4-year follow-up	Medical examination; lumbar X-rays	Prevalence of lumbar syndrome‡ in 315 workers with no LBP up to the end of the first year of exposure: Low exposure: 39%, PR: 1.0 Medium exposure: 59%, PR: 1.5 (1.1–2.0)** High exposure: 72%, PR: 1.6 (1.2–2.0)** Four-year incidence of lumbar syndrome in 111 workers with no LBP at the initial check-up: Low exposure: 46% Medium exposure: 43% High exposure: 67% $a_{wz(8\ h)} < 0.6$ ms^{-2}: RR: 1.0 $a_{wz(8\ h)} > 0.6$ ms^{-2}: RR: 1.3 (0.9–1.9)** for lumbar syndrome $a_{wz(8\ h)} > 0.6$ ms^{-2}: RR: 2.3 (1.3–4.1)** for lumbar radicular syndrome	E: 25 (100%) H: 15 (100%) M: 15 (50%)

[a] Quality score: E, exposure data; H, health effect data; M, methodology, (% of maximum score for each item). LBT, all low back troubles (sciatic pain, acute low back pain, or other low back pain); 1-yr LBP, one-year prevalence of low back pain

[b] Lumbar syndrome, any kind of symptoms in the lumbar region and in the sacral area for which a vertebral cause could be assumed after differential diagnosis. IDR, age-adjusted incidence density ratio; OR/POR, odds ratio/prevalence odds ratio, adjusted for several covariates or at least for age

[c] Crude POR

PR/RR, prevalence ratio/relative risk, adjusted for age; *(90% confidence intervals), **(95% confidence intervals); a_v, vector sum of the frequency-weighted root mean square (r.m.s.) acceleration in the x-, y-, and z-directions according to ISO 2631-1 (ms^{-2}); a_{wz}, frequency-weighted r.m.s. acceleration in the vertical (z) direction; $a_{wz(8\ h)}$, frequency-weighted energy-equivalent r.m.s. acceleration in the vertical (z) direction for a daily exposure of 8 h

[d] WBV dose: $\sum a_{vi}^2 t_i$, where a_{vi} is the vector sum of the frequency-weighted acceleration of vehicle i and t_i is the number of full-time working years driven on vehicle i (year m^2 s^{-4})

have also produced an estimate of lifetime cumulative WBV dose by combining duration of exposure and WBV magnitude according to the time-dependency proposed by ISO 2631-1 [35]: $\sum a_{vi}^2 t_i$ (year m^2s^{-4}), where a_{vi} is the vector sum of the frequency-weighted r.m.s. acceleration of vehicle i and t_i is the number of full-time working years driven on vehicle i [3, 4, 11, 16].

For the assessment of health effects in cross-sectional studies, the investigators used predominantly medical interview or questionnaires identical or similar to the standardised Nordic Questionnaire on musculoskeletal symptoms [43]. In most cases, the occurrence of LBP was investigated with respect to lifetime and the past 12 months. In several studies, additional questions concerned history of sciatic pain, acute LBP, and herniated lumbar disc, this latter supported by radiological documentation. In one study of the professional drivers, the diagnoses of lumbar syndrome (“any kind of symptoms (like lumbago or sciatica) in the lumbar region and in the sacral area for which a vertebral cause could be assumed after differential diagnosis”) and lumbar radicular syndrome (“any symptom of affection of the spinal nerves”) were established on the basis of the results of clinical examination and the findings of lumbar X-rays in two planes [59].

Medical records, providing information on the results of clinical and/or radiological investigations, were the basic data source of cohort studies of disorders of the spinal system, including lumbar intervertebral disc disorders.

The findings of both cross-sectional and cohort epidemiologic studies indicate that there is an increased risk for LBP disorders among occupational groups exposed to WBV when compared to non-exposed control groups. Most of the reviewed studies reported risk estimates for LBP disorders that were adjusted for several confounders linked to individual characteristics (e.g. age, anthropometric variables, smoking, education) and other ergonomic risk factors (e.g. heavy physical work, lifting, twisting and bending). Psychological risk factors at work, such as perceived mental stress and job dissatisfaction, were also taken into account in several cross-sectional studies [3, 4, 10, 11, 16, 46]. Some trend of increasing prevalence of LBP disorders with the increase of lifetime WBV dose was observed in cross-sectional studies of bus drivers [3], tractor drivers [4, 11], fork-lift truck drivers [16], and wheel loaders [9]. A similar trend for increasing back disorders with increasing WBV exposure was reported in a case-control study of disability pensioning due to degenerative changes in the spine of drivers of the transportation industry [12].

The results of the meta-analysis confirms the findings of individual studies. A significant increase in the combined POR for one-year prevalence of LBP (Table 3, Fig. 1) and sciatic pain (Table 4) was found in occupations with exposure to WBV from industrial vehicles. The study on helicopter pilots, which reported the highest POR for LBP, was not included in the meta-analysis because the exposure conditions are not comparable with those arising from driving industrial vehicles [10]. Three studies were also excluded from the meta-analysis because of the lack of external control groups [59], differences in the definition of the outcome [59], no report of risk estimates for LBP [58] or difficulties in the interpretation of such estimates [46].

An excess risk for lumbar disc disorders, including herniated disc, was also found in the WBV-exposed occupational groups compared with the control groups (Tables 5, 6). It is worth noting that, in this regard, the findings of the meta-analysis of cross-sectional studies (summary POR: 1.5; 95% CI: 0.9–2.4) were consistent with those of the meta-analysis of cohort studies (summary IDR: 1.8; 95% CI: 1.1–3.1).

Two large epidemiologic studies based on national health surveys from the USA and Canada also found

Table 3 Results of the meta-analysis of cross-sectional epidemiologic studies of low back pain (LBP) and occupations with exposure to whole-body vibration from industrial vehicles (1986–1997)

Occupational group	Reference	Prevalence exposed group (%)	Prevalence control group (%)	POR (95% CI)	Study weight
Fork-lift truck drivers	[17]	65	52	1.7 (0.9–3.1)	7.3
Tractor drivers	[11]	31	19	2.0 (1.2–3.4)	9.2
Wheel loaders	[9]	47	39	1.3 (0.5–3.2)	4.0
Fork-lift truck drivers	[16]	57	16	7.3 (2.5–22)	2.9
Fork-lift truck drivers	[16]	41	29	1.6 (1.0–2.6)	10.6
Bus drivers	[3]	83	66	3.0 (1.8–5.1)	9.2
Crane operators	[21]	40	20	3.3 (1.5–7.1)	5.1
Straddle-carrier drivers	[21]	31	20	2.5 (1.2–5.4)	5.4
Tractors drivers	[4]	72	37	2.4 (1.6–3.7)	11.9
Summary POR (95% CI)				2.3 (1.8–2.9)	
Homogeneity χ^2				11.2	
Homogeneity degrees of freedom				8	
Homogeneity ρ value				0.19	

One-year prevalence of LBP in the exposed and control groups, point estimates of the prevalence odds ratio (POR) and 95% confidence intervals (CI), adjusted at least for age, are given for each study. Random effects estimation of the summary POR (95% CI) and test for homogeneity between studies are reported

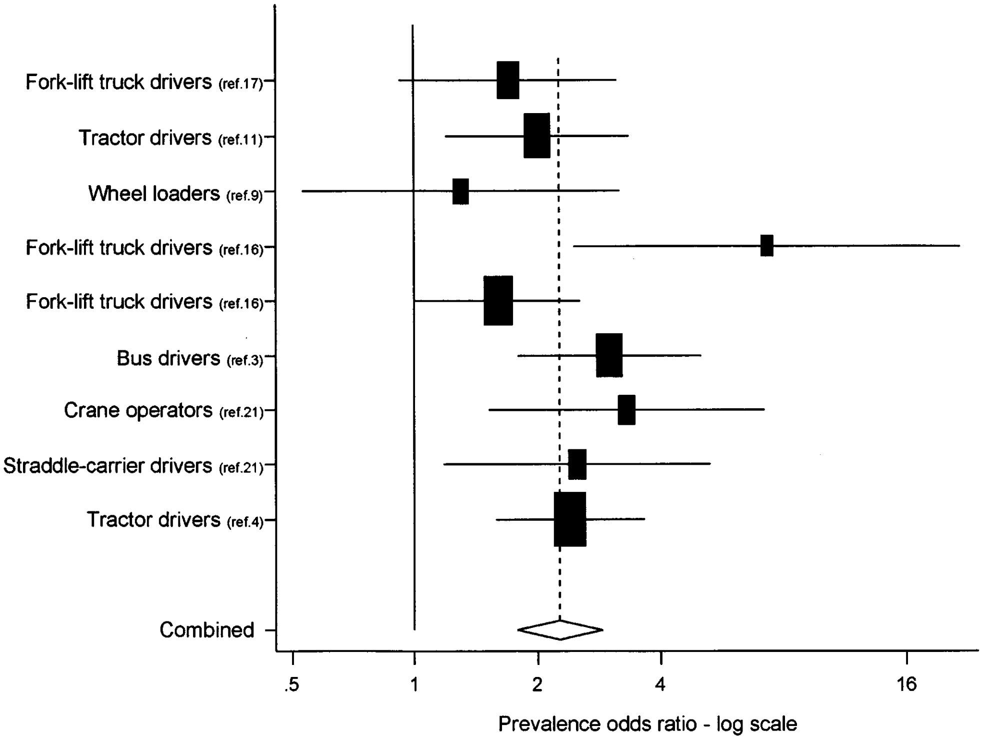

Fig. 1 Prevalence odds ratios (POR) and 95% confidence intervals (CI) for 12-month low back pain in nine driving occupations with exposure to whole-body vibration compared to control groups. The area of each box is inversely proportional to the estimated effect's variance in the study. Random effects estimation of the combined POR and 95% CI is shown (see Table 3 for details)

that the prevalence of (low) back problems in industrial truck drivers, tractor drivers and workers operating vibrating vehicles was higher than that estimated in the US male working population [30] or in workers with no exposure to physical risk factors [44]. Another US study, which used data from the 1989 National Health Interview Survey, reported that workers from transportation occupations were more likely to have a disabling back condition than those in professional occupations [34]. Finally, an increased risk of LBP for "vibration affecting the whole body" was found in a nationwide cross-sectional survey of Danish employees interviewed with a structured questionnaire [69]. These community-based epidemiologic studies were, however, not included in the final review because of the lack of quantitative information on WBV exposure.

Discussion

Criticism of the method

As in any review of the available literature, bias due to selection of studies may have occurred in this review of epidemiologic studies of LBP disorders and occupations with exposure to WBV. Such a selection bias may arise from an incomplete search strategy and from publication bias. However, for this review several databases and

Table 4 Results of the meta-analysis of cross-sectional epidemiologic studies of sciatic pain and occupations with exposure to whole-body vibration from industrial vehicles (1986–1997)

Occupational group	Reference	Prevalence exposed group (%)	Prevalence control group (%)	POR (95% CI)	Study weight
Tractor drivers	[11]	19	13	1.6 (0.9–3.0)	4.6
Wheel loaders	[9]	15	17	1.0 (0.3–3.1)	2.3
Fork-lift truck drivers	[16]	22	10	2.7 (0.6–12)	1.5
Fork-lift truck drivers	[16]	12	12	1.0 (0.5–2.2)	3.6
Subway train operators	[37]	23	7	3.9 (1.7–8.6)	3.5
Bus drivers	[3]	33	22	1.9 (1.2–3.3)	5.5
Tractors drivers	[4]	16	4	3.9 (1.8–8.7)	3.6
Summary POR (95% CI)				2.0 (1.3–2.9)	
Homogeneity χ^2				10.4	
Homogeneity degrees of freedom				6	
Homogeneity ρ value				0.11	

One-year prevalence of sciatic pain in the exposed and control groups, point estimates of the prevalence odds ratio (POR) and 95% confidence intervals (CI), adjusted at least for age, are given for each study. Random effects estimation of the summary POR (95% CI) and test for homogeneity between studies are reported

Table 5 Results of the meta-analysis of cross-sectional epidemiologic studies of herniated lumbar disc and occupations with exposure to whole-body vibration from industrial vehicles (1986–1997)

Occupational group	Reference	Prevalence exposed group (%)	Prevalence control group (%)	POR (95% CI)	Study weight
Tractor drivers	11	8	5	2.1 (0.8–5.6)	4.0
Fork-lift truck drivers	16	4	5	0.8 (0.2–2.6)	2.7
Bus drivers	3	8	7	1.3 (0.6–3.0)	5.9
Tractor drivers	4	7	2	1.8 (0.7–4.7)	4.2
Summary POR (95% CI)				1.5 (0.9–2.4)	
Homogeneity χ^2				1.8	
Homogeneity degrees of freedom				3	
Homogeneity ρ value				0.62	

The prevalence of herniated disc in the exposed and control groups, point estimates of the prevalence odds ratio (POR) and 95% confidence intervals (CI), adjusted at least for age, are given for each study. Random effects estimation of the summary POR (95% CI) and test for homogeneity between studies are reported

a very comprehensive literature collection were consulted. Moreover, some of the used key words, in particular whole-body vibration, were rather specific to be able to detect all of the available studies published during the selected time period (1986–1997). The fact that the literature search was not limited to papers published in English language scientific journals but was extended to non-English language journals as well as to reports, conference proceedings, dissertations, and books may have at least partially avoided this selection bias, including publication bias.

The quality rating method used in this review was updated with respect to the earlier review conducted in 1987 [33]. Although any quality rating system comprises some arbitrary elements of judgement, the present quality score, adapted from Kuiper et al. [42], includes rather 'objective' criteria for the assessment of the quality of exposure data, health effect data, and study design and methodology. This was reflected in the high agreement of the scores independently attributed to the selected studies by the two reviewers. Some quality rating systems use an overall score, based on the addition of all quality criteria, to include individual studies in a review [39]. However, it should be noted that even one low category score may severely reduce the quality of the study. Instead, in the review on hand, the selected studies had to reach at least one-third of the maximum score for each of the three evaluation categories in order to assure a sufficient homogeneous score on the several aspects that characterise an epidemiologic study, i.e. exposure, health outcome and methodology.

Most of the epidemiologic studies selected for this review were of cross-sectional type. It is well known that cross-sectional studies may be subjected to several sources of bias, in particular selection due to the healthy worker effect and inaccuracy in the assessment of the

Table 6 Results of the meta-analysis of cohort studies of back disorders and lumbar disc disorders in occupations with exposure to whole-body vibration from industrial vehicles (1986–1997)

	Reference	Incidence exposed group (per 100 py)	Incidence control group (per 100 py)	IDR (95% CI)	Study weight
Back disorders					
Crane operators	6	0.85	0.47	1.3 (0.8–2.3)	13.3
Crane operators	8	0.57	0.37	1.0 (0.6–1.9)	10.6
Tractor drivers	15	3.03	1.94	1.5 (1.0–2.2)	21.9
Summary IDR (95% CI)				1.3 (0.9–1.7)	
Homogeneity χ^2				0.9	
Homogeneity degrees of freedom				2	
Homogeneity ρ value				0.65	
Lumbar disc disorders					
Crane operators	6	0.61	0.21	2.0 (0.9–4.2)	6.9
Crane operators	8	0.22	0.16	1.1 (0.4–2.9)	4.2
Tractor drivers	15	0.63	0.18	3.1 (1.0–10)	2.8
Summary IDR (95% CI)				1.8 (1.1–3.1)	
Homogeneity χ^2				1.9	
Homogeneity degrees of freedom				2	
Homogeneity ρ value				0.38	

The incidence of disorders per 100 person years (py) in the exposed and control groups, point estimates of the age-adjusted incidence density ratio (IDR) and 95% confidence intervals (CI) are given for each study. Random effects estimation of the summary IDR (95% CI) and test for homogeneity between studies are reported exposure. Possible selection processes caused by health-status turnover have been claimed in some of the cross-sectional studies included in this review and this may have led to an underestimation of the risk estimates for LBP disorders in the study groups. Alternatively, the small sample sizes of some prevalence studies or information bias can have yielded an overestimation of the association between LBP disorders and exposure to WBV. Unfortunately, the magnitude of such biases cannot be quantified. However, the similarity between the risk estimates for lumbar disc disorders found in the cross-sectional and the cohort studies of this review may suggest that at least bias from health-related turnover was not excessively large.

The application of meta-analysis to combine the results of individual studies may be questioned because of the differences in outcomes, characteristics of the study populations, and heterogeneity of the risk estimates [28, 63]. In this review, the use of meta-analytic techniques was considered to be justified because of the general consistency between studies with respect to the anamnestic or clinical definition of LBP disorders [43] and the assessment of WBV exposure according to the guidelines of ISO 2631-1 [35]. Furthermore, data analysis revealed no significant heterogeneity between studies.

Comparison to previous findings

The results of this review confirm the findings of the 1987 review [33] and those of more recent literature surveys of the adverse health effects of WBV exposure [5, 13, 22, 61, 66]. Cross-sectional studies, both individually and combined in a meta-analysis, showed that occupations with exposure to WBV are at higher risk for LBP, sciatic pain, and herniated lumbar disc than control groups not exposed to WBV. In the meta-analysis of this review, the summary POR for LBP and sciatic pain was slightly higher than those reported in the meta-analysis by Boshuizen et al. [13] for cross-sectional studies published up to 1990. However, in both reviews the results of meta-analysis lead to the conclusion that LBP disorders are associated with driving occupations.

Cohort and case-control studies indicate that there is an increased risk for degenerative changes of the spinal system, including lumbar intervertebral disc disorders, in crane operators, tractor drivers and drivers of the transportation industry [6, 7, 12, 15]. This finding is in agreement with the results of an earlier case-control study which suggested that driving of motor vehicles is a risk factor for acute herniated lumbar intervertebral disc [38]. In the meta-analysis conducted by Boshuizen et al. [13], a summary odds ratio of 1.7 (95% CI: 1.1–2.7) for herniated disc was calculated from several case-control studies of occupational drivers investigated before 1987. This risk estimate is consistent with those obtained from the meta-analysis of both cross-sectional and cohort studies included in this review.

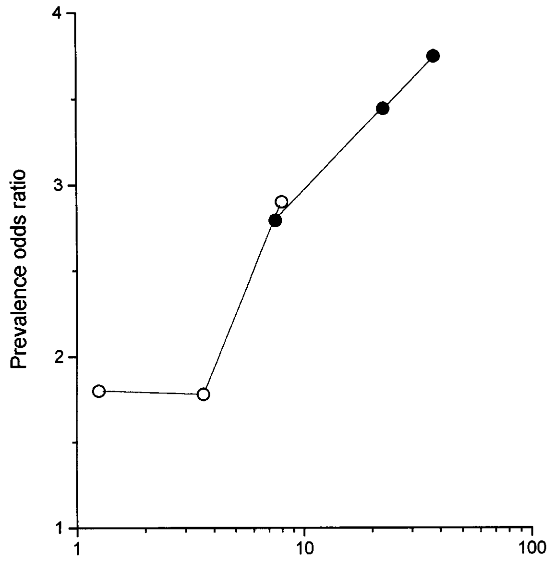

Fig. 2 Prevalence odds ratio for low back pain among tractor drivers as a function of lifetime cumulative whole-body vibration (WBV) dose estimated as $\sum a_{\mathrm{vi}}^2 t_i$ where a_{vi} is the vector sum of the frequency-weighted root mean square acceleration of tractor i and t_i is the number of full-time working years driven on tractor i (year $m^2\ s^{-4}$). ○, study of Boshuizen et al. 1990 [11]; ●, study of Bovenzi and Betta 1994 [4]

In the 1987 review [33], it was reported that firm conclusions on the relationship between WBV exposure and LBP disorders could not be drawn on the basis of the available epidemiologic data. In an outline of the exposure-response relation, Boshuizen et al. [14] observed a trend to higher risks for LBP disorders with exposure to higher magnitude of WBV, but no consistent relation with duration of exposure was seen. These authors suggested that the latter finding could be attributed to health-based selection due to the cross-sectional design of the majority of the studies. In 1993, Seidel stated that no essential progress was made in epidemiologic research to substantiate a reliable exposure-response relationship [61]. Burdorf and Sorock argued that, although dose-response trends were observed in various epidemiologic studies, the observed effect might be due to exposure to WBV or to prolonged sitting in a constrained posture [22]. Driving occupations involve exposure to both WBV and other ergonomic risk factors such as sitting posture, non-neutral trunk movements, and sometimes weight lifting and carrying. Thus, from epidemiologic studies it is difficult to differentiate the relative role of WBV and these other risk factors in the aetiology of LBP disorders and pathological changes in the spinal system of drivers. This also hampers the establishment of a clear quantitative relationship between WBV exposure and risk of adverse health effects [36]. Nevertheless, some elements of exposure-response relationship may be derived from two epidemiologic studies included in this review [4, 11]. These studies, which investigated large samples of tractor drivers, are to a great extent comparable. The investigators used the same methods to measure WBV at the workplace and to assess cumulative vibration dose according to the equal energy principle. The two tractor driver groups differed with respect to mean duration of exposure (10 *vs* 21 years) and vibration magnitude (0.7 *vs* 1.1 ms^{-2}). LBP symptoms were collected with a similar questionnaire and the influence of potential confounders and postural load was taken into account in the study design or data analysis. Figure 2 displays the estimated POR for LBP as a function of the lifetime cumulative WBV dose, suggesting a trend for an increasing risk for LBP with increasing WBV exposure.

Concluding remarks

The findings of this review provide clear evidence for an increased risk for LBP disorders in occupations with exposure to WBV. Biodynamic and physiological experiments have shown that seated WBV exposure can affect the spine by mechanical overloading and excessive muscular fatigue [67, 68], supporting the epidemiologic findings of a possible causal role of WBV in the development of (low) back troubles. The fact that the WBV measured in most of the industrial vehicles involved in this review exceed the 8-h action level of 0.5 ms^{-2}, and even the exposure limit value of 0.7 ms^{-2}, proposed by the European Union Directive for physical agents [24], stresses the relevance of the problem. This should stimulate the adoption of technical and health measures in order to prevent the onset of adverse health effects on the spine of drivers. Comparing the epidemiologic studies included in this review with those conducted before 1986, it may be concluded that research design and the quality of exposure and health effect data in the field of WBV have improved in the last decade. This encouraging perspective may be of help in the scientific development of preventive strategies.

Acknowledgement A slightly adapted version of this paper has been published in the Journal of Sound and Vibration 1998; 215: 595–611. The Authors wish to thank the Editors of the Journal of Sound and Vibration and Academic Press for their kind permission to reproduce the material. The updated version of this review was supported by the European Commission under the Biomed 2 Concerted Action BMH4-CT98-3251 (Vibration Injury Network).

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