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AN UPDATED REVIEW OF EPIDEMIOLOGIC STUDIES ON THE RELATIONSHIP BETWEEN EXPOSURE TO WHOLE-BODY VIBRATION AND LOW BACK PAIN

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The aim of this paper 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 1996. In a systematic search of epidemiologic studies of low back pain (LBP) disorders and occupations with exposure to WBV, 37 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, 16 articles reporting the occurrence of LBP disorders in 19 WBV-exposed occupational groups, reached a sufficient score. The study design was cross-sectional for 13 occupational groups, longitudinal for 5 groups and of case-control type for one group. 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 of 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. Upon 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.

1. 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 U.S.A., Canada, and some European countries, it has been estimated that 4 to 7% of all employees are exposed to potentially harmful WBV [1]. Experimental research has pointed out that exposure to WBV can affect the

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lumbar spine and the connected nervous system [2, 3]. Biodynamic experiments have shown that WBV exposure, combined with a constrained sitting posture, can put the lumbar intervertebral disc at risk of failure [4]. 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 [5–8]. In some countries, back disorders occurring in workers exposed to WBV are considered to be an occupational disease which is compensable [9].

A critical evaluation of the epidemiologic literature on the effects of long-term WBV exposure on the spinal system was published in 1987 [10]. This review indicated that LBP, early degeneration of the lumbar spinal 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 1996.

2. METHODS

2.1. 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 1996 were accepted for inclusion in the review. The literature search was not limited to articles published in English.

2.2. QUALITY RATING OF STUDIES

In the 1987 review [10], 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*. [11]. The quality of each study was evaluated according to criteria concerning the assessment of WBV exposure, assessment of health effects, and methodology (see Table 1). The available epidemiologic studies were assessed by the authors independently. There were 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.

2.3. META-ANALYSIS

A meta-analytic approach was used in order to combine and summarize the results of independent epidemiologic studies [12]. Point estimates and 95% confidence intervals (Cl)

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

		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 $\pm$ sd):		
age, smoking, education		1 for each item
manual handling, bending and twisting,		
heavy physical work,		1 for each item
job dissatisfaction, low decision latitude		
	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		1 for each item
job dissatisfaction, low decision latitude		
	maximum subtotal	8
	maximum total	30

TABLE 2

Summary of epidemiologic studies of low back pain (LBP) *disorders and occupations with exposure to whole-body vibration* (WBV) (1986–1996)

Author(s) (year) [reference number]	Study group	Control group	Vibration magnitude and/ or duration of exposure (mean or range)	Study design	Data source	Results	Quality score†
Brendstrup and Biering–Sørensen (1987) [16]	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 y 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) [39]	Crane operators ($n = 743$)	Maintenance workers ($n = 662$)	a_v 0·25–0·67 ms^{-2} $\leqslant$4–>20 years	Retro-spective (10 years) cohort study	Social insurance medical records	IDR for disability pensioning: 1·3 (0·8–2·1)‡ all back disorders 1·5 (0·6–3·6)‡ spondylosis 2·0 (1·1–3·7)‡ intervertebral disc disorders Increased risk for disability due to intervertebral disc disorders with increasing years of exposure	E: 20 (80%) H: 15 (100%) M: 17 (57%)
Bongers *et al*. (1988) [40]	Crane operators ($n = 743$)	Maintenance workers ($n = 662$)	a_v 0·25–0·67 ms^{-2} $\leqslant$4–>20 years	Retro-spective (10 years) cohort study	Social insurance medical records	IDR for at least one spell of sickness absence of $\geqslant$28 days due to back disorders: 1·0 (0·8–1·3)‡ all back disorders 1·0 (0·4–2·4)‡ spondylarthrosis 1·2 (0·7–2·1)‡ intervertebral disc disorders 1·4 (0·7–2·7)‡ herniated disc	E: 20 (80%) H: 15 (100%) M: 17 (57%)
Bongers *et al*. (1990) [41]	Crane operators ($n = 341$)	Metal workers/ bench fitters ($n = 3130$)	a_v 0·3–0·5 ms^{-2} (estimated)	Retro-spective (40 years) 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) [45]	Drivers of the transport-ation industry ($n = 347$)	All other occupations in transport-ation 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 a back disorders with increasing total lifetime exposure to whole-body vibration	E: 15 (60%) H: 10 (67%) M: 11 (37%)
Boshuizen *et al*. (1990) [42]	Tractor drivers ($n = 423$)	Not or slightly exposed workers ($n = 375$)	a_v 0·72 ms^{-2}	Retro-spective (11 years) 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) [22]	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§	E: 25 (100%) H: 15 (100%) M: 16 (53%)
Bongers *et al*. (1990) [23]	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§	E: 25 (100%) H: 15 (100%) M: 16 (53%)
Bongers *et al*. (1990) [24]	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§	E: 25 (100%) H: 15 (100%) M: 16 (53%)

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TABLE 2 (*continued*)

Author(s) (year) [reference number]	Study group	Control group	Vibration magnitude and/ or duration of exposure (mean or range)	Study design	Data source	Results	Quality score†
Boshuizen *et al.* first study (1990) [25]	Fork-lift truck drivers and freight-container tractor 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 15%) POR: 0·8 (0·3–2·2)‡	E: 25 (100%) H: 15 (100%) M: 16 (53%)
Boshuizen *et al.* second study (1990) [25]	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§	E: 25 (100%) H: 15 (100%) M: 16 (53%)
Johanning (1991) [26]	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 (1993) [32]	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 yr LBT (control group 66%) POR: 3·0 (1·8–5·1)‖ 35% 1 yr acute LBP (control group 24%) POR: 1.9 (1·1–3·1)‖ 33% 1 yr 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§	E: 25 (100%) H: 15 (100%) M: 18 (60%)

Burdorf *et al.* (1993) [33]	Crane operators ($n = 94$) Straddle-carrier (SC) drivers ($n = 95$)	Office workers ($n = 86$)	Crane operators: a_v 0·31 ms^{-2}, 8·1 years. SC 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) [34]	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 yr LBT (control group 37%) POR: 2·4 (1·6–3·7)‖ 36% 1 yr acute LBP (control group 10%) POR: 3·0 (1·8–5·0)‖ 16% 1 yr 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§	E: 25 (100%) H: 15 (100%) M: 14 (60%)
Sandover *et al.* (1994) [36]	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 yr LBP (control group 16%)	E: 15 (60%) H: 10 (67%) M 12 (40%)
Magnusson *et al.* (1996) [38]	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¶ 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%)

† 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; IDR = age-adjusted incidence ratio; OR/POR = odds ratio/prevalence odds ratio, adjusted for several covariaties or at least for age; ¶ Crude POR.

‡ (90% confidence intervals), ‖ (95% confidence intervals);

§ WBV dose = $\Sigma a_{vi}^2 t_i$, 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 $m^2 s^{-4}$)

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

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* (1986–1996). *One-year prevalence of* LBP *in the exposed and control groups, point estimates of the prevalence odds ratio* (POR) *and* 95% *confidence intervals* (Cl), *adjusted at least for age, are given for each study. Random effects estimation of the summary* POR (95% Cl) *and test for homogeneity between studies are reported*

Occupational group	Ref. (no.)	Prevalence exposed group (%)	Prevalence control group (%)	POR (95% Cl)	Study weight
Fork-lift truck drivers	16	65	52	1·7 (0·9–3·1)	7·3
Tractor drivers	22	31	19	2·0 (1·2–3·4)	9·2
Wheel loaders	24	47	39	1·3 (0·5–3·2)	4·0
Fork-lift truck drivers	25	57	16	7·3 (2·5–22)	2·9
Fork-lift truck drivers	25	41	29	1·6 (1·0–2·6)	10·6
Bus drivers	32	83	66	3·0 (1·8–5·1)	9·2
Crane operators	33	40	20	3·3 (1·5–7·1)	5·1
Straddle-carrier drivers	33	31	20	2·5 (1·2–5·4)	5·4
Tractors drivers	34	72	37	2·4 (1·6–3·7)	11·9
Summary POR (95% Cl)				2·3 (1·8–2·9)	
Homogeneity χ^2		11·2			
Homogeneity degrees of freedom		8			
Homogeneity p value		0·19			

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

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 (1986–1996). *One-year prevalence of sciatic pain in the exposed and control groups, point estimates of the prevalence odds ratio* (POR) *and* 95% *confidence intervals* (Cl), *adjusted at least for age, are given for each study. Random effects estimation of the summary* POR (95% Cl) *and test for homogeneity between studies are reported*

Occupational group	Ref. (no.)	Prevalence exposed group (%)	Prevalence control group (%)	POR (95% Cl)	Study weight
Tractor drivers	22	19	13	1·6 (0·9–3·0)	4·6
Wheel loaders	24	15	17	1·0 (0·3–3·1)	2·3
Fork-lift truck drivers	25	22	10	2·7 (0·6–12)	1·5
Fork-lift truck drivers	25	12	12	1·0 (0·5–2·2)	3·6
Subway train operators	26	23	7	3·9 (1·7–8·6)	3·5
Bus drivers	32	33	22	1·9 (1·2–3·3)	5·5
Tractors drivers	34	16	4	3·9 (1·8–8·7)	3·6
Summary POR (95% Cl)				2·0 (1·3–2·9)	
Homogeneity χ^2		10·4			
Homogeneity degrees of freedom		6			
Homogeneity p value		0·11			

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 (1986–1996). *The prevalence of herniated disc in the exposed and control groups, point estimates of the prevalence odds ratio* (POR) *and* 95% *confidence intervals* (Cl), *adjusted at least for age, are given for each study. Random effects estimation of the summary* POR (95% Cl) *and test for homogeneity between studies are reported*

Occupational group	Ref. (no.)	Prevalence exposed group (%)	Prevalence control group (%)	POR (95% Cl)	Study weight
Tractor drivers	22	8	5	2·1 (0·8–5·6)	4·0
Fork-lift truck drivers	25	4	5	0·8 (0·2–2·6)	2·7
Bus drivers	32	8	7	1·3 (0·6–3·0)	5·9
Tractors drivers	34	7	2	1·8 (0·7–4·7)	4·2
Summary POR (95% Cl)				1·5 (0·9–2·4)	
Homogeneity χ^2		1·8			
Homogeneity degrees of freedom	3				
Homogeneity p value		0·62			

according to a random effects model proposed by DerSimonian and Laird [13]. 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-analyzed. 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.

3. RESULTS

Initially, the literature search provided 37 articles which described the occurrence of LBP disorders in WBV-exposed occupational groups or driving occupations. Of these, 25 were cross-sectional studies [14–38], five were cohort studies [39–43], two were case-control studies [44, 45], and five were community-based epidemiologic studies [46–50]. One cross-sectional study reported data on the prevalence of LBP in two different groups of fork-lift truck drivers [25]. Two studies included both cross-sectional and follow-up data on the occurrence of LBP disorders in fork-lift truck drivers and commercial travelers [16, 31].

After applying the above-mentioned evaluation criteria, 21 articles were excluded from the final review. The main exclusion criterion pertained to the lack of sufficient quantitative information on exposure to WBV [15, 17, 19–21, 27–31, 35, 43, 44, 46–50]. 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, 35, 37], incomplete description of potential confounders or other risk factors for LBP, or inadequate control for such confounders in the study design or analysis [14, 15, 28–30, 37], were also causes for the exclusion of studies.

Finally, 16 articles reporting the occurrence of LBP disorders in 19 WBV-exposed occupational groups, met the inclusion criteria. The study design was cross-sectional for 13 occupational groups, longitudinal for five groups and of case-control type for one group.

Table 2 summarizes 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 [33, 39–41], bus drivers [32, 38], tractor drivers [22, 34, 36, 42], and fork-lift truck drivers [16, 25] 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 [23, 33, 34, 38] or manual workers such as maintenance operators [32, 39, 40]. 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 [51]. In general, vibration magnitude was expressed in terms of the vector sum of the frequency-weighted root mean square (r.m.s.) acceleration, with the exception of two studies in which vibration magnitude was measured only in the vertical direction [36, 38]. The reported values of vibration magnitude varied from 0·25–0·67 ms^{-2} in cranes, 0·36–0·56 ms^{-2} in buses, 0·35–1·45 ms^{-2} in tractors, and 0·79–1·04 ms^{-2} in fork lift trucks and freight container tractors. For the drivers of these vehicles, some investigators 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 [51]: $\Sigma a_{vi}^2 t_i$ (year m^2 s^{-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 [22, 25, 32, 34].

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 (1986–1996). *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* (Cl) *are given for each study*. *Random effects estimation of the summary* IDR (95% Cl) *and test for homogeneity between studies are reported*

	Ref. (no.)	Incidence exposed group (per 100 py)	Incidence control group (per 100 py)	IDR (95% Cl)	Study weight
Back disorders					
Crane operators	39	0·85	0·47	1·3 (0·8–2·3)	13·3
Crane operators	41	0·57	0·37	1·0 (0·6–1·9)	10·6
Tractor drivers	42	3·03	1·94	1·5 (1·0–2·2)	21·9
Summary IDR (95% Cl)				1·3 (0·9–1·7)	
Homogeneity χ^2		0·9			
Homogeneity degrees of freedom		2			
Homogeneity p value		0·65			
Lumbar disc disorders					
Crane operators	39	0·61	0·21	2·0 (0·9–4·2)	6·9
Crane operators	41	0·22	0·16	1·1 (0·4–2·9)	4·2
Tractor drivers	42	0·63	0·18	3·1 (1·0–10)	2·8
Summary of IDR (95% Cl)				1·8 (1·1–3·1)	
Homogeneity χ^2		1·9			
Homogeneity degrees of freedom		2			
Homogeneity p value		0·38			

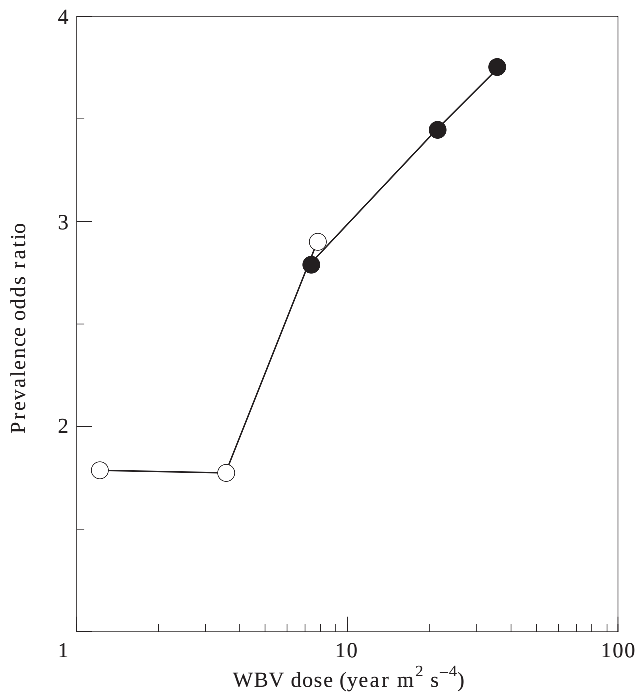

Figure 1. Prevalence odds ratio for low back pain among tractor drivers as a function of lifetime cumulative whole-body vibration (WBV) dose estimated as $\Sigma a_{vi}^2 t_i$, where a_{vi} is the vector sum of the frequency-weighted root mean square acceleration of tractor i and t_i is the number of full-time working years driven on tractor i (year m^2 s^{-4}). ○, Study of Boshuizen *et al*. [22], 1990; ●, Study of Bovenzi and Betta [34], 1994.

For the assessment of health effects in cross-sectional studies, the investigators used predominantly medical interview or questionnaires identical or similar to the standardized Nordic Questionnaire on musculoskeletal symptoms [52]. 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.

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 than for 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 [22, 23, 25, 32, 34, 38]. Some trend of increasing prevalence of LBP disorders with the increase of lifetime WBV dose was observed in cross-sectional studies of bus drivers [32], tractor drivers [22, 34], fork-lift truck drivers [25], and wheel loaders [24]. 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 [45].

The results of the meta-analysis confirms the findings of individual studies. A significant increase in the pooled POR for one-year prevalence of LBP (see Table 3) and sciatic pain (see 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 excluded from the meta-analysis because the exposure conditions are not comparable with those arising from driving industrial vehicles [23].

An excess risk for lumbar disc disorders, including herniated disc, was also found in the WBV-exposed occupational groups compared with the control groups (see Tables 5 and 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 U.S.A. and Canada also found 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 U.S. male working population [49] or in workers with no exposure to physical risk factors [50]. These community-based epidemiologic studies were, however, not included in the final review because of the lack of quantitative information on WBV exposure.

4. DISCUSSION

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 a very comprehensive literature collection was consulted. Moreover, some of the key words used, in particular whole-body vibration, were rather specific and thus able to detect all of the available studies published during the selected time period (1986–1996). 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 [10]. Although any quality rating system comprises some arbitrary elements of judgement, we feel that the present quality score, adapted from Kuiper *et al*. [11], 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 on 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 [53]. One preferred to abstain from this because even one low category score may severely reduce the quality of the study. Instead, in the present review, 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 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 may 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.

Sometimes, the application of meta-analysis to combine the results of individual studies has been questioned because of the differences in outcomes, characteristics of the study populations, and heterogeneity of the risk estimates [54, 55]. In this review, one considers the use of meta-analysis techniques as justified because of the general consistency between studies with respect to the anamnestic or clinical definition of LBP disorders [52] and the assessment of WBV exposure according to the guidelines of ISO 2631-1 [51]. Furthermore, data analysis revealed no significant heterogeneity between studies.

The results of this review confirm the findings of the 1987 review [10] and those of more recent literature surveys of the adverse health effects of WBV exposure [6–8, 56, 57]. 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 when compared to control groups not exposed to WBV. In the meta-analysis of this review, the summary POR for LBP and sciatic pain were slightly higher than those reported in the meta-analysis by Boshuizen *et al*. [56] 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 increase risk for degenerative changes of the spinal system, including lumbar intervertebral disc disorders, in crane operators, tractor drivers and drivers of the transportation industry [39, 40, 42, 45]. 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 an acute herniated lumbar intervertebral disc [58]. In the meta-analysis conducted by Boshuizen *et al*. [56], a summary odds ratio of 1·7 (95% CI: 1·1–2·7) for herniated discs 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. In the 1987 review [10], 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*. [59] 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 [6]. 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 [57]. 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 [60]. Nevertheless, some elements of exposure–response relationship may be derived from two epidemiologic studies included in this review [22, 34]. These studies, in which large samples of tractor drivers were investigated, 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 versus 21 years) and vibration magnitude ($0{\cdot}7$ versus $1{\cdot}1$ 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 1 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.

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 [3, 4], 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-hour action level of $0{\cdot}5$ ms^{-2}, and even the exposure limit value of $0{\cdot}7$ ms^{-2}, proposed by the European Union Directive for physical agents [61], 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. Upon 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.

REFERENCES

1. Comité Européen de Normalisation 1996 *Mechanical vibration—Guide to the health effects of vibration on the human body*, *CEN Report* 12349. Brussels: CEN.
2. M. J. Griffin 1990 *Handbook of human vibration*. London: Academic Press.
3. D. G. Wilder 1993 *American Journal of Industrial Medicine* **23**, 577–588. The biomechanics of vibration and low back pain.
4. D. G. Wilder and M. H. Pope 1996 *Clinical Biomechanics* **11**, 61–73. Epidemiological and aetiological aspects of low back pain in vibration environments—an update.
5. H. Seidel and R. Heide 1986 *International Archives of Occupational and Environmental Health* **58**, 1–26. Long-term effects of whole-body vibration: a critical survey of the literature.
6. H. Seidel 1993 *American Journal of Industrial Medicine* **23**, 589–604. Selected health risks caused by long-term, whole-body vibration.
7. B. O. Wikström, A. Kjellberg and U. Landström 1994 *International Journal of Industrial Ergonomics* **14**, 273–292. Health effects of long-term occupational exposure to whole-body vibration: a review.
8. M. Bovenzi 1996 *Seminars in Perinatology* **20**, 38–53. Low back pain disorders and exposure to whole-body vibration in the workplace.
9. H. Dupuis 1994 *International Archives of Occupational and Environmental Health* **66**, 303–308. Medical and occupational preconditions for vibration-induced spinal disorders: occupational disease no. 2110 in Germany.
10. C. T. J. Hulshof and O. B. A. Veldhuijzen van Zanten 1987 *International Archives of Occupational and Environmental Health* **59**, 205–220. Whole-body vibration and low back pain—a review of epidemiologic studies.
11. J. I. Kuiper, A. Burdorf, J. H. A. M. Verbeek, M. H. W. Frings-Dresen, A. J. van der Beek and E. R. A. Viikari-Juntura 1998 *International Journal of Industrial Ergonomics* (submitted). Epidemiological evidence on manual materials handling as risk factors for back disorders: a systematic review.

12. K. Dickersin and J. A. Berlin 1992 *Epidemiologic Reviews* **14**, 154–176. Meta-analysis: state-of-the-science.
13. R. DerSimonian and N. Laird 1986 *Controlled Clinical Trials* **7**, 177–188. Meta-analysis in clinical trials.
14. E. Occhipinti, D. Colombini, S. Cantoni, O. Menoni, S. Grillo, G. Molteni and A. Grieco 1986 *La Medicina del Lavoro* **77**, 280–292. Changes in the spine of drivers of heavy vehicles (in Italian with English summary).
15. M. Kompier, K. de Vries, F. van Noord, H. Mulders, T. Meijman and J. Broersen 1987 in *Musculoskeletal disorders at work* (P. Buckle, editor), 17–22. London: Taylor & Francis. Physical work environment and musculoskeletal disorders in the busdriver's profession.
16. T. Brendstrup and F. Biering-Sørensen 1987 *Scandinavian Journal of Work, Environment & Health* **13**, 442–452. Effect of fork-lift truck driving on low-back trouble.
17. M. Nakata 1987 *Japanese Journal of Industrial Health* **29**, 279–291. Labor of freight-container tractor drivers and low-back pain. Characteristics of the low-back pain through clinical findings (in Japanese with English summary).
18. A. Burdorf, Y. Musson and D. van Drimmelen 1987 *Tijdschrift voor Sociale Gezondheidszorg* **65**, 548–554. Trillingsbelasting en gezondheid in beroepsgroepen. Deel II: Lichaamstrillingen (in Dutch with English summary).
19. F. H. Müsch 1989 *Proceedings of the Third International Symposium of the International Section of the International Social Security Association for Research on Prevention of Occupational Risks, Vibration at Work, Wien*, 64–67. Lumbalsyndrom bei Erdbaumaschinenfahrern mit langjähriger Ganzkörper-vibrationsbelastung.
20. H. Riihimäki, S. Tola, T. Videman and K. Hänninen 1989 *Spine* **14**, 204–209. Low back pain and occupation. A cross-sectional questionnaire study of men in machine operating, dynamic physical work, and sedentary work.
21. A. Burdorf and H. Zondervan 1990 *Ergonomics* **33**, 981–987. An epidemiological study of low-back pain in crane operators.
22. H. C. Boshuizen, P. M. Bongers and C. T. J. Hulshof 1990 *International Archives of Occupational and Environmental Health* **62**, 109–115. Self-reported back pain in tractor drivers exposed to whole-body vibration.
23. P. M. Bongers, C. T. J. Hulshof, L. Dijkstra, H. C. Boshuizen, H. J. M. Groenhout and E. Valken 1990 *Ergonomics* **33**, 1007–1026. Back pain and exposure to whole body vibration in helicopter pilots.
24. P. M. Bongers, H. C. Boshuizen and C. T. J. Hulshof 1990 *Academisch Proefschrift, Universiteit van Amsterdam*, 205–220. Self-reported back pain in drivers of wheelloaders.
25. H. C. Boshuizen, P. M. Bongers and C. T. J. Hulshof 1992 *Spine* **17**, 59–65. Self-reported back pain in fork-lift truck and freight-container tractor drivers exposed to whole-body vibration.
26. E. Johanning 1991 *Scandinavian Journal of Work, Environment & Health* **17**, 414–419. Back disorders and health problems among subway train operators exposed to whole-body vibration.
27. A. Burdorf, G. Govaert and L. Elders 1991 *Ergonomics* **34**, 909–918. Postural load and back pain of workers in the manufacturing of prefabricated concrete elements.
28. R. Anderson 1992 *Spine* **17**, 1481–1488. The back pain of bus drivers.
29. S. Piccinni, T. Marchi, A. Lorusso and G. Magarotto 1992 *La Medicina del Lavoro* **83**, 146–149. Prevalence of spondylarthropathy among crane operators in the Venice harbour (in Italian with English summary).
30. K. Miyashita, I. Morioka, T. Tanabe, H. Iwata and S. Takeda 1992 *International Archives of Occupational and Environmental Health* **64**, 347–351. Symptoms of construction workers exposed to whole body vibration and local vibration.
31. F. Pietri, A. Leclerc, L. Boitel, J. F. Chastang, J. F. Morcet and M. Blondet 1992 *Scandinavian Journal of Work, Environment & Health* **18**, 52–58. Low-back pain in commercial travelers.
32. M. Bovenzi and A. Zadini 1992 *Spine* **17**, 1048–1059. Self-reported low back symptoms in urban bus drivers exposed to whole-body vibration.
33. A. Burdorf, B. Naaktgeboren and H. C. W. M. de Groot 1993 *Journal of Occupational Medicine* **35**, 1213–1220. Occupational risk factors for low back pain among sedentary workers.
34. M. Bovenzi and A. Betta 1994 *Applied Ergonomics* **25**, 231–241. Low-back disorders in agricultural tractor drivers exposed to whole-body vibration and postural stress.
35. D. Masset and J. Malchaire 1994 *Spine* **19**, 143–146. Low back pain—Epidemiologic aspects and work-related factors in the steel industry.

36. J. Sandover, L. Gardner, P. Stroud and N. Robertson 1994 *Proceedings of United Kingdom Informal Group Meeting on Human Response to Vibration*, *Institute of Naval Medicine*, *Alverstoke*, *Gosport*, 1–21. Some epidemiological issues regarding vibration and tractor driving.
38. M. L. Magnusson, M. H. Pope, D. G. Wilder and B. Areskoug 1996 *Spine* **21**, 710–711. Are occupational drivers at an increased risk for developing musculoskeletal disorders?
39. P. M. Bongers, H. C. Boshuizen, C. T. J. Hulshof and A. C. Koemeester 1988 *International Archives of Occupational and Environmental Health* **60**, 129–137. Back disorders in crane operators exposed to whole-body vibration.
40. P. M. Bongers, H. C. Boshuizen, C. T. J. Hulshof and A. C. Koemeester 1988 *International Archives of Occupational and Environmental Health* **61**, 59–64. Long-term sickness absence due to back disorders in crane operators exposed to whole-body vibration.
41. P. M. Bongers, H. C. Boshuizen and C. T. J. Hulshof 1990 *Academisch Proefschrift*, *Universiteit van Amsterdam*, 145–152. Disability due to back disorders in crane operators in a metal construction company; short communication.
42. H. C. Boshuizen, C. T. J. Hulshof and P. M. Bongers 1990 *International Archives of Occupational and Environmental Health* **62**, 117–122. Long-term sick leave and disability pensioning due to back disorders of tractor drivers exposed to whole-body vibration.
43. H. Riihimäki, E. Viikari-Juntura, G. Moneta, J. Kuha, T. Videman and S. Tola 1994 *Spine* **19**, 138–142. Incidence of sciatic pain among men in machine operating, dynamic physical work, and sedentary work. A three-year follow-up.
44. M. Heliövaara 1987 *Journal of Chronic Diseases* **40**, 259–264. Occupation and risk of herniated lumbar intervertebral disc or sciatica leading to hospitalization.
45. H. C. Boshuizen, P. M. Bongers and C. T. J. Hulshof 1990 *Academisch Proefschrift*, *Universiteit van Amsterdam*, 95–105. An explorative case-referent study of disability due to back disorders in relation to driving.
46. K. Walsh, N. Varnes, C. Osmond, R. Styles and D. Coggon 1989 *Scandinavian Journal of Work*, *Environment & Health* **15**, 54–59. Occupational causes of low-back pain.
47. K. Walsh, M. Cruddas and D. Coggon 1991 *Scandinavian Journal of Work*, *Environment & Health* **17**, 420–424. Interaction of height and mechanical loading of the spine in the development of low-back pain.
48. V. Behrens, P. Seligman, L. Cameron, C. G. T. Mathias and L. Fine 1994 *American Journal of Public Health* **84**, 1780–1785. The prevalence of back pain, hand discomfort, and dermatitis in the US working population.
49. H. R. Guo, S. Tanaka, L. L. Cameron, P. J. Seligman, V. J. Behrens, J. Ger, D. K. Wild and V. Putz-Anderson 1995 *American Journal of Industrial Medicine* **28**, 591–602. Back pain among workers in the United States: national estimates and workers at high risk.
50. J. P. Liira, H. S. Shannon, L. W. Chambers and T. A. Haines 1996 *American Journal of Public Health* **86**, 382–387. Long-term back problems and physical work exposures in the 1990 Ontario Health Survey.
51. International Organization for Standardization 1985 *ISO* 2631-1, *first edition*. Guide for the evaluation of human exposure to whole body vibration. Part 1: General requirements.
52. I. Kuorinka, B. Jonsson, A. Kilbom, H. Vinterberg, F. Biering-Sørensen, G. Andersson and K. Jørgensen 1987 *Applied Ergonomics* **18**, 233–237. Standardised Nordic questionnaire for the analysis of musculoskeletal symptoms.
53. B. W. Koes, W. J. J. Assendelft, G. J. M. G. van der Heijden, L. M. Bouter and P. G. Knipschild 1991 *British Medical Journal* **303**, 1298–1303. Spinal manipulation and mobilization for back and neck pain: a blinded review.
54. J. L. Fleiss and A. J. Gross 1991 *Journal of Clinical Epidemiology* **44**, 127–139. Meta-analysis in epidemiology, with special reference to studies of the association between exposure to environmental tobacco smoke and lung cancer: a critique.
55. W. E. van der Weide, J. H. Verbeek and M. W. van Tulder 1997 *Scandinavian Journal of Work*, *Environment & Health* **23**, 165–178. Vocational outcome of intervention for low-back pain.
56. H. C. Boshuizen, P. M. Bongers and C. T. J. Hulshof 1990 *Academisch Proefschrift*, *Universiteit van Amsterdam*, 223–250. Whole-body vibration and back disorders; a meta-analysis.
57. A. Burdorf and G. Sorock 1997 *Scandinavian Journal of Work*, *Environment & Health* **23,** 243–256. Positive and negative evidence on risk factors for back disorders.

58. J. L. Kelsey and R. L. Hardy 1975 *American Journal of Epidemiology* **102**, 63–73. Driving of motor vehicles as a risk factor for acute herniated lumbar intervertebral disc.
59. H. C. Boshuizen, P. M. Bongers and C. T. J. Hulshof 1990 *Academisch Proefschrift*, *Universiteit van Amsterdam*, 251–269. Whole-body vibration and back disorders; an outline of the dose–response relation.
60. International Organization for Standardization 1997 *ISO* 2631-1, *second edition*. Guide for the evaluation of human exposure to whole body vibration—part 1: general requirements.
61. Council for the European Union 1994 *Official Journal of the European Communities*, *Brussels* 94/*C* 230/03, *No C* 230/3-29. Amended proposal for a Council Directive on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents—Individual Directive in relation to Article 16 of the Directive 89/391/EEC.