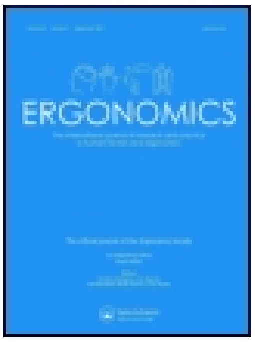

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The impact of operating heavy equipment vehicles on lower back disorders

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Literature reviews examining the relationship between heavy equipment vehicle (HEV) operation and the development of musculoskeletal disorders have generally been qualitative in nature and have not employed an evidence-based assessment procedure. This research determines the extent to which whole-body vibration/shock and working postures are associated with lower back and neck disorders among HEV operators, while accounting for individual (i.e. age, gender, prior history of back or neck disorders) and occupational (i.e. material handling, climatic conditions, psychosocial factors) confounders. Published articles were obtained from a search of electronic databases and from bibliographies in the identified articles. A critical appraisal of these articles was conducted using an epidemiological appraisal instrument (Genaidy *et al.* 2007). The meta-analysis was conducted using statistical techniques employing fixed-effect and random-effect models. Eighteen articles reporting observational studies satisfied the inclusion criteria adopted for this research. The methodological qualities of the published studies ranged from marginal to average. The meta-relative risk was found to be 2.21, indicating that operators exposed to driving HEVs are at more than twice the risk of developing lower back pain in comparison to those not exposed to driving HEVs. Therefore, it seems possible that there is a causal relationship between working as a HEV operator and development of lower back disorders. Prospective cohort studies are urgently needed to confirm the outcomes of this evidence-based methodology (based in part on the meta-analysis) and the biological plausibility should be further explored. The reported findings point to a need for improved ergonomic design of HEVs.

Keywords: vibration; mechanical shock; musculoskeletal disorders; critical review; meta-analysis

1. Introduction

Heavy equipment vehicles (HEVs) are designed to execute specialised, heavy-duty tasks such as transportation, farming and construction activities. Typical HEVs include backhoe loader, bulldozer, compactor, crane, dragline, logging equipment, forklift, front end loader, grader, harvester, paver, dump truck, scraper, skid loader and tractor. The operation of a HEV may expose its operator to multiple risk factors for musculoskeletal disorders (MSDs), including static work postures (e.g. trunk and neck twisting, stooping, deep sideway trunk bending), whole-body vibration, shock (also called jarring and jolting), physical work demands (e.g. walking, pulling, lifting), poor

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climatic conditions (e.g. heat, cold), and psychosocial factors (e.g. job satisfaction) (Troup 1978, Brendstrup and Biering-Sorensen 1987, Bongers *et al.* 1988). The present paper deals with risk of MSDs among HEV operators, but limits the focus to studies that seek to answer the following question: 'To what extent are whole-body vibration/shock and working postures associated with lower back and neck disorders among HEV operators, while accounting for individual (i.e. age, gender, prior history of back or neck disorders) and occupational confounders (i.e. material handling, climatic conditions, psychosocial factors)?'.

Numerous reviews examining the risk factors for MSDs due to operation of HEVs have been published (Troup 1978, Hagberg 1984, Helmkamp *et al.* 1984, Sandover 1988, Boshuizen *et al.* 1990b, Wilder *et al.* 1996, Wilder and Pope 1996, Magnusson and Pope 1998, Pope *et al.* 1998, Sandover 1998, Bovenzi and Hulshof 1999, Teschke *et al.* 1999, Lings and Leboeuf-Yde 2000, Mehta and Tewari 2000, Stayner 2001, Walker-Bone and Palmer 2002, Kittusamy and Buchholz 2004, Ramos-Vieira and Kumar 2004). Most reviews were qualitative in nature and did not employ an evidence-based assessment of the epidemiological methods. Rosenberg and Donald (1995) described an evidence-based approach as a process consisting of four steps: (1) formulation of a clear ergonomic question from a user's problem (in this case, the aforementioned research question); (2) search the literature for relevant reports; (3) critically appraise the evidence for its validity and usefulness; (4) implement useful findings in ergonomics practice (e.g. develop and implement interventions). Most of the reviews mentioned above, although not explicitly designed to answer the research question in this paper, did not include a critical appraisal of published studies. This paper provides a critical appraisal and a meta-analysis designed to strengthen the understanding of the relationship between operation of a HEV and development of low back and neck disorders.

2. Methods

2.1. Search strategy and inclusion criteria

In this critical appraisal the target population was HEV operators and the outcome of interest was lower back and neck disorders. Observational studies were considered, including retrospective/prospective, cohort incidence, case–control, proportional hazards and cross-sectional studies. Initially, there was no restriction on the exposure variable collected from the target population, other than at least one year experience as a HEV operator. Later, measures of exposure to vibration and postures were added.

As indicated in the outline of the search strategy in Table 1, publications were retrieved by a search of electronic databases, including PubMed, NIOSHTIC and NIOSHTIC-2 (up to May 2005) using a combination of the following keywords: (a) forklift/fork-lift and back/neck pain; (b) tractor and back/neck pain; (c) crane and back/neck pain; (d) earth movers; (e) operating engineers and back/neck pain. The details of the combinations of keywords are given in Table 1. In addition to the electronic search, bibliographies in identified papers were reviewed for additional studies. In essence, the titles of articles in the bibliographies were reviewed for relevance. If deemed relevant, the abstracts were extracted, followed by the articles.

The search was restricted to reports published in English; abstracts and reviews were not included. Studies were excluded if they did not present basic data that are usable in the derivation of the meta-analysis risk assessment. If there was more than one article dealing

Table 1. Summary of steps involved in electronic search of databases.

Step 1. Number of abstracts obtained for each database with corresponding keywords

	Databases		
Keyword	PubMed	NIOSHTIC	NIOSHTIC-2
Fork-lift and neck/back pain	4	1	0
Forklift and vibration	6	10	1
Fork-lift and vibration	5	8	0
Tractor and neck/low back	12	11	2
Tractor and neck/back pain	15	14	2
Crane and neck/low back	12	19	2
Crane and neck/back pain	16	14	0
Earth movers	3	6	2
Operating engineers and neck/back pain	9	0	0
Operating engineers and neck/low back	8	1	2

Step 2. Number of abstracts obtained for each type of equipment across all databases

Type of Equipment	Number of Abstracts
Forklift	35
Crane	63
Tractor	56
Earth movers	11
Operating engineers	20

Step 3. Number of abstracts obtained for each type of equipment after elimination of duplication

Type of Equipment	Number of Abstracts
Forklift	32
Crane	33
Tractor	32
Earth movers	11
Operating engineers	12

Step 4. Number of studies obtained for each type of equipment after applying inclusion criteria and adding relevant articles from bibliographies included in identified articles and reviews

Type of Equipment	Number of Studies
Forklift	6
Crane	3
Tractor	3
Earth movers	4
Operating engineers	1

Note: The total number of studies are 13 but three of the studies included more than one type of equipment.
Inclusion criteria:

1. English.
2. Peer reviewed journal.
3. Full text (no abstract).
4. Epidemiological study.
5. Vibration, postures, and/or occupation as exposures variables.

with the same or overlapping population, preference was given to the article that used exposure and outcome measures that were most similar to those used in other articles by different authors.

2.2. *Data extraction*

From all the included studies, the following items were documented: location (US vs. non-US); study design; study period; number of exposed groups; exposure variable; outcome (e.g. prevalence or incidence). The data were extracted from each article by one reviewer and verified by another reviewer. Discrepancies identified by the second reviewer were resolved between the two reviewers in a consensus meeting.

2.3. *Quality assessment*

For all the studies included in the review, the methodological quality was assessed by means of the 'Epidemiological Appraisal Instrument' (EAI) developed by Genaidy *et al.* (2007). The EAI consists of 43 questions grouped into five scales: (1) reporting (17 items); (2) subject selection (seven items); (3) measurement quality (10 items); (4) data analysis (seven items); (5) generalisation of results (two items). Every item in the EAI is rated for a given study using one of the following options: (1) 'not applicable' (not included in score calculation); (2) 'yes' (two points); (3) 'partial' (one point); (4) 'no' (0 points); (5) 'unable to determine' (0 points). The final score for each scale was taken as the average of the values recorded for each item. Four members of the research team conducted the critical appraisal independently. The results of the evaluations were compared and areas of disagreement were discussed and resolved in a follow-up consensus meeting.

It should be noted that each article was critically appraised for the research question formulated in this research, rather than on the basis of the aims cited in each individual article. In order to be objective, this practice should be the basis for systematic reviews dealing with critical appraisals so that studies can be compared on an equal basis. As such, the quality of the studies is compared with regard to the research question in this paper.

2.4. *Statistical methods for meta-analysis*

Reviewed articles were subjected to a meta-analysis to estimate an overall odds ratio on lower back and neck disorders among HEV operators (meta-odds ratio). The confidence limit method was used to calculate the meta-odds ratio and 95% confidence limits (Elwood 2000). This necessitated the extraction of the total number of subjects participating in the exposed and non-exposed groups and the prevalence rates from each individual study. As such, an odds ratio and the corresponding 95% confidence limits were computed for each study and were then used in the calculation of the overall odds ratio. The 'LOGISTIC' procedure of the Statistical Analysis Software (SAS®; SAS Institute Inc., Cary, NC, USA) was used to calculate the odds and 95% confidence limits for each study.

Traditionally, a fixed-effect model is used if there is no heterogeneity among the studies. If this does exist, a random-effects model is preferred. A statistical test of the homogeneity assumption for the fixed-effect approach is given by:

$$Q = \sum_{i=1}^{n} w_i * \{\log(OR_i) - \log(mOR)\}^2$$

where OR_i and mOR are the relative risk for a given study and the meta-relative risk, respectively. The hypothesis would be rejected if Q exceeded $\chi^2_{n-1,\alpha}$ and the random-effects model would be used with a different study weight (W_i^*) that further accounts for the inter-study variation in effect size (Petiti 2000). The weighing factor W_i^* in the DerSimonian and Laird random-effects model is:

$$W_i^* = \frac{1}{\left[D + \left(\frac{1}{w_i}\right)\right]}$$

where w_i is the statistical weight for a given study for the fixed-effect model and is equal to $\left(1/SE_i^2\right)$ with SE_i being the standard error for a given study, and:

$$D = \frac{[Q - (n-1)]^* \sum_{i=1}^{n} W_i}{\left(\sum_{i=1}^{n} W_i\right)^2 - \sum_{i=1}^{n} W_i^2}$$

It should be noted that D is set to 0 if $Q < n-1$. The random-effects model was validated against data provided in Petiti (2000). In this study, an $\alpha \leq 0\%$ or less was adopted for declaring heterogeneity (Greenland 1987).

It was of interest to determine whether the overall quality of the studies might change the results obtained for the meta-analysis. A quality index weighting for the studies as described by Waters *et al.* (2006), was used to perform a second meta-analysis to weight the imapct of the higher quality studies.

3. Results

3.1. Identification of studies

The search of computerised databases identified a total of 185 peer-reviewed articles from PubMed, NIOSHTIC and NIOSHTIC-2. Table 1 provides a summary of the four-step search process. Upon review of published articles and after applying the inclusion criteria listed Table 1, a total of 18 studies were identified. Of those 18 articles, 12 were cross-sectional studies (Brendstrup and Biering-Sorensen 1987, Dupuis and Zerlett 1987, Boshuizen *et al.* 1990c, 1992, Burdorf and Zondervan 1990, Miyashita *et al.* 1992, Burdorf *et al.* 1993, Bovenzi and Betta 1994, Zimmermann *et al.* 1997, Kumar *et al.* 1999, Bovenzi *et al.* 2002, Hoy *et al.* 2005), five were cohort studies (Bongers *et al.* 1988, Tola *et al.* 1988, Boshuizen *et al.* 1990c, Riihimaki *et al.* 1994, Viikari-Juntura *et al.* 1994) and one was a hybrid design (Schwarze *et al.* 1998). The studies by Viikari-Juntura *et al.* (1994), Riihimaki *et al.* (1994) and Tola *et al.* (1988) were based on the same population but they differed in terms of the reported outcome measures (i.e. neck, both neck and shoulder or sciatic pain). Because most of the studies were cross-sectional (with 12 cross-sectional and one possessing a cross-sectional element in a hybrid design), the critical appraisal was conducted on these studies. The five cohort studies were reviewed, but could not be used in the meta-analysis due to differences in the health outcome measures used in the study.

The following studies by Spear *et al.* (1976), Nakata *et al.* (1987), Riihimaki *et al.* (1989), Franzini and Benedyk (1996), Futatsuka *et al.* (1998), Van Poppel *et al.* (1998), Shinozaki *et al.* (2001), Sjaastad and Bakketeig (2002), Toren *et al.* (2002), Holmström and Engholm (2003), Issever *et al.* (2003) and Järvholm *et al.* (2004) were not included because of overlapping population, no specification of vehicle type, lack of data, wrong type of study design (i.e. intervention) or wrong type of outcome (outcome other than MSDs).

3.2. Description of evidence

Table 2 gives the description of evidence for the 13 cross-sectional/hybrid studies in terms of exposure, outcome, study design, study population and main results. The highlights of this evidence are:

(1) All studies used a cross-sectional design except that by Schwarze *et al.* (1998), which was hybrid (cross-sectional with prospective cohort component).
(2) Lower back pain was investigated as an outcome in all studies. Neck pain was only measured in two studies (i.e. Dupuis and Zerlett 1987 and Zimmermann *et al.* 1997).
(3) All studies but one (Zimmermann *et al.* 1997) had control groups.
(4) Studies came from different parts of the world: UK (one); Italy (two); Germany (two); Netherlands (four); Japan (one); USA (one); Sweden (one); India (one).
(5) No single study examined all the covariates/confounders cited in the research question (as shown by Table 3). Boshuizen *et al.* (1992), Bovenzi and Betta (1994) and Bovenzi *et al.* (2002) were the only studies that made a significant effort to account for the majority of confounders/covariates, but even these studies did not sufficiently account for all of the factors (for example, psychosocial factors were not adequately evaluated).
(6) Associations with lower back pain demonstrated that four in six studies had a significant relationship at the 5% level for forklift operators, two in three studies for crane operators, all three studies for tractor operators and one in three studies for earth moving operators.

The description of evidence for the three prospective (Tola *et al.* 1988, Riihimaki *et al.* 1994, Viikari-Juntura *et al.* 1994) and two retrospective (Bongers *et al.* 1988, Boshuizen *et al.* 1990a) cohort studies is given in Table 4. These studies were based on moderately sized populations and adequate follow-up periods (adjusted at a minimum for age). Although the studies could not be used in the present meta-analysis, the findings demonstrated that there was a significant association between the task of operating heavy equipment machinery and development of lower back and neck disorders.

3.3. Critical appraisal of study quality

The studies identified from the literature search were subjected to a critical appraisal using the EAI (Genaidy *et al.* 2007). Each study was evaluated separately by four assessors. Thereafter, a consensus was established through follow-up meetings.

An overall appraisal of the studies suggested that the quality of individual studies ranged from marginal (0.5 on 0–2 scale) to average (1.0 on 0–2 scale) (Figure 1). Figure 2 provides a summary of the different methodological qualities for each study. The following can be deduced:

(a) Studies scored the highest values for the reporting scale in comparison to the other scales (range: 0.75–1.3).

Table 2. Summary of description of evidence for cross-sectional studies.

Type of Equipment	Source	Description
Forklift	Hoy *et al.* (2005)	
	Exposure	Whole-body vibration and postural load among forklift operators
	Outcome	Lower back pain
	Study design	Cross-sectional
	Study population	23 forklift operators 23 workers from other departments who did not drive vehicles at work (control group) Paper mill company in the UK
	Main results	Lower back pain in last 12 months was significantly more prevalent among drivers than 12-month prevalence for forklift group (65%) 12-month prevalence for controls (35%) Odds ratio for forklift operators 3.52 (95% CI 1.04–11.83) (not adjusted for confounders)
	Bovenzi *et al.* (2002)	
	Exposure	Whole-body vibration and postural load among forklift, crane, and straddle carrier
	Outcome	Lower back pain
	Study design	Cross-sectional
	Study population	88 forklift drivers 85 straddle carrier operators 46 crane operators 85 maintenance workers (control group) Transportation company in Northern Italy
	Main results	Whole-body vibration and postural loading were significantly associated with lower back pain 12-month prevalence ratio for forklift operators 1.42 (95% CI 1.13–1.78) (adjusted for covariates) 12 month LBP prevalence ratio for crane operators 0.96 (95% CI 0.68–1.35) (adjusted for covariates)
	Schwarze *et al.* (1998)	
	Exposure	Whole-body vibration among forklift, and earth moving machinery operators
	Outcome	Physician diagnosed ''lumbar syndrome''
	Study design	Cross-sectional
	Study population	159 forklift operators 64 truck drivers 165 operators of earth moving machinery operators 65 controls (workers in same companies not exposed to whole body vibration) Workers from more than 30 companies in Germany
	Main results	Prevalence of lumbar syndrome among forklift operators (0.65), earth moving machinery operators (0.60), and controls (0.58)
	Miyashita *et al.* (1992)	
	Exposure	Whole body vibration among workers (forklift and earth moving machinery operators)
	Outcome	Lower back pain
	Study design	Cross-sectional

(*continued*)

Table 2. (*Continued*).

Type of Equipment	Source	Description
	Study population	184 power shovel operators
		127 bulldozer operators
		44 forklift operators
		85 office workers (control group)
		Construction workers from different companies in Japan
	Main results	Lower back pain was only significantly higher among forklift operators
		12-month prevalence for forklift operators (50%), bulldozer operators (36%), and control (27%)
	Boshuizen *et al.* (1992)	
	Exposure	Whole body vibration among forklift operators
	Outcome	Lower back pain
	Study design	Cross-sectional
	Study population	242 drivers
		210 referent workers (workers from the same companies who were not exposed to whole-body vibration)
		Workers drawn from six ship companies in the Rotterdam harbour (Netherlands)
	Main results	Lower back pain significantly higher among exposure group
		Overall 12-month odds ratio 2.2 (90% CI 1.03–4.7) (adjusted for confounders)
	Brendstrup and Biering-Sorensen (1987)	
	Exposure	Occupation as exposure (forklift operators)
	Outcome	Lower back pain
	Study design	Cross sectional
	Study population	240 male forklift operators from 13 companies in Copenhagen
		Control group from Copenhagen County (399 working men)
	Main results	Forklift operators had significantly higher lower back pain than controls
		12-month prevalence for exposure and control groups are 0.65 and 0.47, respectively
Cranes	Bovenzi *et al.* (2002)	See forklift equipment
	Burdorf *et al.* (1993)	
	Exposure	Occupation as exposure
	Outcome	Lower back pain
	Study design	Cross sectional
	Study population	94 crane operators
		95 straddle carrier drivers
		86 office workers (control group)
		Males working for a large transportation company in the Port of Rotterdam
	Main results	12-month prevalence among crane operators (50%) and office workers (34%)
		Odds ratio for newly developed cases of lower back pain in the current job was 3.29 (1.52–7.12) among crane operators

(*continued*)

Table 2. (*Continued*).

Type of Equipment	Source	Description
	Burdorf and Zondervan (1990)	
	Exposure	Occupation as exposure
	Outcome	Lower back pain
	Study design	Cross sectional
	Study population	33 crane operators 30 crane helpers, general operators, maintenance workers (control group) Workers employed in a steel factory in the Netherlands
	Main results	12-month prevalence of LBP among crane operators (61%) and controls (27%) LBP odds ratio equalling 3.6 (1.2–10.6) (adjusted for confounders)
Tractors	Kumar *et al.* (1999)	
	Exposure	Whole-body vibration among tractor driving farmers
	Outcome	Lower back pain and pathologic changes in the lower back
	Study design	Cross sectional
	Study population	50 tractor driving farmers 50 non-tractor driving farmers (control group) Selected from two villages in the Sonipat District, Haryana, India
	Main results	Prevalence of reported back symptoms higher in tractor driving farmers (56%) as compared to non-tractor driving farmers (32%) Degenerative changes in the back similar for both groups
	Bovenzi and Betta (1994)	
	Exposure	Whole-body vibration and postural load among tractor drivers
	Outcome	Lower back pain
	Study design	Cross sectional
	Study population	1155 tractor drivers 220 office workers (control group) Drivers from Trentino-Alto Adige, Italy
	Main results	12 month prevalence among tractor drivers (71.7%) and controls (36.8%) 12 month odds ratio for tractor operators 2.39 (1.57–3.66) (adjusted for covariates)
	Boshuizen *et al.* (1990a)	
	Exposure	Whole-body vibration in agricultural tractor drivers
	Outcome	Lower back pain
	Study design	Cross sectional
	Study population	450 tractor drivers 110 non-exposed workers (control group)
	Main results	Prevalence of lower back pain among tractor drivers (38.1%) and control group (19.1%) for a vibration dose >5 years Odds ratio 2.8 (90% CI 1.64–5.0) (vibration dose >5 years m^2s^4)
Earth Movers	Schwarze *et al.* (1998)	See forklift equipment
	Miyashita *et al.* (1992)	See forklift equipment

(*continued*)

Table 2. (*Continued*).

Type of Equipment	Source	Description
	Dupuis and Zerlett (1987)	
	Exposure	Whole-body vibration in earth-mover operators
	Outcome	Various back symptoms including discomfort and lumbar syndrome
	Study design	Cross sectional
	Study population	352 earth-moving machine operators (at least 3 yr exposure) 315 controls (not exposed to vibration) Workers drawn for Germany
	Main results	Prevalence for earth-moving machinery operators (0.69) and controls (0.42)
Operating Engineers	Zimmermann *et al*. (1997)	
	Exposure	Occupation as construction operating engineers
	Outcome	Various musculoskeletal disorders
	Study design	Cross sectional
	Study population	410 operating engineers, part of a union in Iowa
	Main results	The job factors perceived almost problematic were: working in the same position for periods and bending and twisting the back

Table 3. Summary of potential confounders/covariates in different studies.

Source	Confounders/Covariates
Hoy *et al*. (2005)	Exercise habit, lifting during work, job satisfaction and smoking.
Bovenzi *et al*. (2002)	Body mass index, smoking, mental stress on current job and back trauma.
Schwarze *et al*. (1998)	Body mass index, prior spinal injuries, heavy lifting, load to the spine by leisure activities, and age.
Miyashita *et al*. (1992)	None reported.
Boshuizen *et al*. (1992)	Age, experienced mental stress, number of years lifting greater than 10 kg more than 25 times per day while twisting the spine, number of times per day lifting a weight of 10 kg or more with a twisted spine, body height, smoking, percentage of time looking backward, and number of hours sitting uninterrupted.
Brendstrup and Biering-Sorensen (1987)	Age, length of employment, and daily driving hours.
Burdorf *et al*. (1993)	History of heavy physical work, exposure to whole-body vibration, history of work requiring prolonged sitting, cold and draught in current job, working under severe pressure and job satisfaction in the current job.
Burdorf and Zondervan (1990)	Age, height, weight, heavy physical work, and frequent lifting.
Kumar *et al*. (1999)	Exposed and non-exposed groups are matched for age, gender, ethnic group, land-holding, and work routine.
Bovenzi and Betta (1994)	Age, body mass index, education, sports activity, car driving, marital status, mental stress, climatic conditions, back trauma, and postural load.
Boshuizen *et al*. (1990a)	Age, height, smoker/non-smoker, twisting, lifting, experienced mental workload, and employing company.
Dupuis and Zerlett (1987)	None reported.
Zimmermann *et al*. (1997)	None reported.

Table 4. Summary of description of evidence for prospective and retrospective cohort studies.

Type of Equipment	Source	Description
Machine Operators	Viikari-Juntura *et al.* (1994)	
	Exposure	Occupation as exposure (machine operators)
	Outcome	Neck pain
	Study design	Prospective cohort
	Study population	688 machine operators – earthmovers and longshoremen specialised in motorised stevedoring (at beginning of study) 553 carpenters (at beginning of study) 591 office workers – control group (at beginning of study) All workers from Finland
	Main results	12-month prevalence of severe neck pain (>30 days) in machine operators and controls were 28% and 9%, respectively 12-month prevalence of severe neck pain after three year follow-up were 40% and 12%, respectively Odds ratio for machine operators vs. office workers (95% CI) in terms of change in severe neck pain over three year follow-up 4.2 (2.0–9.0)
	Riihimaki *et al.* (1994)	
	Exposure	Occupation as exposure (machine operators)
	Outcome	Sciatic pain
	Study design	Prospective cohort
	Study population	688 machine operators – earthmovers and longshoremen specialised in motorised stevedoring (at beginning of study) 553 carpenters (at beginning of study) 591 office workers – control group (at beginning of study)
	Main results	Rate ratios of three year cumulative incidence of mild and severe sciatic pain (95% CI) were 2.90 (1.22–6.90) and 5.58 (2.27–13.8), respectively
	Tola *et al.* (1988)	Overlapping population with Viikari-Juntura *et al.* (1994). The only difference is the outcome (combined neck and shoulder)
Cranes	Bongers *et al.* (1988)	
	Exposure	Crane operators exposed to vibration
	Outcome	Back disability defined according to International Disease Classification
	Study design	Retrospective cohort (10 year follow-up)
	Study population	743 crane operators (at beginning of study) 662 floor workers (control group) (at beginning of study) Workers from Netherlands
	Main results	Incidence density ratio (per 100 person years) for disability due to degeneration of intervertebral disc 2.95 (90% CI 1.20–7.25) (adjusted for age and work shift) Incidence density ratio for disability due to displacement of intervertebral disc 1.41 (90% CI 0.58–3.42)

(*continued*)

Table 4. (*Continued*).

Type of Equipment	Source	Description
Tractors	Boshuizen *et al.* (1990c)	
	Exposure	Tractor operators exposed to vibration
	Outcome	Back disability defined according to International Disease Clasification
	Study design	Retrospective (11 year follow-up)
	Study population	689 tractor operators (at beginning of study) 109 workers (control group) (at beginning of study) Workers from Netherlands
	Main results	Age adjusted incidence density ratio of intervertebral disc disorders (90%CI) 3.1 (1.16–8.3)

(b) There was a wide range in the scoring for the subject selection quality (range: 0–0.75).

(c) The majority of studies were uniformly marginal (about 0.5) in terms of measurement quality with the remainder scoring somewhat poorly (<0.5).

(d) The data analysis methods were widely scattered between very poor (0.0) and average (1.0) scores. This was greatly impacted by the lack of consideration for some important individual and environmental covariates/confounders.

(e) The ability to generalise the findings to other populations is questionable (all values were equal to 0.0). This may be attributed in part to the lack of information about the participation rate and the lack of reporting the criteria for sample size calculations.

Figure 3 provides a closer look at the measurement quality of individual studies. Review of quality ratings suggest that investigators paid more attention to the exposure and outcome methods than to blinding and observation period methods. The scoring for exposure and outcome quality scales of most studies was close to being rated 'marginal' (0.66). Since blinding procedures and reporting of observation period across the groups and subject population were not discussed in any of the papers, it was not possible to determine if investigators considered these principles in the conduct of their studies.

Figure 4 summarises the methodological qualities of study description (an evaluation of the extent to which the different aspects of the study are clearly reported) and execution (an evaluation of how well the study is designed and analysed and of how well the results can be generalised) across all the investigations. The overall quality (across the 43 elements) was, on average, marginal. The reporting index – the extent to which the study is clearly described, allowing the reader to make an accurate evaluation of the study including study hypothesis/aim/objective, study design, exposure/intervention, outcome, covariates and confounders, statistical tests and main findings – was rated the highest, scoring average values. The subject selection quality (i.e. extent to which subject selection and recruitment have been conducted to minimise

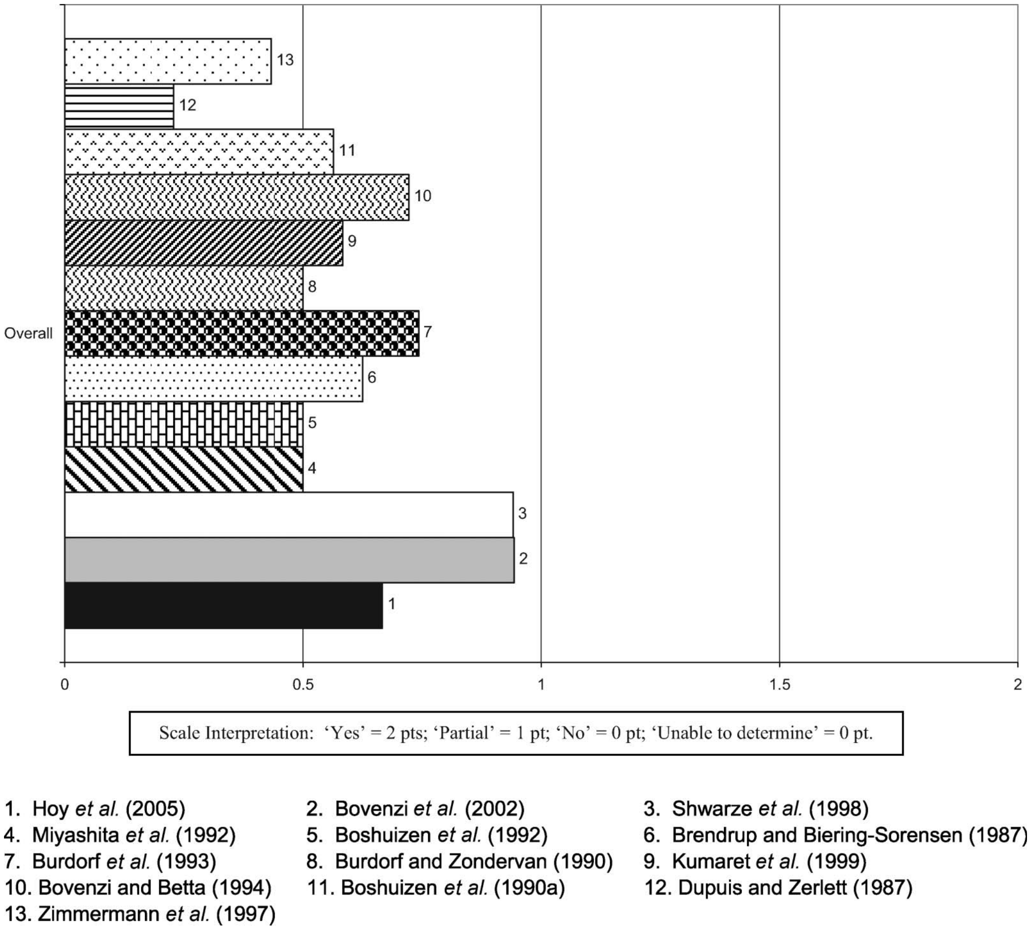


Figure 1. Overall critical appraisal for individual studies.

bias) and the data analysis quality (i.e. extent to which the study has analysed the data using appropriate statistics and accounted for confounders and covariates) were, on average, marginal. Measurement quality – the extent to which the methods have been uniformly followed for measuring and recording of data and applied with the same precision to all groups – was somewhat poor and study generalisation was in question (i.e. extent to which the results are applicable to the eligible population and can be extended to other groups).

3.4. Meta-relative risk

Tables 5 to 8 provide documentation of the meta analyses conducted for operators of forklifts, cranes, tractors and earth-moving machinery, respectively. Results of the fixed-effect and random-effect models are presented for each group. Heterogeneity was found for all groups except forklift operators. Therefore, the random-effects models were used for crane, tractor and earth moving operators. The fixed-effect model was applied for

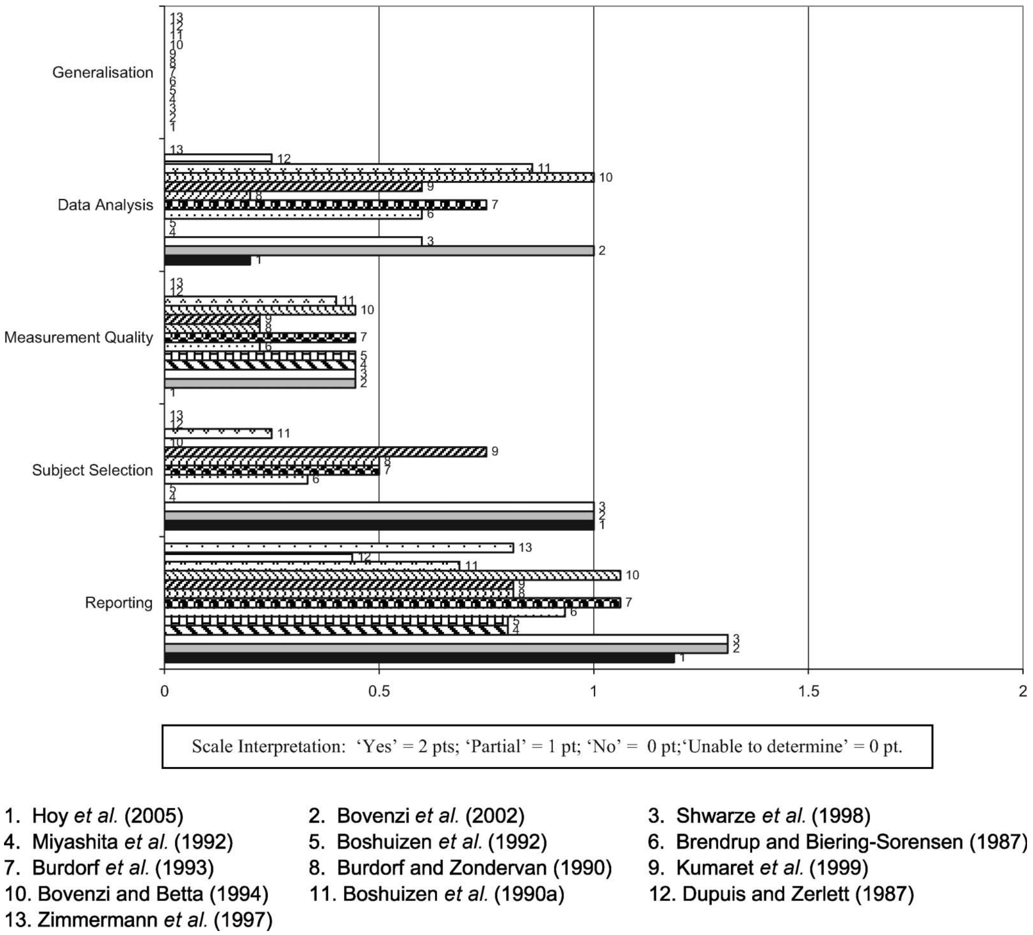


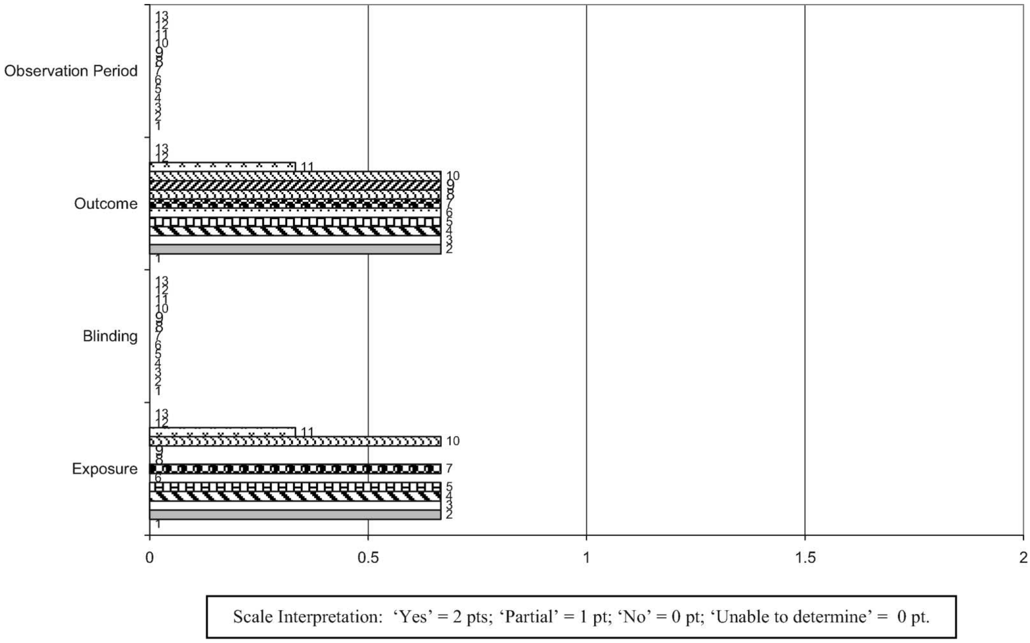
Figure 2. Detailed critical appraisal for individual studies.

forklift operators. The meta-relative risk for the different groups was as follows from highest to lowest:

(1) Tractor – 3.0 (95% CI 1.6–5.6).
(2) Forklift – 2.1 (95% CI 1.6–2.6).
(3) Crane – 1.9 (95% CI 0.9–3.8).
(4) Earth moving – 1.8 (95% CI 0.9–3.8).

The overall estimate was only significant at the 5% level for the forklift and tractor operators.

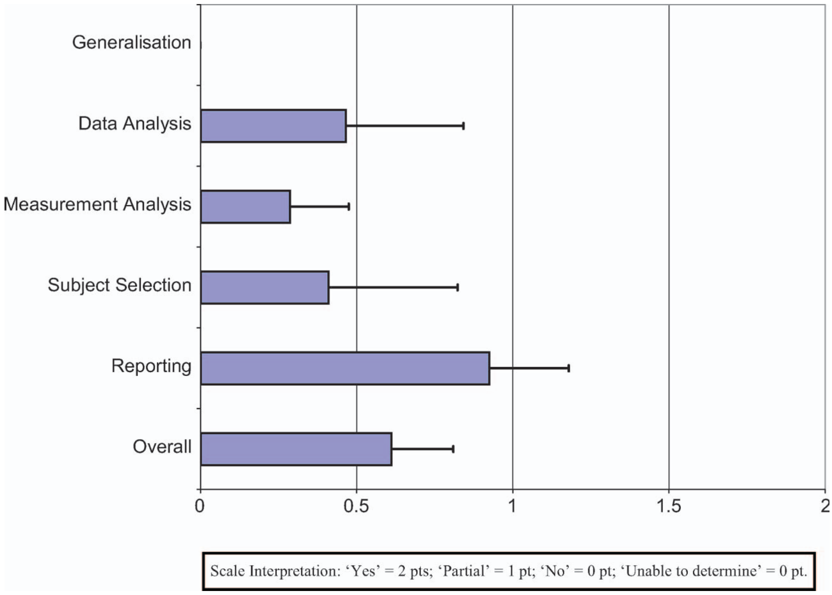
Table 9 displays the meta-analysis details for heavy equipment operators across all studies. Because heterogeneity was present across the studies, the meta-relative risk for the random-effects model was adopted and was equal to 2.209 (95% CI 1.8–3.0). This was significant at the 5% level. These results suggest that there is a significant association between lower back pain and heavy equipment operators. This association was based on 3151 exposed operators and 1728 controls, and on crude estimates not accounting for potential confounders/covariates.



Scale Interpretation: 'Yes' = 2 pts; 'Partial' = 1 pt; 'No' = 0 pt; 'Unable to determine' = 0 pt.

1. Hoy *et al.* (2005)
2. Bovenzi *et al.* (2002)
3. Shwarze *et al.* (1998)
4. Miyashita *et al.* (1992)
5. Boshuizen *et al.* (1992)
6. Brendrup and Biering-Sorensen (1987)
7. Burdorf *et al.* (1993)
8. Burdorf and Zondervan (1990)
9. Kumaret *et al.* (1999)
10. Bovenzi and Betta (1994)
11. Boshuizen *et al.* (1990a)
12. Dupuis and Zerlett (1987)
13. Zimmermann *et al.* (1997)

Figure 3. Critical appraisal of measurement quality of individual studies.



Scale Interpretation: 'Yes' = 2 pts; 'Partial' = 1 pt; 'No' = 0 pt; 'Unable to determine' = 0 pt.

Figure 4. Detailed critical appraisal across all studies.

Table 5. Meta-analysis for lower back pain among forklift operators.

Study (i)	Sample Size for Exposed Group (Prevalence)	Sample Size for Non-Exposed Group (Prevalence)	Odds Ratio (OR)	Ln (OR)	95% CL Lower	95% CL Upper	Variance	Weight (w_1)	Weight $(w_1)^2$	w_1 ln OR	Heterogeneity	D	Weight (w_2)
1	23 (0.652)	23 (0.348)	3.516	1.257	1.045	11.831	0.383	2.610	6.810	3.281	0.723		2.569
2	88 (0.78)	85 (0.52)	3.384	1.219	1.745	6.563	0.114	8.758	76.700	10.676	2.085		8.314
3	159 (0.65)	65 (0.54)	1.577	0.456	0.877	2.833	0.090	11.158	124.493	5.083	0.847		10.447
4	44 (0.50)	44 (0.27)	2.667	0.981	1.097	6.484	0.205	4.868	23.694	4.775	0.304	0.006	4.727
5	196 (0.41)	107 (0.31)	1.546	0.436	0.938	2.548	0.065	15.386	236.739	6.703	1.343		14.067
6	169 (0.65)	399 (0.47)	2.135	0.758	1.471	3.098	0.036	27.682	766.313	20.996	0.021		23.685
Total	679.00	723.00						70.461	1234.749	51.514	5.323		63.809
Summary Ln OR = $\Sigma(w_i * \ln OR_i)/\Sigma(w_i)$ =					0.731								
Summary OR = exp(ln OR) =					2.077								
95% CI for Summary OR = exp(ln $OR_i \pm 1.96 * ((1/\Sigma w_i)\hat{}0.5)$)) =								1.645		2.624			
α level for Homogeneity Test					0.378								

Study.
1. Hoy *et al.* (2005).
2. Bovenzi *et al.* (2002).
3. Shwarze *et al.* (1998).
4. Miyashita *et al.* (1992).
5. Boshuizen *et al.* (1992).
6. Brendstrup and Biering-Sorensen (1987)

Note: w_1 – fixed effect weight; w_2 – random effect weight; w_i – weight calculated as inverse of variance.

Table 6. Meta-analysis for lower back pain among crane operators.

Study (i)	Sample Size for Exposed Group (Prevalence)	Sample Size for Non-Exposed Group (Prevalence)	Odds Ratio (OR)	Ln (OR)	95% CL Lower	95% CL Upper	Variance	Weight (w_1)	Weight $(w_1)^2$	w_1 ln OR	Heterogeneity	D	Weight (w_2)
1	46 (0.522)	85 (0.529)	0.970	−0.030	0.473	1.989	0.134	7.448	55.468	−0.227	2.512	0.257	2.554
2	94 (0.500)	86 (0.337)	1.965	0.675	1.08	3.591	0.094	10.592	112.187	7.155	0.166		2.844
3	33 (0.606)	30 (0.267)	4.231	1.442	1.453	12.3	0.297	3.363	11.309	4.851	2.676		1.803
Total	173	201						21.402	178.963	11.779	5.355		7.201
Summary Ln OR = $\Sigma(w_i*\ln OR_i)/\Sigma(w_i)$ =						0.550							
Summary OR = exp(ln OR) =						1.734							
95% CI for Summary OR = exp(ln $OR_i \pm 1.96*((1/\Sigma w_i)$^0.5))) =								1.135		2.649			
α level for Homogeneity Test						0.069							
Summary $LnOR_{dl}$		0.617											
Summary OR_{dl}		1.854											
95% CI for Summary OR_{dl}								0.893		3.848			

Study.
1. Bovenzi *et al.* (2002).
2. Burdorf *et al.* (1993).
3. Burdorf and Zondervan (1990).

Note: w_1 – fixed effect weight; w_2 – random effect weight; w_i – weight calculated as inverse of variance.

Table 7. Meta-analysis for lower back pain among tractor operators.

Study (i)	Sample Size for Exposed Group (Prevalence)	Sample Size for Non-Exposed Group (Prevalence)	Odds Ratio (OR)	Ln (OR)	95% CL Lower	95% CL Upper	Variance	Weight (w_1)	Weight $(w_1)^2$	w_1 ln OR	Heterogeneity	D	Weight (w_2)
1	50 (0.560)	50 (0.320)	2.704	0.995	1.197	6.112	0.173	5.785	33.464	5.754	0.421		2.493
2	1155 (0.861)	220 (0.573)	4.639	1.534	3.386	6.357	0.026	38.753	1501.800	59.467	2.822	0.228	3.935
3	450 (0.311)	110 (0.191)	1.914	0.649	1.143	3.205	0.069	14.454	208.919	9.383	5.475		3.361
Total	1655	380						58.992	1744.183	74.604	8.718		9.789
Summary Ln OR = $\Sigma(w_i{*}\ln OR_i)/\Sigma(w_i) =$						1.265							
Summary OR = exp(ln OR) =						3.542							
95% CI for Summary OR = $\exp(\ln OR_i \pm 1.96{*}((1/\Sigma w_i)^\wedge 0.5))) =$								2.744		4.572			
α level for Homogeneity Test						0.013							
Summary $LnOR_{dl}$		1.093											
Summary OR_{dl}		2.983											
95% CI for Summary OR_{dl}								1.595		5.582			

Study.
1. Kumar *et al.* (1999).
2. Bovenzi and Betta (1994).
3. Boshuizen *et al.* (1990a).

Note: w_1 – fixed effect weight; w_2 – random effect weight; w_i – weight calculated as inverse of variance.

Table 8. Meta-analysis for lower back pain among earth moving operators.

Study (i)	Sample Size for Exposed Group (Prevalence)	Sample Size for Non-Exposed Group (Prevalence)	Odds Ratio (OR)	Ln (OR)	95% CL Lower	95% CL Upper	Variance	Weight (w_1)	Weight $(w_1)^2$	w_1 ln OR	Heterogeneity	D	Weight (w_2)
1	165 (0.600)	65 (0.580)	1.066	0.064	0.595	1.91	0.089	11.298	127.653	0.722	6.864		2.450
2	127 (0.362)	44 (0.250)	1.703	0.532	0.787	3.687	0.155	6.447	41.566	3.432	0.623	0.320	2.106
3	352 (0.688)	315 (0.416)	3.09	1.128	2.248	4.245	0.026	37.958	1440.804	42.823	3.079		2.890
Total	644	424						55.703	1610.023	46.978	10.567		7.447
Summary Ln OR = $\Sigma(w_i{*}\ln OR_i)/\Sigma(w_i)$ =						0.843							
Summary OR = exp(ln OR) =						2.324							
95% CI for Summary OR = $\exp(\ln OR_i \pm 1.96{*}((1/\Sigma w_i)^{\wedge}0.5)))$ =								1.787		3.022			
α level for Homogeneity Test						0.005							
Summary $LnOR_{dl}$		0.609											
Summary OR_{dl}		1.839											
95% CI for Summary OR_{dl}								0.897		3.773			

Study.
1. Schwarze *et al.* (1998).
2. Miyashita *et al.* (1992).
3. Dupuis and Zerlett (1987).

Note: w_1 – fixed effect weight; w_2 – random effect weight; w_i – weight calculated as inverse of variance.

Table 9. Meta-analysis for lower back pain among all operators – without study quality.

Study (i)	Sample Size for Exposed Group (Prevalence)	Sample Size for Non-Exposed Group (Prevalence)	Odds Ratio (OR)	Ln (OR)	95% CL Lower	95% CL Upper	Variance	Weight (w_1)	Weight $(w_1)^2$	w_1 ln OR	Heterogeneity	D	Weight (w_2)
1	23 (0.652)	23 (0.348)	3.516	1.257	1.045	11.831	0.383	2.610	6.810	3.281	0.343		1.855
2	88 (0.78)	85 (0.52)	3.384	1.219	1.745	6.563	0.114	8.758	76.700	10.676	0.920		3.702
3	159 (0.65)	65 (0.54)	1.577	0.456	0.877	2.833	0.090	11.158	124.493	5.083	2.155		4.073
4	44 (0.50)	44 (0.27)	2.667	0.981	1.097	6.484	0.205	4.868	23.694	4.775	0.036		2.767
5	196 (0.41)	107 (0.31)	1.546	0.436	0.938	2.548	0.065	15.386	236.739	6.703	3.247		4.527
6	169 (0.65)	399 (0.47)	2.135	0.758	1.471	3.098	0.036	27.682	766.313	20.996	0.516		5.207
7	46 (0.522)	85 (0.529)	0.970	−0.030	0.473	1.989	0.134	7.448	55.468	−0.227	6.379		3.446
8	94 (0.500)	86 (0.337)	1.965	0.675	1.08	3.591	0.094	10.592	112.187	7.155	0.510	0.156	3.995
9	33 (0.606)	30 (0.267)	4.231	1.442	1.453	12.3	0.297	3.363	11.309	4.851	1.008		2.206
10	50 (0.560)	50 (0.320)	2.704	0.995	1.197	6.112	0.173	5.785	33.464	5.754	0.058		3.042
11	1155 (0.861)	220 (0.573)	4.639	1.534	3.386	6.357	0.026	38.753	1501.800	59.467	15.847		5.503
12	450 (0.311)	110 (0.191)	1.914	0.649	1.143	3.205	0.069	14.454	208.919	9.383	0.873		4.442
13	165 (.0600)	65 (0.580)	1.066	0.064	0.595	1.91	0.089	11.298	127.653	0.722	7.804		4.091

(continued)

Table 9. (*Continued*).

Study (i)	Sample Size for Exposed Group (Prevalence)	Sample Size for Non-Exposed Group (Prevalence)	Odds Ratio (OR)	Ln (OR)	95% CL Lower	95% CL Upper	Variance	Weight (w_1)	Weight $(w_1)^2$	w_1 ln OR	Heterogeneity	D	Weight (w_2)
14	127 (0.362)	44 (0.250)	1.703	0.532	0.787	3.687	0.155	6.447	41.566	3.432	0.848		3.215
15	352 (0.688)	315 (0.416)	3.09	1.128	2.248	4.245	0.026	37.958	1440.804	42.823	2.063		5.487
Total	3151	1728						206.559	4767.918	184.875	42.607		57.558
Summary Ln OR = $\Sigma(w_i*\ln OR_i)/\Sigma(w_i)$ =						0.862							
Summary OR = exp(ln OR) =						2.367							
95% CI for Summary OR = exp(ln OR_i ± 1.96*((1/Σw_i)^0.5))) =								1.846		3.035			
α level for Homogeneity Test						0.000							
Summary $LnOR_{dl}$		0.793											
Summary OR_{dl}		2.209											
95% CI for Summary OR_{dl}								1.777		3.016			

Study.
1. Hoy *et al*. (2005).
2. Bovenzi *et al*. (2002).
3. Shwarze *et al*. (1998).
4. Miyashita *et al*. (1992).
5. Boshuizen *et al*. (1992).
6. Brendstrup and Biering-Sorensen (1987).
7. Bovenzi *et al*. (2002).
8. Burdorf *et al*. (1993).
9. Burdorf and Zondervan (1990).
10. Kumar *et al*. (1999).
11. Bovenzi and Betta (1994).
12. Boshuizen *et al*. (1990a).
13. Schwarze *et al*. (1998).
14. Miyashita *et al*. (1992).
15. Dupuis and Zerlett (1987).

Note: w_1 – fixed effect weight; w_2 – random effect weight; w_i – weight calculated as inverse of variance.

Accounting for the overall study, quality slightly improved the results (Table 10). The meta-relative risk increased to 2.32 relative to the 2.21 obtained without incorporating the study quality.

4. Discussion

Numerous reviews have been reported in the published literature on the relationship between MSDs and risk factors among HEV operators. These reviews were largely qualitative and lacked the rigorous methodology of an evidence-based approach. This research was conducted to fill the gap by conducting a meta-analysis and a critical appraisal of the published literature to examine the association between lower back/neck disorders and operators of HEVs. Across all studies, a crude meta-relative risk of 2.2 was found, suggesting that operators of heavy equipment are at more than twice the risk of acquiring lower back disorders than controls who do not operate HEVs. This primary finding is discussed in the following sections.

4.1. Critical appraisal of reported studies

The methodological qualities of the published studies ranged from marginal to average. Although there was a wide variance among the studies in terms of quality attributes, the subject and data analysis methods were marginal and measurement quality was somewhat poor. As such, study generalisation would be limited.

The evidence was mostly based on cross-sectional designs and non-US studies. In addition, only lower back outcomes were examined among HEV operators. Musculoskeletal outcomes should be examined in other body regions, such as the neck and shoulders.

4.2. Association between lower back pain and types of heavy equipment

The meta-analysis results suggest that the meta-odds ratio for tractor drivers was almost 3.0 and that for forklift operators it was 2.0. This result may be explained in part by the relative proportion of exposure to low intensity steady-state whole-body vibration and exposure to high intensity mechanical shock induced while driving various HEVs. To illustrate this point, the studies by Bovenzi *et al.* (2002) and Bovenzi and Betta (1994) are compared. These studies had similar methods and procedures. Both studies had a cross-sectional design with both exposed and non-exposed groups. The exposure variables were whole-body vibration and posture. Among other types of outcomes, lower back pain in the last 12 months was measured. The odds ratios for lower back pain were 2.39 (95% CI 1.57–3.66) and 1.42 (95% CI 1.13–1.78) for tractor and forklift operators, respectively, and were adjusted for several covariates. Although the intensity levels of mechanical shocks were not reported in the two studies, the weighted root mean square (rms) acceleration for whole-body vibration for forklifts was 0.90 m/s^2 (SD 0.77) (Bovenzi *et al.* 2002) and the weighted rms acceleration for tractors was 1.97 m/s^2 (Bovenzi and Betta 1994).

Results of the meta-analysis further indicated that the meta-odds ratio was slightly higher for forklift operators than for crane operators. These findings may be supported by the exposure data summarised in Table 11. The frequency weighted rms and cumulative vibration exposure were higher for forklifts than for cranes (see Appendix 1 for different definitions of vibration loading in the articles reviewed). On average, the frequency weighted rms for tractors was the highest, followed by that for forklifts, then for cranes.

Table 10. Meta-analysis for lower back pain among all operators – with study quality.

Study (i)	Sample Size for Exposed Group (Prevalence)	Sample Size for Non-Exposed Group (Prevalence)	Odds Ratio (OR)	Ln (OR)	95% CL Lower	95% CL Upper	Variance	Weight (w_1)	Study Quality	Weight (w_{1a})	Weight $(w_{1a})^2$	w_{1a} ln OR	Heterogeneity	D	Weight (w_2)
1	23 (0.652)	23 (0.348)	3.516	1.257	1.045	11.831	0.383	2.610	0.333335	0.870	0.757	1.094	0.136		0.854
2	88 (0.78)	85 (0.52)	3.384	1.219	1.745	6.563	0.114	8.758	0.47143	4.129	17.046	5.033	0.527		3.803
3	159 (0.65)	65 (0.54)	1.577	0.456	0.877	2.833	0.090	11.158	0.47059	5.251	27.570	2.392	0.866		4.736
4	44 (0.50)	44 (0.27)	2.667	0.981	1.097	6.484	0.205	4.868	0.25	1.217	1.481	1.194	0.017		1.187
5	196 (0.41)	107 (0.31)	1.546	0.436	0.938	2.548	0.065	15.386	0.25	3.847	14.796	1.676	0.698		3.563
6	169 (0.65)	399 (0.47)	2.135	0.758	1.471	3.098	0.036	27.682	0.3125	8.651	74.835	6.561	0.092		7.336
7	46 (0.522)	85 (0.529)	0.970	−0.030	0.473	1.989	0.134	7.448	0.333335	2.483	6.163	−0.076	1.976		2.361
8	94 (0.500)	86 (0.337)	1.965	0.675	1.08	3.591	0.094	10.592	0.37143	3.934	15.477	2.657	0.136	0.021	3.638
9	33 (0.606)	30 (0.267)	4.231	1.442	1.453	12.3	0.297	3.363	0.25	0.841	0.707	1.213	0.284		0.826
10	50 (0.560)	50 (0.320)	2.704	0.995	1.197	6.112	0.173	5.785	0.291665	1.687	2.847	1.678	0.030		1.630
11	1155 (0.861)	220 (0.573)	4.639	1.534	3.386	6.357	0.026	38.753	0.36111	13.994	195.835	21.474	6.335		10.849
12	450 (0.311)	110 (0.191)	1.914	0.649	1.143	3.205	0.069	14.454	0.28205	4.077	16.620	2.647	0.184		3.759

(*continued*)

Table 10. (*Continued*).

Study (i)	Sample Size for Exposed Group (Prevalence)	Sample Size for Non-Exposed Group (Prevalence)	Odds Ratio (OR)	Ln (OR)	95% CL Lower	95% CL Upper	Variance	Weight (w_1)	Study Quality	Weight (w_{1a})	Weight $(w_{1a})^2$	w_{1a} ln OR	Heterogeneity	D	Weight (w_2)
13	165 (.0600)	65 (0.580)	1.066	0.064	0.595	1.91	0.089	11.298	0.47059	5.317	28.269	0.340	3.384		4.789
14	127 (0.362)	44 (0.250)	1.703	0.532	0.787	3.687	0.155	6.447	0.25	1.612	2.598	0.858	0.175		1.560
15	352 (0.688)	315 (0.416)	3.09	1.128	2.248	4.245	0.026	37.958	0.114285	4.338	18.818	4.894	0.308		3.980
Total	3151	1728						206.559	4.812	62.246	423.820	53.635	15.149		54.871
Summary Ln OR = $\Sigma(w_i{*}\ln OR_i)/\Sigma(w_i)$ =						0.862									
Summary OR = exp(ln OR) =						2.367									
95% CI for Summary OR = exp(ln OR_i ± 1.96*((1/Σw_i)^0.5))) =								1.846		3.035					
α level for Homogeneity Test						0.368									
Summary $LnOR_{dl}$		0.839													
Summary OR_{dl}		2.315													
95% CI for Summary OR_{dl}								1.777		3.016					

Study.
1. Hoy *et al.* (2005).
2. Bovenzi *et al.* (2002).
3. Shwarze *et al.* (1998).
4. Miyashita *et al.* (1992).
5. Boshuizen *et al.* (1992).
6. Brendstrup and Biering-Sorensen (1987).
7. Bovenzi *et al.* (2002).
8. Burdorf *et al.* (1993).
9. Burdorf and Zondervan (1990).
10. Kumar *et al.* (1999).
11. Bovenzi and Betta (1994).
12. Boshuizen *et al.* (1990a).
13. Schwarze *et al.* (1998).
14. Miyashita *et al.* (1992).
15. Dupuis and Zerlett (1987).

Note: w_1 – fixed effect weight; w_{1a} – weight based on study quality; w_2 – random effect weight; w_i – weight calculated as inverse of variance.

Table 11. Summary of vibration measurements.

Source	Equipment	Frequency-weighted root-mean-square accelerations (m/s^2) Mean (SD)	Cumulative vibration exposure (yr m^2/s^4) Mean(SD)
Bovenzi *et al.* (2002)	Forklift	0.90 (0.77)	9.2 (12.2)
	Mobile Cranes	0.53 (0.27)	2.0 (2.2)
	Overhead Cranes	0.22 (0.12)	
Schwarze *et al.* (1998)	Forklift	0.45 (0.18)	12.8 (7.7)
	Earth Moving Machinery	0.67 (0.30)	20.1 (9.8)
Boshuizen *et al.* (1992)	Small Forklift	0.80	4.2 (5.8)
	Large Forklift	0.79	2.7 (3.5)
Burdorf *et al.* (1993)	Crane	0.31	–
Bovenzi and Betta (1994)	Tractors	1.07 (range: 0.52–1.47)	–
Boshuizen *et al.* (1990a)	Tractor in the field	0.60	–
	Tractor on the road	1.10	–

Note: SD – Standard deviation.

The aforementioned results suggest that exposure to steady state whole-body vibration may not account for the full association with lower back pain. It is possible that this may be attributed in part to the mechanical shocks induced during rough rides and high accelerations. Sandover (1998) suggested that mechanical shocks are short duration (20–50 ms), high acceleration forces (e.g. weighted rms values up to 5.8 m/s^2 measured over a 4-s period and unweighted peak values of at least 20 m/s^2 vibration). He further indicated, although without direct proof, that mechanical shocks have a greater influence on both human health and subjective discomfort than the long term rms. Moreover, in a previous paper we presented a new framework for evaluating potential risk of back disorders due to whole body vibration and repeated mechanical shock that included a detailed discussion of the likely differences in how exposure to steady state vibration and mechanical shocks (e.g. jarring and jolting) might affect development of lower back pain for HEV operators (Waters *et al.* 2007).

In conclusion, from an epidemiological perspective, the aforementioned results suggest that exposure to mechanical shocks may be a potential contributor to the onset of lower back pain (Sandover 1998). Both steady state and transitory vibration should be measured simultaneously in health studies of heavy equipment in order to determine their relative contribution to lower back risk. It is of utmost importance to conduct full exposure assessment of both types of vibration exposure to better understand the resultant health risks due to operation of HEVs.

4.3. Association between lower back pain and vibration and postural load exposure variables

HEV operators may be exposed to a number of risk factors for MSDs. Among the most important are vibration and awkward posture. Only two studies examined the combined effect of vibration and postural load on lower back pain. Table 12 presents the odds ratio for lower back pain as a function of postural load or cumulative vibration exposure (adjusted for age). These results suggest that lower back pain increases with an increase in vibration load or postural load. The combined effect of both exposure variables is displayed in Table 13. The combined effect is clearly demonstrated. It should be noted that it is assumed that the vibration load consists of both the steady state and transitory components as previously mentioned.

4.4. Possibility of a causal relationship

In light of the evidence presented in this research, one should ask whether working as a HEV operator is causally related to lower back and neck disorders. The bulk of the evidence is presented for lower back pain and is discussed with regard to several criteria of causality (Teschke *et al.* 1999) as listed below:

(a) Consistency of association – is the association found repeatedly in studies of different populations, in different conditions, with different designs?
(b) Strength of association – how high is the risk in exposed populations compared to unexposed populations? Is the risk high enough to exclude chance or confounding as possible explanations?

Table 12. Odds ratios for lower back pain (adjusted for age).

Exposure Variable	Bovenzi *et al.* (2002)	Bovenzi and Betta (1994)
Postural Load		
Mild	1.0	1.0
Moderate	1.37 (0.92–2.02)	1.54 (0.80–2.95)
Hard	1.79 (1.23–2.66)	2.19 (1.19–4.03)
Very Hard	2.03 (1.41–2.93)	3.27 (1.80–5.96)
Cumulative Vibration Exposure (yr m^2/s^4)		
0	1.0	–
<1	1.22 (0.92–1.61)	–
1–4	1.08 (0.82–1.43)	–
>4	1.35 (1.06–1.72)	–
0	–	1.0
<15	–	1.69 (1.10–2.59)
15–30	–	2.34 (1.52–3.58)
>30	–	2.63 (1.70–4.05)

Table 13. Odds ratio for combined effect of vibration and postural load (Bovenzi and Betta 1994).

Total Vibration Dose (year m^2/s^4)	Postural Load			
	Mild	Moderate	Hard	Very Hard
5	1.29	1.79	2.5	3.48
10	1.41	1.96	2.73	3.79
20	1.55	2.15	2.99	4.16
30	1.63	2.27	3.16	4.39
40	1.70	2.36	3.29	4.58

Note: Analysis is made with reference to control subjects exposed to mild postural load and unexposed to vibration. Odds ratio is adjusted for age and several other confounders.

(c) Dose–response – does the effect increase in a predictable way, as the exposure intensity, duration or dose (intensity times duration) increase?
(d) Temporal relationship – does the effect appear after the exposure? Is there usually an induction period between first exposure and disease onset and, if so, is the timing of the disease plausible in relation to the exposure?
(e) Plausibility – is the association plausible given the science and clinical knowledge about the disease?

The results shown in Table 9 suggest that the relationships reported are elevated (i.e. relative risk >1) and are fairly consistent in 14 out of the 15 study groups. The meta-relative risk is considered high with overall risk being greater than 1.0. In many studies, some covariates and confounders were accounted for. As such, it appears that the association is likely not to be due to chance. This is further supported by the earlier discussions on the different types of vehicles and role of exposure to vibration and postural loading. For example, the meta-relative risk for tractor operators was higher than that for forklift operators. Therefore, the transitory vibration (mechanical shocks) may play a possible role in the harmful effect, in addition to those induced by the steady-state whole-body vibration and postural loading.

Few investigators have researched the dose–response relationships between exposure variables and MSDs. Table 14 provides a summary of data from the published literature. A general trend cannot be deduced from the data presented because of the limited range of exposure data. In a few instances, there was a larger increase in the point estimate with an increase in the duration of exposure.

Limited evidence is obtained from prospective and retrospective cohort studies. Studies from Finland and the Netherlands consistently report elevated risks for lower back and neck outcomes among heavy equipment operators, particularly for severe outcomes.

The aforementioned discussion suggests that there is a possibility of a causal relationship between working as a heavy equipment operator and lower back pain. This is further supported by comparison of the vehicle vibration levels to those reported in the whole body vibration standard ISO 2631–1.2 of the International Organization for Standardization (1997) (see Tables 15 and 16). In many instances, the ISO standard values have been exceeded.

5. Concluding remarks

Causal relationship between exposure and health outcomes is traditionally described linguistically by three levels: more likely than not (i.e. strong evidence); possible (i.e. moderate evidence); or unlikely (i.e. weak evidence). On the basis of the evidence presented and analysed in this report, it appears that the causal relationship between working as a heavy equipment operator and lower back pain may be described at a minimum as ‘possible’ and may be upgraded with limited additional evidence to higher than ‘possible’ but definitely lower than ‘more likely than not’. The rationale for this decision is summarised below.

Initially, a ‘possible’ level is assigned because the bulk of the evidence was based on: (1) cross-sectional studies; (2) consistency among most studies in reporting elevated risk (i.e. >1); (3) strong association between exposure and lower back pain; (4) confounding being accounted for in many studies; (5) moderate evidence of dose–response relationship. The final risk may be upgraded to higher than ‘possible’ but less than ‘more likely than not’ because of the limited evidence derived from prospective and retrospective cohort studies.

Table 14. Summary of dose-response data for lower back pain (odds ratio and 95% CI).

Source	Type of Equipment	Outcome	Description of Dose-Response Data		
Bovenzi *et al.* (2002)	Straddle carriers, fork-lift trucks, and freight-container tractors	Lower back pain	Equivalent Vibration Magnitude (m/s^2 rms)		
			<0.46	0.46–0.79	>0.79
			1.04 (0.82–1.33)	1.11 (0.89–1.38)	1.24 (1.01–1.53)
			Cumulative Vibration Exposure (year m^2/s^4)		
			<1	1–4	>4
			1.07 (0.83–1.39)	0.99 (0.76–1.28)	1.27 (1.02–1.58)
			Duration of exposure (driving years)		
			1–6	6–12	>12
			1.25 (0.98–1.59)	1.11 (0.85–1.45)	1.27 (1.04–1.56)
Bovenzi and Betta (1994)	Tractors	Lower back pain	Equivalent Vibration Magnitude (m/s^2 rms)		
			0.5–1.0	1.0–1.25	>1.25
			2.39 (1.52–3.76)	2.87 (1.83–4.49)	2.29 (1.43–3.68)
			Total Vibration Dose (years m^2/s^4)		
			<15	15–30	>30
			2.33 (1.48–3.67)	3.04 (1.92–4.82)	2.36 (1.48–3.74)
			Duration of exposure (driving years)		
			5–15	16–25	>25
			2.65 (1.68–4.18)	2.31 (1.46–3.64)	2.74 (1.69–4.45)

(*continued*)

Table 14. (*Continued*).

Source	Type of Equipment	Outcome	Description of Dose-Response Data				
Boshuizen *et al.* (1990a)	Tractors	Lower back pain	Equivalent Vibration Magnitude (m/s^2 rms)				
			0.3–0.55	0.55–0.7	0.7–0.9	>0.9	
			1.98 (0.97–4.0)	1.66 (0.82–3.4)	2.10 (1.07–4.1)	1.38 (0.52–3.7)	
			Vibration Dose (years m^2/s^4)				
			0–2.5	2.5–5	>5		
			1.80 (1.11–2.9)	1.78 (1.04–3.1)	2.8 (1.64–5.0)		
			Years of full time exposure				
			0–5	5–10	>10		
			2.44 (0.84–7.1)	2.5 (0.85–7.6)	3.6 (1.21–11)		
Boshuizen *et al.* (1990a)	Tractors		Total Vibration Dose (year m^2/s^4)				
			0–0.5	0.5–2.5	2.5–5.0	>5.0	
		Disorders of the intervertebral disc	1	4.1 (0.53–10)	11 (1.7–267)	7.2 (0.92–179)	
Bongers *et al.* (1988)	Cranes		Years of exposure				
			≤4	5–9	10–14	15–19	≥20
		Displacement of intervertebral disc	1.41	2.03	3.99*	3.13	16.9
		Degeneration of intervertebral disc	2.95*	3.81**	5.77**	4.99**	5.73**
		All intervertebral disc disorders	2.00*	2.74**	4.90**	4.45**	6.84**

Note: Odds ratio for lower back pain with 95% confidence intervals for all studies except Bongers *et al.* (1988) and Boshuizen *et al.* (1990a). Incidence density ratio per 100 person years for Bongers *et al.* (1988) and Boshuizen *et al.* (1990a).

*Significant at the 5% level.

**Significant at the 1% level.

Table 15. Levels of exposure to whole body vibration.

Author (Year)	Industry; Study Conditions; Study Objectives	Measurement Location; Device Type; Sample Duration	Vehicle Types	Vehicle Specifics	Vibration Exposure Levels (Exposure in Root Mean Square m/s^2 unless otherwise specified)	Dominant Vibration Frequencies (Hz)	Compliance with ISO 2631 (EL, FDP)	Peak Exposure or Crest Factors (CF) (CF = a_{peak}/a_{rms})	Jolts and Shocks	Determinants of Vibration Exposure (other than vehicle type)
Hoy *et al.* (2005)	Paper mill company; Normal operating conditions; Health study	At seat; Tri-axial accelerometer; Sampling duration approx. 5 min	Forklifts	Forklift	x-axis 0.31 (SD–0.072) y-axis 0.29 (SD–0.089) z-axis 0.57 (SD–0.124)	5–7 Hz	Measured values were below the EU Physical Agents Directive on Vibration Exposure action level of 0.5 m/s^2, but not the z axis	Peak x-axis 3.35 (SD–0.848) y-axis 3.37 (SD–1.186) z-axis 13.53 (SD–6.351) Crest Factor x-axis 11.08 (SD–2.252) y-axis 12.01 (SD–4.507) z-axis 26.54 (SD–17.228)	NR	NR
Bovenzi *et al.* (2002)	Port machinery; Normal working conditions; Health study	"In agreement with ISO 2631 guidelines"	Forklift, mobile cranes, and overhead cranes	Forklift Mobile cranes Overhead cranes	$a_{vector\ sum} = 0.90$ m/s^2 $a_{vector\ sum} = 0.53$ m/s^2 $a_{vector\ sum} = 0.22$ m/s^2	2–5 Hz (z-axis) 1.25–4 HZ (x and z-axis)	NR	NR	NR	NR
Kumar *et al.* (1999)	Tractors; Normal operating conditions; Health study	At seat; Tri-axial accelerometer; Sampling duration NR	Tractors	Tractors	NR	7 Hz	Measured values exceeded FDP 4 hour limit;	NR	NR	NR
Schwarze *et al.* (1998)	Different vehicles; Normal working conditions; Health study	Measurement location NR; Device Type NR; Sampling duration NR	Forklift and earth moving machinery	Forklift earth moving machinery	$a^* = 0.45$ m/s^2 $a^* = 0.67$ m/s^2	NR	NR	NR	NR	NR
Bovenzi and Betta (1994)	Tractors; Normal operating conditions; Health study	At seat; Tri-axial accelerometer; Sampling duration NR	Low-power tractors (45–85 hp)	Fiat (50–70 hp) n = 14 Ford (45–60 hp) n = 23 Fendt (58–64 hp) n = 9 International (58 hp) n = 2 Lamborghini (65–80 hp) n = 2 Massey Ferguson (50–85 hp) n = 3	$a_{vector\ sum} = 1.24$ (mean, range 0.58–2.00) $a_{vector\ sum} = 0.96$ (mean, range 0.36–2.03) $a_{vector\ sum} = 0.89$ (mean, range 0.53–1.25) $a_{vector\ sum} = 1.08$ (mean, range 0.85–1.30) $a_{vector\ sum} = 1.05$ (mean, range 0.86–1.25) $a_{vector\ sum} = 1.41$ (mean, range 0.84–1.82)	2.5–4 Hz	For estimated daily average exposure (2.5 hours), mean value (1.1 m/s^2) of frequency weighted acceleration is below EL (1.4 m/s^2)	NR	NR	NR

(*continued*)

Table 15. (*Continued*).

Author (Year)	Industry; Study Conditions; Study Objectives	Measurement Location; Device Type; Sample Duration	Vehicle Types	Vehicle Specifics	Vibration Exposure Levels (Exposure in Root Mean Square m/s^2 unless otherwise specified)	Dominant Vibration Frequencies (Hz)	Compliance with ISO 2631 (EL, FDP)	Peak Exposure or Crest Factors (CF) (CF = a_{peak}/a_{rms})	Jolts and Shocks	Determinants of Vibration Exposure (other than vehicle type)
Burdorf *et al.* (1993)	Large transport company; Normal working conditions; Health study	Measurement location NR; Vibration meter and piezoelectric accelerometer; Sampling duration approx. 5 min	Cranes	Crane n = 20	$a_{vector\ sum} = 0.31$ m/s^2	NR	NR	NR	NR	NR
Boshuizen *et al.* (1992)	Heavy equipment; Normal working conditions; Health study	At seat; Tri-axial accelerometer; Sampling duration approx. 5 min	Forklifts and freight tractor	Small forklift Large forklift Freight container tractor	$a_{vector\ sum} = 0.80$ m/s^2 $a_{vector\ sum} = 0.79$ m/s^2 $a_{vector\ sum} = 1.04$ m/s^2	3.15 Hz 2.5 Hz 1.6, 2.5 Hz	Acceleration levels for forklifts exceeded FDP 4 hour limit; levels for tractor exceeded 2.5 hour limit	Crest factor all above 6.	NR	NR
Boshuizen *et al.* (1990a)	Agricultural vehicles; Normal working conditions; Health study	Measurement location NR; Tri-axial accelerometer; Sampling duration NR	Tractors	Tractor in field Tractor on the road	$a^{**} = 0.60$ m/s^2 $a^{**} = 1.10$ m/s^2	NR	NR	NR	NR	NR

EL–Exposure Level (Exposure Limit applies to situations where the health and safety of the worker, such as back injuries and injuries to internal organs, is of concern.).

FDP–Fatigue Decreased Proficiency Level (Fatigue Decreased Proficiency Boundary is applied to the situations where maintaining operator efficiency of a vehicle is of concern, such as situations where operators are required to work with safe manipulation of controls or to read the gauges accurately.) Crest Factor–the ratio of the peak value to the rms acceleration ($a_{peak}/a_{r.m.s}$); NR–Non Reported.

*Frequency-weighted energy-acceleration (8 hr); **Equivalent vibration magnitude ($aeq = \mathrm{sqrt}(\Sigma(a_i^2 t_i)/t_i)$).

Table 16. Exposure levels and compliance with ISO comfort zones.

			Vibration Exposure Levels				Compliance with ISO 2631 Comfort Zone					
Study	Vehicle Type		*x*-axis	*y*-axis	*z*-axis		Less than 0.315 m/s^2 not uncomfortable	0.315 m/s^2 to 0.63 m/s^2 a little uncomfortable	0.5 m/s^2 to 1 m/s^2 fairly uncomfortable	0.8 m/s^2 to 1.6 m/s^2 uncomfortable	1.25 m/s^2 to 2.5 m/s^2 very uncomfortable	Greater than 2 m/s^2 extremely uncomfortable
Hoy *et al.*[i] (2005)	Forklift	Mean	0.31	0.29	0.57	***0.7107***			X			
Bovenzi *et al.*[ii] (2002)	Forklift	Mean	0.18	0.35	0.64	***0.75133***			X			
	Mobile Cranes	Mean	0.37	0.21	0.32	***0.53235***			X			
	Overhead Cranes	Mean	0.11	0.07	0.11	***0.17059***	X					
Schwarze *et al.*[iii] (1998)	Forklift	Mean		***0.45***								
	Heavy machinery	Mean		***0.67***								
Bovenzi and Betta[v] (1994)	Tractors	Mean		***1.07***						X	X	
Burdorf *et al.*[ii] (1993)	Crane	Mean	0.15	0.11	0.17	***0.25199***	X					
Boshuizen *et al.*[i] (1992)	Small Forklift	Mean	0.55	0.37	0.44	***0.79561***			X	X		
	Large Forklift	Mean	0.43	0.29	0.59	***0.78556***			X	X		
Boshuizen *et al.*[vi] (1990a)	Tractor in the fields	Mean		***0.6***					X			
	Tractor on the road	Mean		***1.1***						X		
	Bulldozer	Mean		***0.6***					X			
	Excavator	Mean		***0.4***				X				
	Shovel	Mean		***1.1***						X		
Dupuis and Zerlett[vii] (1987)	Forklift	Mean		***0.4–2.0***				X	X	X	X	
	Agricultural tractors	Mean		***0.4–1.25***				X	X	X	X	
	Excavators	Mean		***0.3–1.3***			X	X	X	X	X	

Notes

i-Mean acceleration (RMS) (m/s^2).

ii-Frequency-weighted root mean square (RMS) (m/s^2).

iii-Frequency-weighted energy-equivalent acceleration (m/s^2).

iv-Peak acceleration all directions (m/s^2)

v-Vector sum of frequency-weighted acceleration (RMS) (m/s^2).

vi-Equivalent vibration magnitude (m/s^2).

vii-Weighted root mean square (RMS) (m/s^2).

In light of the findings of this research, it is clear that prospective cohort studies are needed to confirm the conclusions. In doing so, attention should be paid to the different methodological qualities of the study, such as subject selection, measurement quality, confounders and generalisation. With regard to exposure assessment, the impact of steady-state and transitory phases of vibration and postural loading on lower back and neck disorder outcomes should be assessed. In addition, the biological plausibility of the present findings should be explored with regard to experimental findings.

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Appendix 1

Definition of vibration loading terms in reviewed articles

Vector sum or frequency-weighted (rms) acceleration (a_v)', is defined as follows:

$$a_v = [(1.4a_{wx})^2 + (1.4a_{wy})^2 + a_{wz}^2]^{1/2}$$

where *wx, wy, wz* are the axes.
Cumulative vibration exposure is defined as $\left[\sum a_{vi}^2 t_i\right]$ (units for this term are year m^2/s^4).

$$\text{Equivalent vibration magnitude} = \left[\sum (a_{vi}^2 t_i)/t_i\right]^{1/2} \text{ units for this term are m/s}^2)$$

where a_{vi} is the estimated vector sum of the frequency-weighted acceleration measured on machine i driven for time t_i in years.