Available online at www.sciencedirect.com
ScienceDirect
Journal of Sound and Vibration 298 (2006) 480–491
JOURNAL OF SOUND AND VIBRATION
www.elsevier.com/locate/jsvi

Modelling the effects of exposure to whole-body vibration on low-back pain and its long-term consequences for sickness absence and associated work disability

A. Burdorf[a,*], C.T.J. Hulshof[b]

[a]Department of Public Health, Erasmus MC, University Medical Center Rotterdam, Rotterdam, The Netherlands
[b]Coronel Institute for Occupational and Environmental Health, Academic Medical Center, University of Amsterdam, Amsterdam, The Netherlands

Received 2 May 2006; received in revised form 9 May 2006; accepted 8 June 2006
Available online 1 August 2006

Abstract

Background: Exposure to whole-body vibration (WBV) is a well-known risk factor for the occurrence of low-back pain (LBP). Little is known about the long-term course of back pain in workers exposed to WBV and the consequences for (temporary) disability, due to lack of cohort studies with sufficiently long follow-up periods.
Methods: A systematic review of the literature was performed to assess associations between exposure to WBV and LBP, sickness absence due to low-back disorders and permanent disability. A meta-analysis was used to estimate the prevalences of LBP and sickness absence due to low-back disorders in occupational populations, depending on relevant exposure characteristics. These prevalences were converted into probabilities for transitions between no complaints, LBP, sickness due to LBP, and disability. A Markov model was applied to evaluate a hypothetical cohort of workers without LBP at the start of the cohort and a follow-up of 40 years (40 cycles of 1 year) to reflect a long-life career with continuous exposure to WBV.
Results: In this hypothetical cohort it was estimated that among workers with the highest exposure to WBV on average about 47 weeks of their working life were lost due to sick leave because of LBP, which is approximately 2.5% of their working life. When all workers on prolonged sick leave for 52 weeks would remain disabled for the rest of their working life, a maximum of 23.4% of their working life could be lost due to high WBV exposure. Among workers without or low exposure to WBV the corresponding losses were 0.8% and 7.8%, respectively.
Conclusion: The approach to assess years of work lost due to an occupational exposure may provide a more adequate description for stakeholders than the traditional measures of relative risk or attributable risk fraction. The concept of work years lost may also facilitate a better appreciation of the potential benefits of preventive measures.

*Corresponding author. Tel.: +31 10 463 8469; fax: +31 10 463 8475.
E-mail address: a.burdorf@erasmusmc.nl (A. Burdorf).

0022-460X/$ - see front matter
doi:10.1016/j.jsv.2006.06.023

1. Introduction

It is well documented that exposure to whole-body vibration (WBV) is a risk factor for the occurrence of low-back pain (LBP) [1–3]. The most common sources of occupational exposure to WBV are cars, vans, forklift trucks, lorries, tractors, buses, and loaders [4]. It has been estimated that in Western countries 4–7% of all employees are exposed to potentially harmful WBV [1]. Although, exposure–response relationships are lacking for the association of frequency, duration, magnitude, and direction of the vibration spectrum with back disorders, there are indications that daily exposure to WBV for 8 h with an average magnitude above $0.5\,\mathrm{m\,s^{-2}}$ rms in the dominant axis may significantly contribute to the occurrence of back disorders [5,6]. In the recent European Guideline this value has been adopted to distinguishing between possible hazardous and harmless work situations [7].

Despite the recognition of exposure to WBV as risk factor for LBP, little is known about the impact of prolonged exposure to WBV on the long-term course of LBP and associated consequences for work disability. LBP in occupational populations is usually characterized by a high recurrence rate of relapses of pain [8]. Prospective studies have indicated that LBP is quite persistent with strong fluctuations in severity of complaints, expressed by recurrent episodes interspersed with periods free from pain [9]. Yet, it remains largely unknown whether exposure to WBV is an important prognostic factor for aggravation of LBP and associated disability. This ambiguity may be partly explained by the lack of cohort studies with sufficiently long follow-up periods to identify determinants of persistence and/or recurrence of LBP and subsequent morbidity. However, the sparse information from cohort studies on health outcomes other than prevalence of LBP may be used to predict the long-term course of LBP in occupational groups with relevant exposure to WBV. In this regard, a particularly useful technique is a Markov model of prognosis, which can be used for health events of discrete nature that happen more than once over time [10]. A Markov model assumes that the subject is always in one of a finite number of health states, for example no complaints, back pain, and sickness absence due to back pain. The course of disease is modelled by transitions from one state to another during a specified period of time. In a longitudinal study on musculoskeletal symptoms among newspaper workers this approach was used to demonstrate that during a 1-year follow-up equivalent proportions of workers improved as worsened in symptoms and that these fluctuations in severity could be described well by transitions between different states of symptoms or disability [11]. In a longitudinal study among forestry workers with 3-year follow-up a transition model was also applied, demonstrating that working with a flexed trunk or working with a hand above shoulder level were consistently associated with the occurrence of current radiating neck pain [12]. This approach may be extended over longer periods than the actually observed follow-up period. Under the assumption that the transition probabilities are constant over time, a Markov chain may be created by repeating each cycle a certain number of times to represent a meaningful time interval, for example employment in the same job for 30 years or more.

In order to understand the possible impact of prolonged exposure to WBV on the long-term course of back complaints and associated sickness absence and work disability, a literature review was performed to determine the dynamic pattern of incidence, recurrence, and severity of back complaints in occupational groups with exposure to WBV. Subsequently, a Markov model was applied to mimic the long-term consequences of LBP in a hypothetical cohort of workers with different levels of WBV exposure. The aims of this study were: (i) to analyse the effects of WBV exposure on the occurrence of LBP and the transition from LBP into sickness absence due to LBP, and (ii) to predict the long-term consequences of prolonged exposure to different levels of WBV on LBP and associated permanent work disability.

2. Methods

2.1. Retrieval of studies

A search in Medline (by Pubmed) and Embase was conducted for systematic reviews on LBP in occupational groups with exposure to WBV. The reviews were deemed acceptable when a meta-analytic approach was used to summarize the available evidence into a pooled point estimate of the strength of association between WBV exposure and LBP [1,13]. The first review included nine study populations [14–20] and the second review was based on 16 study populations [14,15,17,18,21–28]. A further search for original articles was conducted in Medline and Embase with the following key words: (low) back pain, sciatic pain, spinal disorders, (whole-body) vibration, postural load, epidemiology, occupation, and driving. References cited in the retrieved studies were also examined. Only articles published in the past 20 years were accepted for inclusion. Original articles were only included when (i) describing a cohort study with information on the incidence of LBP over a specified period of follow-up and a quantitative estimate of the association with WBV exposure [26,29], and (ii) reporting on the occurrence of specific outcomes such as sick leave and permanent disability in relation to WBV exposure [30,31]. With regard to the latter inclusion criterion, only studies were retrieved that presented information on frequency and duration of sick leave or disability over a specified time period in order to be able to calculate the annual incidence of sick leave or permanent disability. Whenever possible, measures of prevalence, incidence, and risk were retrieved from the included articles. When information on risk estimates was not presented, for all studies that provided sufficient raw data unadjusted risk estimates with 95% confidence intervals were calculated.

2.2. Data analysis

In the studies selected for the analysis the average exposure to WBV in the occupational groups was categorized into three levels of exposure: low, moderate, and high. Workers with a daily exposure to WBV for 8 h with an average magnitude less than $0.5\,\mathrm{m\,s^{-2}}$ were regarded as low exposed [7] and essentially combined with the workers without any WBV exposure into the no/low WBV exposure group. A daily exposure to WBV for eight hours with an average magnitude between 0.5 and $1.0\,\mathrm{m\,s^{-2}}$ was considered a moderate exposure level and a daily 8-h exposure to WBV above $1.0\,\mathrm{m\,s^{-2}}$ was regarded as high [13].

A meta-analytical approach was chosen to pool the information on prevalence and incidence of LBP, sick leave, and permanent disability in the selected studies, thereby weighing the prevalence and incidence by the size of the study population. The summarized evidence from the reviews was used to estimate the pooled 12-month prevalence of LBP at three levels of WBV exposure [1,13]. Original studies were used to complement the necessary information on the natural course of LBP in exposed populations. The incidence was defined as the proportion of workers with a new episode of LBP during a 12 months follow-up after at least a period of 12 months free of any LBP. The incidence rates in two longitudinal studies were pooled into an estimate of the average annual incidence of LBP [26,29]. One original study described the occurrence of at least one period of sick leave due to LBP in the past 12 months [31]. Another original study was used to assess the annual incidence of permanent disability due to LBP among exposed workers [30].

A simulation was carried out on a hypothetical cohort of workers with prolonged exposure to WBV, all aged 25 years, who were free of LBP in the previous 12 months, with a follow-up period of 40 years. A Markov chain approach was used with 1 year increments of time during which a subject may make a transition from one health state to another [10]. In this analysis, four health states were defined: no LBP, LBP in the past 12 months, sickness absence in the past 12 months due to LBP, and permanent work disability after a prolonged sickness absence of 52 weeks due to LBP. The latter health state was based on the definition in a study on disability among crane operators [30]. This health state was considered an absorbing state, i.e. transition to another state from within this state is regarded to be impossible. The transition probabilities were assumed to be constant over time, i.e. the transition from one health state to another health state in a given year is independent from the health status in earlier 1-year cycles. The transition probabilities were derived from the meta-analytical information on occurrence of LBP, sick leave, and permanent disability. The cohort simulation with the Markov chain approach (a Monte Carlo simulation) was conducted with software programme DATA TreeAge [32]. The cohort simulation started with healthy subjects at age 25 years, who were followed-up for a 40-year career in the same job with a constant level of WBV exposure. For each level of WBV exposure the total burden of low-back disease was calculated during this 40-year working life, expressed by the average number of weeks with sickness absence and the average number of weeks with permanent work disability. The average number of weeks with sickness absence was set at 3 weeks, based on the study of Bovenzi among port machinery operators where the modus period of sick leave was 8–30 days [31] and the well-known three-phase LBP model of the Quebec task force showing that approximately 50% of the workers had return to work after 3–4 weeks [33]. For the permanent disability a distinction was made between workers who, after 52 weeks of sickness absence, were assumed to be able to move into another job without WBV exposure and those who remained permanently disabled for the rest of their working life.

A sensitivity analysis with several scenarios was conducted to evaluate the effect of the specific assumptions on the estimated total burden of LBP disease. This analysis concerned (1) the introduction of a latency period between first exposure to WBV and first increase in risk on LBP, (2) a period of permanent disability of 26 weeks instead of 52 weeks, (3) a situation with a 2-fold incidence of LBP with less impact on sickness absence and permanent disability (0.5-fold), and (4) a situation of a lower incidence of LBP (0.5-fold) with the same impact on sickness absence and permanent disability as the third scenario. The latency period in the first scenario was set at 5 years, based on the review of Bovenzi and Hulshof who estimated that the risk on LBP increased after a vibration dose of 3 year $m^2 s^{-4}$ which roughly equates to 6 years of intermediate exposure to WBV and 3 years of high exposure to WBV [1]. This latency period also corresponds well with the requirements in several countries for recognition of LBP due to exposure to WBV as an occupational disease [6].

3. Results

Table 1 summarizes the risk estimates for different levels of exposure to WBV and the underlying frequency measures of health outcomes. The pooled odds ratios in both systematic reviews varied between 1.4 and 2.3 and the most recent review presented a 1.2-fold risk for workers with high WBV exposure relative to those with moderate WBV exposure [13]. In the two original cohort studies a large difference was observed in the annual incidence of LBP among unexposed workers, varying between 4% and 14%.

In Table 2 the basic epidemiological measures of frequency of low-back disorders are presented as pooled results from the studies described in Table 1. The estimated 1-year incidence of LBP was 6.7% among unexposed workers and 13.9% among moderately exposed workers. Assuming a 1.2-fold risk between high

Table 1
Associations between exposure to whole-body vibration (WBV) and the occurrence of low-back pain (LBP) and associated sick leave in review studies and selected individual studies

Source	No. of studies	Exposure to WBV	Health outcome	Risk measure	Health outcome (%)	
					Exp[a]	Con[a]
Reviews						
Bovenzi and Hulshof [1]	9	All WBV exposure	Prevalence 1-year LBP	OR = 2.3 (1.8–2.9)	54	35
Lötters et al. [13]	13	WBV > 0.5 $m s^{-2}$	Prevalence 1-year LBP	OR = 1.4 (1.2–1.6)	45	30
	3	WBV > 1.0 $m s^{-2}$	Prevalence 1-year LBP	OR = 1.6 (na)	61	30
Original studies						
Pietri et al. [26]		> 20 h driving a vehicle	Annual incidence LBP	RR = 2.0 (1.3–3.1)	13	4
Schwarze et al. [29]		WBV > 0.6 $m s^{-2}$ versus < 0.6 $m s^{-2}$	Annual incidence lumbar syndrome (4 yrs, re-assessed to 1 year)	RR = 1.3 (0.0–1.9)	18	14
Bongers et al. [30]		0.25–0.67 $m s^{-2}$ (v)	Annual incidence disability pension (re-assessed to 1 year)	RR = 1.3 (0.8–2.1)	0.85	0.47
Bovenzi et al. [31]		Mean < 0.5 $m s^{-2}$ (v)	Prevalence 1-year sick leave	OR = 0.8 (0.4–1.8)	14	16
		Mean 0.92 $m s^{-2}$ (v)		OR = 2.9 (1.3–6.4)	36	16

[a]Exp = exposed population, con = reference population not exposed, na = not available.

Table 2
Overview of estimated incidence and prevalence of low-back pain (LBP) and associated sick leave in occupational populations with exposure to whole-body vibration (WBV), based on a pooled analysis of selected studies in Table 1

Measure	Exposure level[a]	Weighted level (%) (95% CI)	Included studies
Information from selected studies			
Annual incidence LBP	No/low WBV exposure	6.7 (6.4–6.9)	[26,29]
	Moderate WBV exposure	13.9 (13.4–14.5)	[26,29]
Annual incidence sick leave LBP	No/low WBV exposure	14.8 (13.0–16.6)	[31]
	Moderate WBV exposure	36.4 (30.3–42.4)	[31]
Annual incidence disability pension (>52 weeks sick leave)	No/low WBV exposure	0.47 (0.45–0.49)	[30]
	Moderate WBV exposure	0.85 (0.81–0.89)	[30]
1-year prevalence LBP	No/low WBV exposure	30.4 (30.1–30.6)	[1,13]
	Moderate WBV exposure	45.6 (45.3–45.9)	[1,13]
	High WBV exposure	61.0 (60.6–61.4)	[1]

[a]No or low exposure $<0.5\,\mathrm{m\,s^{-2}}$, moderate exposure 0.5–$1.0\,\mathrm{m\,s^{-2}}$ and high exposure $>1.0\,\mathrm{m\,s^{-2}}$.

and moderate exposure, the annual incidence of LBP among workers with high exposure would be approximately 16.7%. The estimates on the 1-year incidence of sick leave due to LBP were derived from a study on port machinery operators [31]. The detailed description in the article allowed the calculation of the fraction of workers with LBP who took at least one period of sick leave due their complaints in the previous year. For workers with LBP and no/low WBV exposure this fraction was 28% and for workers with LBP and moderate WBV exposure this fraction was 46%. Again using the assumption of a 1.2 for risk for high exposure relative to moderate exposure, the corresponding fraction was estimated to be about 55% among highly exposed workers with LBP. The study of Bongers reported an annual disability rate of 0.47 per 100 person-years among workers with no exposure to WBV [30]. Assuming a baseline prevalence of LBP of 30% [1,13], this suggests that among workers with LBP about 1.5% became permanently disabled within a given year. When applying the pooled prevalences of LBP of 46% for moderate exposure and 61% for high exposure, the corresponding figures for workers with LBP becoming disabled are 2.0% and 2.4%.

Fig. 1 describes the Markov process used in the simulation of the hypothetical cohort of workers, at the start all 25-years old and without LBP, with different levels of exposure to WBV. This model incorporates all events of interest with work disability after 52 weeks of sickness absence due to LBP as absorbing state, i.e. recovery from this state was assumed to be impossible. The Markov sign ($\lhd$) indicates that another cycle of 1 year will follow. The full Markov tree is only presented for the intermediate exposure level, but exactly similar trees were used for the patterns among those workers with no/low exposure and those with high exposure.

The estimated incidence rates for LBP, sick leave, and disability determined the transition probabilities from no LBP to the health states LBP in the past 12 months, sickness absence in the past 12 months due to LBP, and permanently work disabled after a prolonged sickness absence of 52 weeks. For the Markov model it is also essential to estimate the probabilities of recovery to better health states and the probabilities of recurrence of the health state in the next year. Under the assumption that the 1 year incidence rates and the 1 year prevalences remained constant, the recurrence of LBP in a given year was derived as 84% among worker with no/low WBV exposure, 84% among workers with moderate WBV exposure, and 88% among workers with high WBV exposure.

Table 3 presents the matrix with transition probabilities for different levels of WBV exposure among the distinguished health states, as derived from the literature. Among subjects with LBP the probability to take sick leave was $p = 0.484$ for those with a high WBV exposure and $p = 0.235$ for those with a no/low WBV exposure. The probability on taking sick leave due to LBP in a given year among subjects without LBP in the previous year was higher among those with a high exposure than those with low exposure, $p = 0.092$ and 0.019, respectively. A comparable difference was observed for recurrence of sickness absence with $p = 0.484$ and 0.235, respectively.

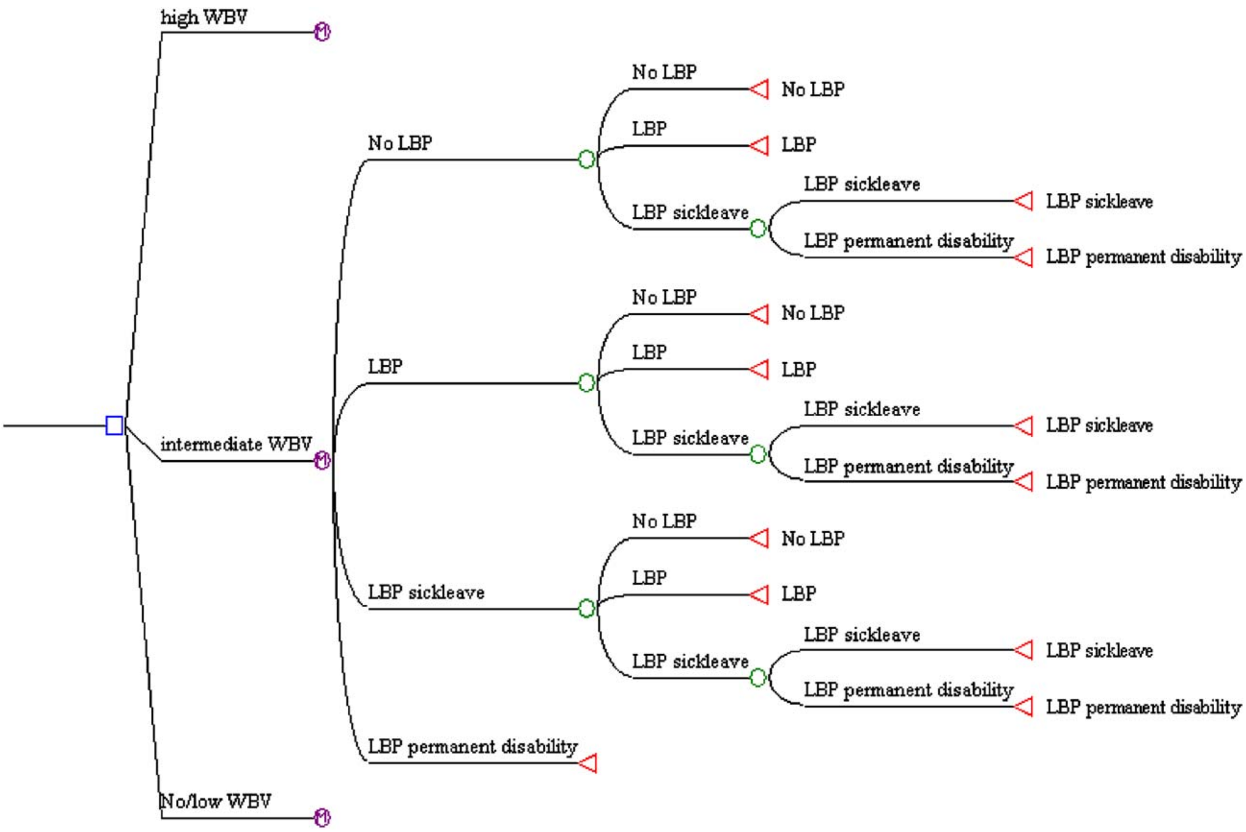

Fig. 1. The Markov process used in the simulation of a hypothetical cohort of workers, at the start all 25 years old and without low back pain (LBP), with different levels of exposure to whole-body vibration (WBV).

Table 3
Matrix of transition probabilities for three levels of exposure to whole-body vibration (WBV) among the distinguished health states for low-back pain (LBP) during a 1 year follow-up among workers

Baseline		Follow-up			
		No LBP	LBP	LBP sick leave	LBP disability
No or low exposure ($<0.5\,\mathrm{m\,s^{-2}}$)	No LBP	0.933	0.048	0.019	0.00
	LBP	0.160	0.605	0.235	0.00
	LBP with sick leave	0.160	0.605	0.235	0.055
Intermediate exposure (0.5–1.0 $\mathrm{m\,s^{-2}}$)	No LBP	0.861	0.075	0.064	0.00
	LBP	0.160	0.454	0.386	0.00
	LBP with sick leave	0.160	0.454	0.386	0.044
High exposure ($>1.0\,\mathrm{m\,s^{-2}}$)	No LBP	0.833	0.075	0.092	0.00
	LBP	0.120	0.396	0.484	0.00
	LBP with sick leave	0.120	0.396	0.484	0.044

Figs. 2 and 3 depict the results of the simulation of the hypothetical cohort. The prevalence of LBP in the past 12 months (with and without sickness absence) reached a maximum after about 8–12 years of exposure to WBV and subsequently remained stable for the no/low exposed group and dropped progressively with the

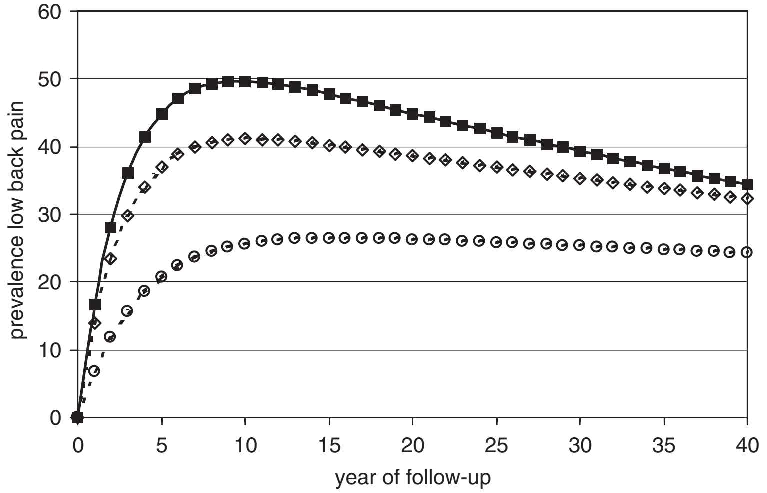

Fig. 2. Projected effect of three levels of WBV exposure (high, moderate, low) on the prevalence of low back pain in a hypothetical cohort with 40 years of follow-up among workers exposed to whole-body vibration. ■ high exposure to WBV, ◇ intermediate exposure to WBV, ○ no exposure to WBV.

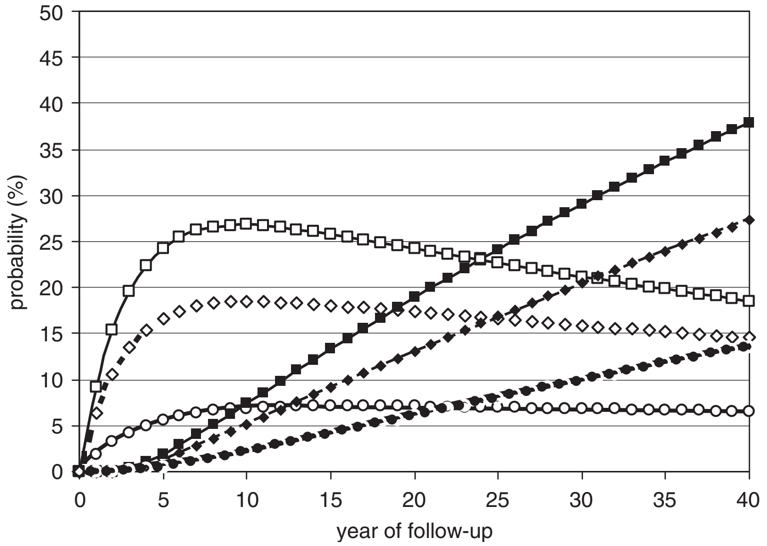

Fig. 3. Projected effect of three levels of WBV exposure (high, moderate, low) on the annual probability of sick leave due to low back pain and the cumulative probability of workers with long-term sickness absence (>52 weeks) in a hypothetical cohort with 40 years of follow-up among workers exposed to WBV. □ sickness absence due to high exposure to WBV, ◇ sickness absence due to intermediate exposure to WBV, ○ sickness absence without exposure to WBV, ■ disability due to high exposure to WBV, ◆ disability due to intermediate exposure to WBV, ● disability without exposure to WBV.

level of WBV exposure (Fig. 2). The plateau in the no/low-exposed group was close to the underlying assumption of a prevalence of LBP of 30%. In the intermediate and high exposure groups the plateau was reached around 41% and 50%, respectively, and dropped quickly due to disabled workers leaving the cohort. A similar pattern was observed for sickness absence due to LBP, albeit a lower prevalence (Fig. 2). The cumulative proportion of subjects becoming permanently work disabled (>52 weeks of sickness absence) increased with linear trend over time. In the no/low exposure group about 14% of the hypothetical cohort will have become disabled during the 40 years of follow-up. In the moderate exposed group and the highly exposed group these proportions were 27% and 38%, respectively.

Table 4 summarizes the impact of WBV exposure on weeks of work lost during working life due to sickness absence and permanent work disability. Among workers with the highest exposure to WBV on average about 47 weeks of their working life were lost due to sick leave because of LBP, which is approximately 2.5% of their working life. Assuming that all workers on permanent disability did not return to another job without WBV exposure but remained disabled for the rest of their working life on average about 23.4% of their working life was lost due to high WBV exposure. Among workers with a no/low exposure to WBV the corresponding losses were 0.8% and 7.8%, respectively.

The sensitivity analysis in Table 5 demonstrates that the introduction of a latency period of 5 years had little effect on the burden of low-back disease. The assumptions on the transition probabilities from back pain to sickness absence and from sickness absence to permanent disability had the largest impact on the estimated

Table 4
Work weeks lost because of sickness absence due to low-back pain (LBP) and to permanent disability (>52 weeks sick leave) due to LBP during a 40-year career of an individual worker exposed to whole-body vibration (WBV) during 40 years

	Weeks of sickness absence LBP	Weeks of permanent disability LBP among those who returned to another job	Weeks of permanent disability LBP among those who remained permanently disabled
	Mean	Mean	Mean
No/low WBV exposure	7.8	7.0	137.8
Moderate WBV exposure	19.5	14.1	290.3
High WBV exposure	27.0	19.6	412.1

Table 5
Sensitivity analysis with different scenarios on work weeks lost because of sickness absence due to low-back pain (LBP) and to permanent disability (>52 weeks sick leave) due to LBP during a 40 year career of an individual worker exposed to whole-body vibration (WBV) during 40 years

	Weeks of sickness absence LBP	Weeks of permanent disability LBP among those who returned to another job	Weeks of permanent disability LBP among those who remained permanently disabled
	Mean	Mean	Mean
Scenario 1: Latency period of 5 years			
No/low WBV exposure	6.8	6.1	135.0
Moderate WBV exposure	17.3	12.4	285.2
High WBV exposure	24.1	17.4	405.5
Scenario 2: Duration of disability of 26 weeks			
No/low WBV exposure	7.8	3.5	68.9
Moderate WBV exposure	19.5	7.1	145.2
High WBV exposure	27.0	9.8	206.1
Scenario 3: 2-fold incidence LBP and 0.5-fold sickness absence and permanent disability			
No/low WBV exposure	6.8	3.1	61.2
Moderate WBV exposure	15.6	5.8	115.3
High WBV exposure	21.3	7.7	158.3
Scenario 4: 0.5-fold incidence LBP and 0.5-fold sickness absence and permanent disability			
No/low WBV exposure	2.5	1.2	21.8
Moderate WBV exposure	7.3	2.6	50.6
High WBV exposure	11.4	4.1	78.8

total burden of low-back disease, followed by the assumption on duration of disability, and the estimated incidence of LBP.

4. Discussion

In a hypothetical cohort of workers with a career of 40 years of continuous exposure to WBV it was estimated that among workers with the highest exposure to WBV on average about 47 weeks of their working life were lost due to sick leave because of LBP, which is approximately 2.5% of their working life. When all workers on prolonged sick leave for 52 weeks would remain disabled for the rest of their working life on average about 23.4% of their working life was lost due to high WBV exposure. Among workers with a no/low exposure to WBV the corresponding losses were 0.8% and 7.8%, respectively.

These results of the modelling approach based upon a Markov model heavily depend on the underlying assumptions, as presented in Tables 2 and 3. The 1-year prevalence of LBP was derived from two reviews [1,13] that pooled the available information from different studies, which had used comparable definitions of back pain (Table 2). The estimated 1 year incidence of LBP of 14% among worker with intermediate WBV exposure compares well with an annual incidence of 11–13% in a general working population study [34], but is considerably lower than observed incidences of 20–28% among scaffolders [35] and 26% among nurses [36]. The estimated high yearly recurrence of LBP has been reported in several studies and reflects the finding that a history of LBP is a strong predictor of future episodes [8,35,37]. The Markov model assumed that among workers with LBP in the unexposed group 28% had an associated sick leave period and in the intermediate WBV exposure group 46% took at least one period of sick leave [31]. These figures are roughly double the observed proportions in populations with high exposure to physical load, such as 21% among scaffolders [38] and 24% among nurses [36]. The profound consequence of a lower proportion of workers with LBP taking sick leave was demonstrated in the sensitivity analysis (see Table 5).

The input for the modelling approach was limited to the effect of WBV exposure on LBP and associated health states. Since WBV exposure is often accompanied by prolonged sitting in a constrained posture, the estimated consequences in terms of total work time lost during working lifetime may be more a reflection of the integral exposure profile of professional drivers than the specific exposure to WBV. However, a recent systematic review concluded that sitting-while-at-work is not associated with LBP, indicating that the estimated effects are primarily the result of WBV exposure [39]. The analysis also does not take into account the specific effects of work-related risk factors, such as psychosocial factors and manual materials handling, that may vary considerable among drivers. Hence, the presented results may not adequately reflect the potential consequences among professional drivers with concomitant exposure, such as drivers who have to load and unload the truck themselves.

It is of interest to observe that the hypothetical cohort quickly reached a peak in the prevalence of LBP around 26–50% after 8–12 years, depending on the level of WBV exposure. After this peak the prevalence among exposed workers dropped slowly in the next 30 years. This pattern illustrates that in longitudinal studies with a follow-up period of a few years the overall prevalence will remain very stable, whereas individual trajectories of LBP during the follow-up will show a dynamic pattern. Indeed, in a longitudinal study across 8 years is was observed that the annual prevalence varied between 73% and 76% and that the proportion of repeated increase of LBP (19%) was approximately as large as the proportion of repeated decrease of LBP (17%) [40]. As a consequence, it may be difficult to distinguish incident cases from recurrent cases since the case definition largely depends on the particular time window of study. Hence, this implies that studies on risk factors for LBP should include both incidence and recurrence of complaints. The pattern of slowly decreasing prevalence of LBP after 8–12 years described the healthy worker effect in this hypothetical cohort due to workers leaving the study population due to becoming work disabled.

The sensitivity analysis demonstrating the large impact of varying the underlying assumptions within a reasonable range. The estimates of working weeks lost due to sickness absence among workers with the highest exposure to WBV varied between 11.4 and 27 weeks. For weeks of permanent disability larger differences were observed, ranging from 78.8 to 412 weeks. The estimated burden of low-back disease was strongly influenced by the assumption whether workers on prolonged sick leave for 52 weeks will be able to change towards jobs with no WBV exposure or will remain disabled for the rest of their working life. The latter assumption showed that about 23.4% of the working life was lost among workers with high WBV exposure. This estimate is highly unlikely and certainly the upper limit of any effect of WBV exposure on work time lost, since it is not conceivable that no rehabilitation programmes will be implemented for professional drivers on prolonged sick leave.

The Markov chain used in the current analysis was completely defined by the transition distribution among the distinguished health states of LBP during the first year of follow-up and held constant for 40 years. This implies that workers had the same job with similar WBV exposure over 40 years and that individual characteristics of workers (e.g. physical capabilities) remained also unchanged. The prediction does not take into account the full history of complaints of an individual worker, such as nature and severity of previous LBP, although chronicity of LBP will have a worse prognosis than acute LBP [8]. However, there are only few longitudinal studies available to evaluate whether this important assumption is reasonable over a prolonged period of many years. A study among nurses with 8 years of follow-up concluded that LBP has more a recurrent than a progressive nature [40]. Another study among nurses with 8 consecutive questionnaires each 3 months apart showed that the presence of symptoms within the past 9–12 months were most relevant for the probability of recurrence [41]. Although the Markov model may be expanded with features such as cycle specific covariates (e.g. a lower transition probability for LBP to sickness absence in the first few years), and non-constant transition probabilities (e.g. a progressively higher probability of permanent work disability with increasing cycle number, reflecting an effect of cumulative exposure), in the absence of epidemiological information the risks were considered constant over time. The other assumptions of workers holding the same job for 40 years and unchanged individual characteristics may also not hold true, but epidemiological evidence is too scarce to present meaningful adjustments for their effects in the Markov chain model. Hence, the estimated number of weeks lost to sickness absence due to LBP in the hypothetical cohorts highly depends on these assumptions underlying the modelling approach. However, the advantage of the proposed modelling approach is that potential consequences for long-term work ability become apparent that may go unnoticed in cohort studies with a few years of follow-up. Nevertheless, validation against longitudinal studies with substantial follow-up periods of over 5 years is required to evaluate whether the prediction is a reasonable expression of long-term effects on sickness absence and work disability.

In traditional statistical analysis odds ratios illustrate the influence of WBV exposure on LBP and associated work disability, but these measures may not be sufficient for conveying the impact of WBV exposure on public health. The assessment of work time lost due to back pain, or alternatively expectancy of healthy working life [42], may be more useful to decision makers to appreciate the necessity for workplace interventions. The modelling of a hypothetical cohort presents an assessment of the long-term benefits of interventions directed at reducing WBV exposure by calculating the average number of cycles spent in each health state. By applying a quality factor to each state (utility) the expected cumulative utility accrued for the entire Markov process may be compared for alternative intervention strategies in a cost-effectiveness analysis. The expected benefits may also be tailored to an existing occupational population by estimating the cohort-specific transition probabilities and by using the actual distribution of health states as starting composition of the hypothetical cohort to be followed over time.

In conclusion, the Markov model presents a methodology that demonstrates the potential impact of long-term exposure to WBV on LBP and associated disability. The approach of years of work lost is a more adequate description for work-related risk factors that accelerate the onset of a more or less inevitable disease, such as LBP, than relative risks or attributable risk fractions [42]. The perceived significance of an average loss of 2.5–23.4% of work time during a working life due to high WBV exposure may provide for decision makers a better measure of adverse effect than an odds ratio of 2.3 for LBP. The concept of work years lost may also facilitate a better appreciation of the potential benefits of preventive measures.

Acknowledgements

This research was partly supported by the European Commission under the Framework 5 Quality of Life and Management of Living Resources programme—Project No. QLK4-2002-02650 (VIBRISKS).

References

[1] M. Bovenzi, C.T.J. Hulshof, An updated review of epidemiological studies on the relationship between exposure to whole-body vibration and low back pain (1986–1997), *International Archives of Occupational and Environmental Health* 72 (1999) 351–365.

[2] A. Burdorf, G. Sorock, Positive and negative evidence for risk factors of work-related back disorders, *Scandinavian Journal of Work Environment & Health* 23 (1997) 243–256.

[3] S. Lings, C. Leboeuf-Yde, Whole-body vibration and low back pain: a systematic cirtical review of the epidemiologic literature 1992–99, *International Archives of Occupational and Environmental Health* 73 (2000) 290–297.

[4] K.T. Palmer, M.J. Griffin, H. Bendall, B. Pannett, D. Coggon, Prevalence and pattern of occupational exposure to whole-body vibration in great Britain: findings from a national survey, *Occupational and Environmental Medicine* 57 (2000) 229–236.

[5] International Organization for Standardization ISO 2631-1, Guide for the evaluation of human exposure to whole-body vibration—part 1: general requirements, second ed., ISO, Geneva, 1997.

[6] C.T.J. Hulshof, G. van der Laan, I.T.J. Braam, J.H.A.M. Verbeek, The fate of Mrs. Robinson: criteria for recognition of whole-body vibration injury as an occupational disease, *Journal of Sound and Vibration* 253 (2002) 185–194.

[7] The European Parliament and the Council of the European Union, Directive 2002/44/EC, On the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (vibration), *Official Journal of the European Communities* L 177 (2002) 13–19.

[8] L. Hestbaek, C. Leboeuf-Yde, C. Manniche, Low back pain: what is the long-term course? A review of studies of general patient populations, *European Spine Journal* 12 (2003) 149–165.

[9] M. Von Korff, Studying the natural course of back pain, *Spine* 19 (1994) 2041S–2046S.

[10] F.A. Sonnenberg, R. Beck, Markov models in medical decision making: a practical guide, *Medical Decision Making* 13 (1993) 322–338.

[11] D.C. Cole, M. Manno, D. Beaton, M. Swift, Transitions in self-reported musculoskeletal pain and interference with activities among newspaper workers, *Journal of Occupational Rehabilitation* 12 (2002) 163–174.

[12] E. Viikari-Juntura, R. Martikainen, R. Luukkonen, P. Mutanen, E.P. Takala, H. Riihimaki, Longitudinal study on work related and individual risk factors affecting radiating neck pain, *Occupational and Environmental Medicine* 58 (2001) 345–352.

[13] F. Lötters, A. Burdorf, J. Kuiper, H. Miedema, Model for the work-relatedness of low-back pain, *Scandinavian Journal of Work Environment & Health* 29 (2003) 431–440.

[14] M. Bovenzi, A. Zadini, Self-reported low back symptoms in urban bus drivers exposed to whole-body vibration, *Spine* 17 (1992) 1048–1059.

[15] M. Bovenzi, A. Betta, Low back disorders in agricultural tractor drivers exposed to whole-body vibration and postural stress, *Applied Ergonomics* 25 (1994) 231–241.

[16] P.M. Bongers, H.C. Boshuizen, C.T.J. Hulshof, Self-reported back pain in drviers of wheelloaders, in: P.M. Bongers, H.C. Boshuizen (Eds.), *Academisch Proefschrift Universiteit van Amsterdam*, 1990, pp. 205–220

[17] H.C. Boshuizen, P.M. Bongers, C.T.J. Hulshof, Self-reported back pain in tractor drivers exposed to whole-body vibration, *International Archives of Occupational and Environmental Health* 62 (1990) 109–115.

[18] H.C. Boshuizen, P.M. Bongers, C.T.J. Hulshof, Self-reported back pain in fork-lift truck and freight-container tractor drivers exposed to whole-body vibration, *Spine* 17 (1992) 59–65.

[19] T. Brendstrup, F. Biering-Sorensen, Effect of fork-lift truck driving on low-back trouble, *Scandinavian Journal of Work Environment & Health* 13 (1987) 442–452.

[20] A. Burdorf, B. Naaktgeboren, H.C.W.M. de Groot, Occupational risk factors for low back pain among sedentary workers, *Journal of Occupational Medicine* 35 (1993) 1213–1220.

[21] J. Alcouffe, P. Manillier, M. Brehier, C. Fabin, F. Faupin, Analysis by sex of low-back pain among workers from small companies in the Paris area: severity and occupational consequences, *Occupational and Environmental Medicine* 56 (1999) 696–701.

[22] A. Burdorf, G. Govaert, L. Elders, Postural load and back pain of workers in the manufacturing of prefabricated concrete elements, *Ergonomics* 34 (1991) 909–918.

[23] A. Kumar, M. Varghese, D. Mohan, P. Mahajan, P. Gulati, S. Kale, Effect of whole-body vibration on the low back: a study of tractor-driving farmers in north India, *Spine* 24 (1999) 2506–2515.

[24] S. Linton, Risk factors for neck and back pain in a working population, *Work and Stress* 4 (1990) 41–49.

[25] M.L. Magnusson, M.H. Pope, D.G. Wilder, B. Areskoug, Are occupational drivers at an increased risk for developing musculoskeletal disorders?, *Spine* 21 (1996) 710–717.

[26] F. Pietri, A. Leclerc, L. Boitel, J.F. Chastang, J.F. Morcet, M. Blondet, Low-back pain in commercial travelers, *Scandinavian Journal of Work Environment & Health* 18 (1992) 52–58.

[27] H. Saraste, G. Hultman, Life conditions of persons with and without low back pain, *Scandinavian Journal of Rehabilitation Medicine* 19 (1987) 109–113.

[28] Y. Xu, E. Bach, E. Orhede, *Occupational and Environmental Medicine* 54 (1997) 741–745.

[29] S. Schwarze, G. Notbohm, H. Dupuis, E. Hartung, Dose–response relationships between whole-body vibration and lumbar disk disease—a field study on 388 drivers of different vehicles, *Journal of Sound and Vibration* 215 (1997) 613–628.

[30] P.M. Bongers, H.C. Boshuizen, C.T.J. Hulshof, A.C. Koemeester, Back disorders in crane operators exposed to whole-body vibration, *International Archives of Occupational and Environmental Health* 60 (1988) 129–137.

[31] M. Bovenzi, I. Pinto, N. Stacchini, Low back pain in port machinery operators, *Journal of Sound and Vibration* 253 (2002) 3–20.

[32] TreeAge Software Inc., *DATA TreeAge Version 3.5 for Health Care*, TreeAge, Williamstown, MA, 1998.
[33] J.W. Frank, A.S. Brooker, S.E. DeMaio, M.S. Kerr, A. Maetzel, H.S. Shannon, T.J. Sullivan, R.W. Norman, R.P. Wells, Disability resulting from occupational low back pain: Part II: what do we know about secondary prevention? A review of the scientific evidence on prevention after disability begins, *Spine* 21 (1996) 2918–2929.
[34] W.E. Hoogendoorn, P.M. Bongers, H.C.W. de Vet, J.W. Twisk, W. Van Mechelen, L.M. Bouter, Comparison of two different approaches for the analysis of data from a prospective cohort study: an application to work related risk factors for low back pain, *Occupational and Environmental Medicine* 59 (2002) 459–465.
[35] L.A.M. Elders, A. Burdorf. Prevalence, incidence, and recurrence of low-back pain in scaffolders during a 3 year follow-up study, *Spine* 29 (2004) e101–e106.
[36] J.P. Jansen, H. Morgenstern, A. Burdorf, Dose–response relations between occupational exposures to physical and psychosocial factors and the risk of low-back pain, *Occupational and Environmental Medicine* 61 (2004) 972–979.
[37] L.H. Pengel, R.D. Herbert, C.G. Maher, K.M. Refshauge, Acute low-back pain: systematic review of its prognosis, *British Medical Journal* 327 (2003) 323.
[38] S.M. Moldano, A. Burdorf, L.A.M. Elders, Factors associated with medical care-seeking due to low-back pain in scaffolders, *American Journal of Industrial Medicine* 40 (2001) 275–281.
[39] J. Hartvigsen, C. Leboeuf-Yde, S. Lings, E.H. Corder, Is sitting-while-at-work associated with low back pain? A systematic, critical literature review, *Scandinavian Journal of Public Health* 28 (2000) 230–239.
[40] I. Maul, T. Läubli, A. Klipstein, H. Krueger, Course of low back pain among nurses: a longitudinal study across eight years, *Occupational and Environmental Medicine* 60 (2003) 497–503.
[41] J. Smedley, H. Inskip, C. Cooper, D. Coggon, Natural history of low back pain: a longitudinal study in nurses, *Spine* 23 (1998) 2422–2426.
[42] M. Nurminen, Working population health metrics, *Scandinavian Journal of Work Environment & Health* 30 (2004) 339–349.