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Combined exposures of whole-body vibration and awkward posture: a cross sectional investigation among occupational drivers by means of simultaneous field measurements

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ABSTRACT
Objective: Multifactorial workloads such as whole-body vibration (WBV), awkward posture and heavy lifting are potential predictors for low back pain (LBP). In this study, we investigate the association between LBP and these exposures among 102 professional drivers. Methods: The combined exposures of WBV and posture are measured at different workplaces. Health and personal data as well as information about lifting tasks are collected by a questionnaire. Results: The daily vibration exposure value (odds ratio 1.69) and an index for awkward posture (odds ratio 1.63) show significant association with the occurence of LBP. Awkward posture and heavy lifting appear to be more strongly associated with sick leave than WBV exposure. Furthermore, a combination of the measurement results of WBV and awkward posture into one quantity also shows significant correlation to LBP. Conclusion: The combined exposure of WBV and awkward posture can be described in terms of the daily vibration exposure and the index for awkward posture. This facilitates work place assessments and future research in this area.

Practitioner Summary: For the first time, quantitative measures combining whole-body vibration and awkward posture exposures have shown to correlate with the occurrence of low back pain significantly. This validates the proposed quantities and measurement methods, which facilitate workplace assessments and assist in the design of further studies which are necessary to establish a causal exposure–response relationship.

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KEYWORDS
Whole-body vibration; awkward posture; field measurements; low-back pain; combined exposures

1. Introduction

According to a survey in Germany from 2012 (Brennscheidt et al. 2012), 4.8 million employees are exposed to awkward posture and 1.5 million employees to high vibration exposure and shocks. A large number of employees also reported manual materials handling (MMH) (7.6 million). These exposures are often associated with musculoskeletal symptoms (Bernard 1997; Bovenzi 2015, Bovenzi et al. 2015). In the same German survey, low back pain (LBP) and local pain at the cervical spine and the shoulders are the pains most reported during or immediately after the activity, and more than 60% of the persons who reported pain are undergoing medical treatment.

Therefore, in order to investigate the adverse health effect of whole-body vibration (WBV), other cofactors such as MMH, psychosocial stress and especially awkward posture need to be considered (Bovenzi 2015; Lotters et al. 2003). Morgan et al. (Morgan and Mansfield 2014) have presented a review of expert opinions on the effects of combined exposure to trunk rotation and WBV, as commonly experienced by operators of agricultural machinery. The results show that operators as well as experts considered the combined exposure to be a risk factor for the development of back pain.

There are several procedures investigating combined exposures of WBV and other cofactors: using observational analysis, questionnaires, biomechanical research or direct field measurements. For instance, the exposures 'trunk bent at work' and 'lifting with bending/twisting' have shown a significant effect in terms of increasing the risk of LBP while exposed to WBV (Bovenzi et al. 2006), (Tiemessen, Hulshof, and Frings-Dresen 2008) using observational methods and questionnaires. In biomechanical research, Fritz et al. (Fritz and Schäfer 2010) assess the forces within a rigid-mass model of the lumbar spine and compare the effects of different postures during exposure to WBV. The bent-forward

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postures result in an increase in the temporal mean values of the compressive forces and of the shear forces in the dorsoventral direction compared to the upright sitting posture. However, due to the complexity of measuring posture quantitatively, no epidemiological analysis has so far investigated the combination of these exposures by means of quantitative data and their relationship to LBP.

The CUELA posture measuring system ('computer-assisted recording and long-term analysis of musculoskeletal loads') has been introduced for field measurements of combined exposure to WBV and posture (Raffler et al. 2010), (Hermanns et al. 2008). This system permits the quantitative analysis of posture as body angles during exposure to WBV. Thus, the measurements provide an objective and quantitative description of such exposures (Raffler et al. 2016). However, its relationship to adverse health effect is still unknown.

Therefore, the aims of this study are:

- collecting measurement data of WBV exposure and postural stress for a chosen study population.
- investigate these combined exposures in terms of suitable measures and their relationship to LBP.

2. Subjects and methods

2.1. Study population

Since this study does not aim at a causal dose–response relation, the study population has been selected based on the following criteria:

(1) The measured exposures should reflect the previous lifetime exposure of the subjects (WBV exposure for over 10 years, at least one year of WBV exposure in the current company).
(2) The subjects should have a similar age (40–50 years).
(3) The subjects should not have had any musculoskeletal disease or disorder before beginning their occupational training.
(4) Favourable and unfavourable postures should be present as well as low and high WBV exposures. These should be present while working in: busses and locomotives (group 1), cranes and gantry cranes (group 2), earth-moving machinery (group 3), forklift trucks (group 4).

For the first group, bus and locomotive drivers are assumed to be exposed to low WBV, while sitting upright and using the backrest. The workplaces of group 2 involve bent-forward postures, since the load has to be controlled. At the same time, the WBV exposure should be as low as for group 1. The drivers in group 3 should be exposed to higher WBV exposure than the drivers in groups 1 and 2. They are expected to move materials or to perform construction tasks such as excavating and compacting while sitting upright and using the backrest. Thus, due to the diversity of vehicle types and operating tasks large distributions for WBV exposure and maybe also postural behaviour are expected. Finally, in the fourth group, forklift drivers are also supposed to be exposed to higher WBV exposure than the drivers in group 1 and 2. Forklift drivers are assumed to move materials while driving forwards, backwards and rotating the upper body.

Due to criteria 1–3, one can expect that the effect of age on the outcomes is smaller than for studies without age restrictions. In addition, the exposure measured in this cross-sectional study should lead to a good estimate for the previous lifetime exposure.

All drivers have been in good health and have not been suffering from noteworthy physical complaints at the time of the study. All drivers and employers have given informed consent prior to participating in this study on a voluntary basis. The Ethics Committee of the Medical Faculty, RWTH Aachen University has approved the study and the study design. A positive ethics committee vote has been received.

In total, 129 subjects from 10 companies have participated in this study. The WBV- and postural exposures have been measured for 58 subjects. Out of these, 31 subjects have filled out a questionnaire regarding the individual exposure history, further cofactors and musculoskeletal symptoms (nordic questionnaire (Kuorinka et al. 1987)). The remaining 71 subjects participated only in the survey.

2.2. Measurement and analysis of WBV

In accordance with (DIN EN 14253: 2007), (ISO 8041: 2005) and (ISO 2631-1: 1997), WBV measurements are conducted in three orthogonal axes $l = \{x, y, z\}$ (x fore and aft, y lateral and z vertical) at the seat surface and at the seat mounting point. The acceleration measured at the seat mounting point allows to detect artefacts and is not discussed in the present study. The duration of measurements T_M has been long enough to capture the working conditions (for WBV and posture exposures) in a representative way.

Vibration signals are detected at 480 Hz and weighted according to (ISO 2631-1: 1997) to yield frequency-weighted vibration signals $a_{wl}(t)$, which are averaged using the root-mean-square (RMS) method:

$$a_{wl} = \left(\frac{1}{T_M} \int_0^{T_M} a_{wl}^2(t) \mathrm{d}t \right)^{\frac{1}{2}} \tag{1}$$

In order to have only one value which takes into account the effect of three axes, one can calculate the vibration

Table 1. CUELA posture measuring system. Degrees of freedom used in this work are printed in bold face.

Body region for sensor attachment	*Degree of freedom derived from sensor data*
Head	**Neck flexion (lateral/sagittal)**
	Neck flexion (lateral/sagittal)
	Neck torsion
Thoracic spine (TS)	**Thoracic inclination (lateral/sagittal)**
Lumbar spine (LS)	**Trunk inclination (lateral/sagittal)**
	Back flexion (lateral/sagittal)
	Back torsion
Thigh	Hip flexion/extension
Lower leg	Knee flexion/extension

total value (vector sum) of the frequency-weighted acceleration values $a_{v1.4}$ (ISO 2631-1: 1997):

$$a_{v1.4} = \sqrt{1.4^2 a_{wx}^2 + 1.4^2 a_{wy}^2 + a_{wz}^2} \tag{2}$$

If a_{wl} and $a_{v1.4}$ are representative for a given task of a day, one can use them to define daily vibration dose values which also depend on the daily exposure duration T. The daily vibration exposure $A(8)$ is defined as the largest resulting value, after correcting the RMS value a_{wl} in x- and y-direction by a constant and normalising the duration dependence to $T_0 = 8\text{h}$ (EU-Directive 2002/44/EC 2002:

$$A(8) = \max\left\{1.4a_{wx}\sqrt{\frac{T}{T_0}}; 1.4a_{wy}\sqrt{\frac{T}{T_0}}; a_{wz}\sqrt{\frac{T}{T_0}}\right\} \tag{3}$$

2.3. Measurement and analysis of posture

Drivers' posture has been detected by using the CUELA system (Raffler et al. 2010), (Amari, Caruel, and Donati 2015; Hermanns et al. 2008). Making use of inertial/kinematic sensor technology, the CUELA system records the detected posture continuously as an angular measurement. The system can be attached to the subject's clothing, without hindering the subjects during their work. Table 1 shows the sensor arrangement, the regions of the body, the locations of sensor attachment, and the respective body angles or degrees of freedom (DOFs). In addition to the measurements, video recording is used for investigating the tasks and activities of the drivers during a shift and also for monitoring the alignment of the sensors.

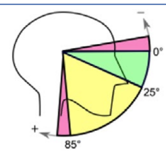
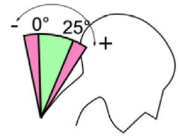
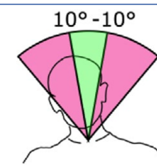
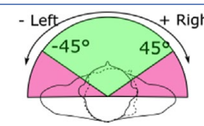
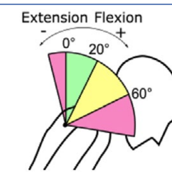
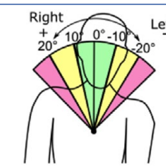
The movements are recorded directly at a sampling rate of 50 Hz by using triaxial accelerometers and gyroscopes. In order to prevent aliasing problems, the analogue output signal of each accelerometer is passed through a low-pass filter with a cut-off frequency of 10 Hz. At the beginning of a measurement, all body angles are initialised. The posture during initialisation (zero joint position) is an upright standing posture with the subject looking straight ahead. Thus, subject-specific angle offsets and errors caused by the sensor attachment can be eliminated. Overall, movement artefacts are less than ±1° in low-vibration environments and ±4° during rough vibrations with high amplitudes and low frequencies (Raffler et al. 2010) (Hermanns et al. 2008). Other artefacts such as interference of sensors with the backrest or subject's clothes were detected a posteriori by video analysis.

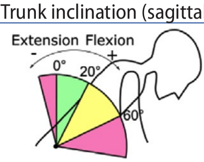
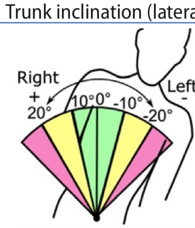
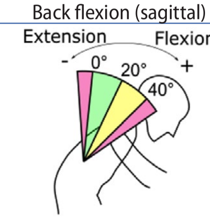
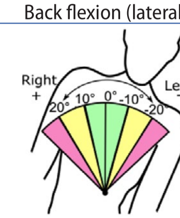
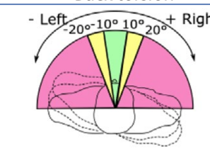
In this study, the median differences of the zero joint position before and after the measurement ranged from 1.7° to 5.1° depending on the DOF. The measurement duration has been the same as for the WBV exposures given in Table 3.

With reference to (ISO 11226: 2000) and (DIN EN 1005-4: 2005), three categories are defined for classification of the body angles as 'neutral' green, 'moderate' yellow and 'awkward' red. For the upper body, 11 DOFs are specified in this study. Table 2 shows the description of the categories for all 11 DOFs. This assessment scheme follows a quasi-static approach, since it does not differentiate between abrupt movements (e.g. recoil) and slowly varying movements as long as the posture reaches the same angular interval. The assessment of posture by dynamic quantities has been proposed in the literature. For example, it has been proposed that a function which describes discomfort should include the RMS value of the angular acceleration of a DOF (Rahmatalla and DeShaw 2011). However, this is out of the scope of this study.

The percentage of working time spent in each category of Table 2 can thus be shown for each DOF. In the

Table 2. Description of the categories for 11 degrees of freedom (upper body).

	Body angle					
Category	Head inclination (sagittal)	Neck flexion (sagittal)	Neck flexion (lateral)	Neck torsion	Thoracic inclination (sagittal)	Thoracic inclination (lateral)
						
Neutral	0° to 25°, <0° Full head support	0° to 25°	−10° to 10°	−45° to 45°	0° to 20°, <0° Full back support	0° to 10°
Moderate	25° to 85°				20° to 60°	10° to 20° or −20° to −10°
Awkward	<0° or >85°	<0° or >25°	<−10° or >10°	<−45° or >45°	<0° or >60°	<−20° or >20°

	Body angle				
Category	Trunk inclination (sagittal)	Trunk inclination (lateral)	Back flexion (sagittal)	Back flexion (lateral)	Back torsion
					
Neutral	0° to 20°, <0° Full back support	0° to 10°	0° to 20°	0° to 10°	−10° to 10°
Moderate	20° to 60°	10° to 20° or −20° to −10°	20° to 40°	10° to 20° or −20° to −10°	10° to 20° or −20° to −10°
Awkward	<0° or >60°	<−20° or >20°	<0° or >40°	<−20 or >20°	<−10 or >10°

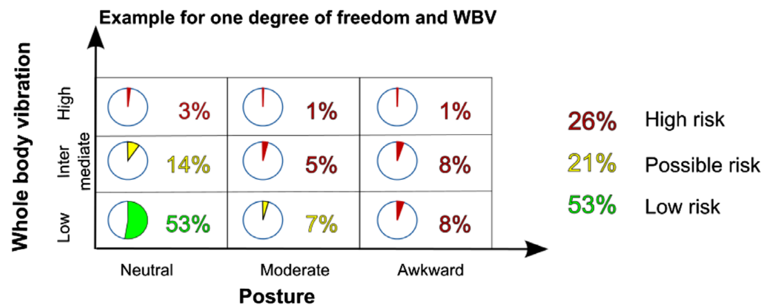


Figure 1. 3 × 3 matrix scheme with whole-body vibration categories on the vertical axis and posture categories on the horizontal axis.
Notes: The matrix entries show the percentage of the measured duration spent in each combination of categories. Right: Three risk categories summarised from the matrix.

Table 3. Frequency-weighted root-mean-square acceleration magnitude (a_{wl}) of vibration measured on the three orthogonal axes $l = \{x, y, z\}$ on the seat surface and the vibration total value, as mean values (standard deviation).

Machine group	Vehicle (number)	Duration of measurement [minutes]	Frequency weighted acceleration magnitude [ms^{-2}] a_{wx}	a_{wy}	a_{wz}	$a_{v1.4}$	$A(8)$	$A(8)$
1	Bus (4)	108 (9)	0.12 (0.01)	0.13 (0.01)	0.20 (0.01)	0.32 (0.01)	0.22 (0.00)	0.20 (0.02)
	Locomotive (6)	85 (22)	0.10 (0.04)	0.15 (0.04)	0.18 (0.03)	0.29 (0.04)	0.19 (0.01)	
2	Crane (13)	74 (13)	0.11 (0.04)	0.11 (0.05)	0.16 (0.11)	0.27 (0.14)	0.16 (0.05)	0.17 (0.05)
	Gantry crane (6)	98 (20)	0.21 (0.02)	0.11 (0.04)	0.17 (0.03)	0.37 (0.04)	0.21 (0.00)	
3	Dumper (8)	83 (14)	0.32 (0.11)	0.43 (0.15)	0.50 (0.24)	0.91 (0.33)	0.63 (0.20)	0.59 (0.17)
	Excavator (5)	76 (14)	0.43 (0.10)	0.26 (0.08)	0.31 (0.14)	0.78 (0.17)	0.60 (0.18)	
	Wheel loader (2)	91 (11)	0.52 (0.06)	0.58 (0.01)	0.43 (0.11)	1.18 (0.08)	0.74 (0.13)	
	Bulldozer (3)	88 (16)	0.34 (0.04)	0.25 (0.09)	0.42 (0.14)	0.73 (0.17)	0.52 (0.04)	
	Grader (1)	71 ()	0.22 ()	0.25 ()	0.28 ()	0.54 ()	0.33 ()	
	Compactor (1)	50 ()	0.24 ()	0.38 ()	0.27 ()	0.69 ()	0.48 ()	
4	Forklift truck (9)	79 (25)	0.24 (0.03)	0.23 (0.04)	0.27 (0.13)	0.56 (0.06)	0.35 (0.03)	0.35 (0.05)

previous published study (Raffler et al. 2010), an index R_{DOF} has been introduced to summarise non-neutral posture. If the observed duration of the i^{th} DOF in the non-neutral category ($t_{a,i}$) is greater than 30% of the daily exposure duration (T), the DOF in question is regarded as an 'awkward' DOF. The index R_{DOF} is quantified as follows:

$$R_{DOF} = \sum_{i=1}^{i=11} c_i \,; c_i = \begin{cases} 0 & \text{if } \frac{t_{a,i}}{T} \cdot 100\% < 30\% \\ 1 & \text{if } \frac{t_{a,i}}{T} \cdot 100\% \geq 30\% \end{cases} \quad (4)$$

where c_i counts if a DOF exceeds 30% of the exposure duration in the non-neutral category, and in this study $0 \leq R_{DOF} \leq 11$. The index R_{DOF} is a straightforward way to combine the measured postural exposure data.

2.4. Analysis of combined exposure to WBV and posture

The preceding subsections specify several quantities which describe WBV and posture exposures. At a workplace, however, it is desirable to combine the different data into one quantity for the assessment. Therefore, we have also investigated such a combination, which relies on time spent in defined categories for each exposure. Considering EU Directive (2002/44/EC 2002) and an epidemiological study (Notbohm, Schwarze, and Albers 2009), the three categories for WBV are described as 'low' $a_{v1.4} < 0.5$ m/s^2, 'intermediate' 0.5 m/s$^2 \leq a_{v1.4} < 1$ m/s^2 and 'high' $a_{v1.4} \geq 1$ m/s^2. The three categories for posture (neutral, moderate and awkward) are described in Table 2. The combination of all these categories together, gives rise to a 3 × 3 matrix scheme (Raffler et al. 2010), with WBV categories on the vertical axis and posture categories on the horizontal axis.

In Figure 1, an example of lateral trunk inclination and WBV shows the combination of both exposures and their summarisation to the risk categories for one driver. The matrix entries show the percentage of the measured time spent in each combination of categories with respect to the total time of the measurement, which represents the daily exposure duration: for this example (53% low vibration and neutral posture), (7% low vibration and moderate posture) and (8% low vibration and awkward posture) etc. The sum of these colour-coded combinations defines the risk categories: low-risk category (green combination), possible-risk category (yellow combinations) and high-risk category (red combinations).

In analogy to Equation (4), an index R_{WBV-P} for the risk combination is proposed. If the observed duration of the i^{th} (DOF and WBV) in the non-low risk category ($t_{h,i}$) is greater than 30% of the daily exposure duration (T), the combination in question is considered to be a risky combination. The at-risk combinations ($R_{WBV\text{-}P}$) are counted as follows:

$$ {}_{\mathrm{WBV-P}} = \sum_{i=1}^{i=11} c_i ; c_i = \begin{cases} 0 & \text{if } \frac{t_{h,i}}{T} \cdot 100\% < 30\% \\ 1 & \text{if } \frac{t_{h,i}}{T} \cdot 100\% \geq 30\% \end{cases} \quad (5) $$

where c_i counts the risky combinations, and in this study $0 \leq R_{WBV\text{-}P} \leq 11$.

2.5. Questionnaire

A self-administered questionnaire, including (amongst others) questions on medical and occupational history, has been sent to each driver one week before the medical investigation. Doctors have collected and checked the filled-in questionnaires during the medical examination. In cases of uncertainty and incompleteness, doctors have provided clarification and support for the drivers to fill in the questionnaires.

The questionnaire requests information on the driver's occupational history as well as further load factors such as MMH and psychosocial factors. Among these load factors, only MMH has shown a significant effect to the outcomes. Therefore, only the results for MMH data will be discussed in this article. MMH has been divided into lifting, carrying and pulling/pushing. Also the weight and the percentage of daily exposure duration have been included in the question. However, often the questions have not been answered in such detail, so that MMH and other items had to be treated as dichotomous questions (yes/no).

The outcome variables are assessed in the last section of the questionnaire, which records health complaints. It uses a modified version of the Nordic questionnaire on musculoskeletal symptoms (Kuorinka et al. 1987). The drivers are asked about the occurrence of pain in the neck, shoulder, upper and lower back region in the last 12 months or ever in their occupational lives. Drivers who report musculoskeletal symptoms are requested to answer additional items concerning duration, frequency, pain radiation, pain intensity and disability, symptom-related health care use, treatment (e.g. medication or physical therapy) and sick leave due to symptoms in the previous 12 months.

Based on the items included in the medical section of the questionnaire, two outcomes are defined as follows:

(1) 12 m-LBP: pain or discomfort in the low-back area between the twelfth rib and the gluteal folds, with or without radiating pain in one or both legs, lasting one day or longer in the previous 12 months.
(2) Sick leave: sick leave due to LBP in the previous 12 months.

3. Results and discussion – description of factors

3.1. Measurements – study population

Altogether, 58 persons have been visited for WBV and posture measurements: 10 Bus and locomotive drivers, 19 crane operators, 20 earth moving machine operators and 9 forklift drivers. They were on average 46.1 years old (SD = 8.4 years); although some drivers have not met the condition of 40–50 years old (28 subjects, ranging from 21 to 62 years old), all subjects are included into the study. They are on average 22.9 years exposed to WBV (SD = 9.7 years), with 21.6 years in the current company (SD = 9.9 years). Thus, the requirements 1 and 3 for the study population (Section 2) have been met by all subjects.

3.2. Measurements – WBV

The mean and standard deviation values of the frequency-weighted RMS accelerations measured at the driver-seat interfaces on the machines and vehicles used by professional drivers are presented in Table 3.

The duration of the measurements ranges from 50 min for the compactor to 108 min for buses, which is sufficient to capture the representative working conditions. While the z-axis (vertical) weighted acceleration is the dominant component of vibration measured in most of the machines, gantry cranes and excavators show on average maxima on the x-axis (fore and aft). A maximum on the y-axis (shoulder-shoulder) is only measured for the wheel-loaders and one compactor. The total vibration value ($a_{v1.4}$) of the weighted RMS accelerations ranged on average from 0.27 to 1.18 ms^{-2} for locomotives/cranes and wheel-loaders, respectively.

It has been proposed in the preceding section to discuss the exposures by groups: Table 3 shows for the group 1 of bus and locomotive drivers, as well as for the group 2 of crane and gantry crane operators, that the WBV exposure is indeed very similar within the groups and also between the groups. The average RMS values for the other vehicles are above those of the first two groups. While for the forklift trucks the comparatively small standard deviations justify the label 'group' as a sub sample of similar exposure, this is definitively not the case for the proposed group of the 'earth moving machines'. The values for this group are characterized by a broad variation in WBV exposures due to the different types of machinery, as expected.

3.3. Measurements – posture

The angular distribution of adopted posture among the 58 measured drivers is presented in Figure 2. In this study,

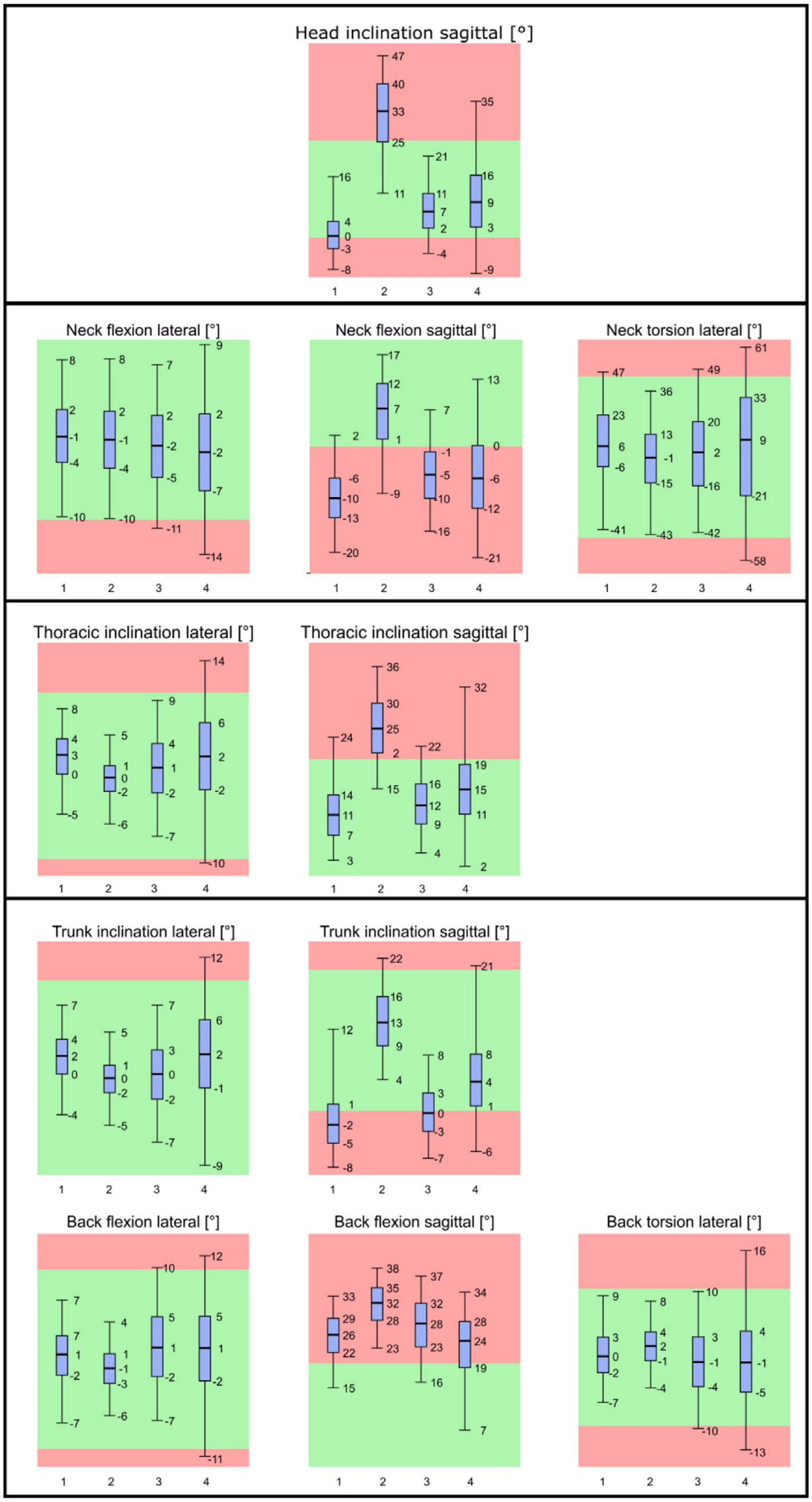
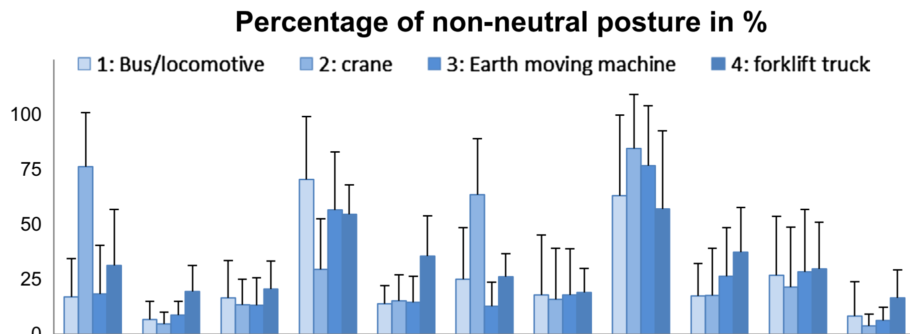


Figure 2. The angular distribution of the measured adopted posture among machine groups.

Notes: Data are given as box plots indicating the 5th, 25th, 50th, 75th and 95th percentiles of body angles. Boxes separate body angles associated with the head, the neck, the thoracic spine and the spine as a whole. Neutral angle ranges have green background, non-neutral angle ranges have red background. 1: bus and locomotive drivers; 2: crane operators; 3: earth-moving machine drivers; 4: forklift truck drivers.



	Thoracic inclination sag.	Thoracic inclination lat.	Neck flexion lat.	Neck flexion sag.	Neck torsion	Head inclination sag.	Back flexion lat.	Back flexion sag.	Back torsion	Trunk inclination sag.	Trunk inclination lat.
1	17	7	17	71	14	25	18	63	17	27	8
2	76	5	13	29	15	64	16	84	18	21	4
3	18	9	13	57	15	13	18	77	26	28	6
4	31	19	21	54	35	26	19	57	37	30	16

Figure 3. Measures of exposure to non-neutral posture as percentage of measurement duration among machine groups for each degree of freedom in the upper body posture.
Note: Data are given as mean values.

Table 4. The percentage of subjects who showed certain amount for R_{DOF}.

Percentage of subjects with	Machine group: Bus/locomotive	Crane	Earth-moving machine	Forklift truck
$R_{DOF} = 0$	20	10	35	45
$R_{DOF} = 1$	30	11	30	33
$R_{DOF} = 2$	20	37	30	22
$R_{DOF} = 3$	30	26	5	0
$R_{DOF} = 4$	0	16	0	0

Table 5. The percentage of subjects who showed certain amount for $R_{WBV\text{-}P}$.

Percentage of subjects with	Machine group: Bus/locomotive	Crane	Earth-moving machine	Forklift truck
$R_{WBV\text{-}P} = 0$	10	5	0	11
$R_{WBV\text{-}P} = 1$	30	11	15	11
$R_{WBV\text{-}P} = 2$	20	32	20	56
$R_{WBV\text{-}P} = 3$	40	32	30	22
$R_{WBV\text{-}P} = 4$	0	21	10	0
$R_{WBV\text{-}P} = 5$	0	0	10	0
$R_{WBV\text{-}P} = 6$	0	0	5	0
$R_{WBV\text{-}P} = 7–10$	0	0	0	0
$R_{WBV\text{-}P} = 11$	0	0	10	0

the 'moderate' and 'awkward' categories are merged in the non-neutral category (see Table 2).

The different postural behaviour of crane operators (group 2) mainly affects the following angles in the sagittal direction: head inclination, neck flexion, thoracic and trunk inclination. This difference sets group 2 apart from the other groups, and especially from group 1 which has a similar WBV exposure. As for the other two groups, one can only see that the spread between the 5th and 95th percentile for the DOFs (and often also between the 25th and 75th percentile) is largest for the forklift truck drivers, especially for the lateral DOFs and the torsions. This relates to the frequent backward driving (forcing the driver to turn the upper body to one side), to observing the loads, and to a more dynamic movement in general.

Figure 3 contains the measured percentages of time spent in non-neutral posture for each DOF. The average time spent in non-neutral postures is largest for sagittal body angles for crane operators, as expected from Figure 2. Sagittal thoracic inclination and head inclination show the highest percentages, 76 and 64%, respectively, for crane operators.

Concerning sagittal neck flexion, all the three groups except crane operators show on average high percentages in the non-neutral range of movement (54–71%). There is a possibility that non-neutral neck flexion negatively affects other regions of the spine such as the thoracic region or the shoulder-arm area, which is not the focus of this article.

By means of the time spent in the non-neutral range of movement the R_{DOF} value was calculated (Equation 4, Table 4). The maximum R_{DOF} is four for the crane operators, which is caused by awkward sagittal body angles; 16% of the subjects have reached this value. For the other groups the R_{DOF} value did not differ remarkably.

3.4. Measurements – combined WBV and posture exposure

Table 5 shows the combined exposure of WBV and posture as $R_{WBV\text{-}P}$ (Equation 5). Due to the high WBV exposure for earth moving machinery and forklift truck drivers, the $R_{WBV\text{-}P}$ values increase. Twenty-five percent of earth moving machinery operators have reached the value of 5 and beyond for $R_{WBV\text{-}P}$.

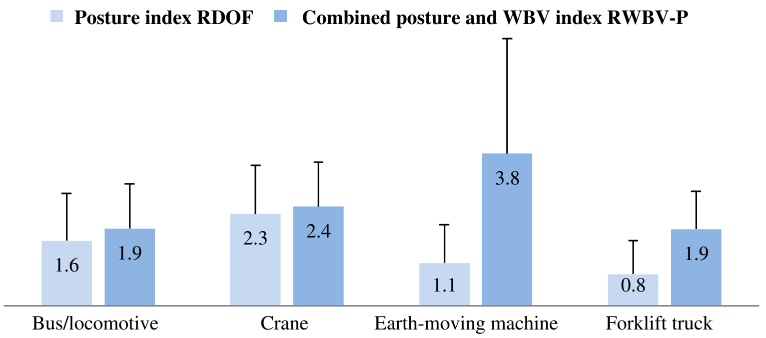


Figure 4. The average R_{DOF} and R_{WBV-P} for each machine group.

Table 6. Self-reported data about manual material handling (MMH): data are given as percentage of subjects for each group, N = number of subjects in each group.

	Bus/locomotive	Crane	Earth-moving machinery	Forklift truck
MMH	(N = 12)	(N = 39)	(N = 26)	(N = 25)
Lifting (%)	8	26	50	28
Carrying (%)	8	26	35	24
Pulling/pushing (%)	8	15	42	24

Table 7. Information on prevalence of low-back pain (LBP) in the last 12 months and sick leave due to LBP. Data are given as percentages of subjects for each group.

Outcome (%)	Bus/locomotive	Crane	Earth-moving machine	Forklift truck
12-month LBP	33	51	69	36
Sick leave due to LBP	0	49	27	21

Table 8. Regression models for the 12 months prevalence of low back pain (12 m-LBP) and sick leave.

12 m-LBP (final model)			Sick leave (final model)		
Variables	OR (95% CI)	*p*-value	Variables	OR (95% CI)	*p*-value
$A(8) \times 10$	1.69 (1.18–2.4)	0.004	$A(8) \times 10$	1.08 (0.71–1.62)	0.726
R_{DOF}	1.63 (1.05–2.55)	0.03	R_{DOF}	2.04 (1.15–3.61)	0.014
			Lifting	6.26 (2.16–18.11)	0.001
Test for interaction effect					
R_{DOF} x $A(8) \times 10$	1.19 (0.76–1.85)	0.361	R_{DOF} x $A(8) \times 10$	0.77 (0.47–1.25)	0.468
Variable			Variable		
$R_{WBV\text{-}P}$	1.37 (0.92–2.04)	0.121	$R_{WBV\text{-}P}$	2.34 (1.31–4.18)	0.004

Figure 4 compares the average R_{DOF} values with average $R_{WBV\text{-}P}$ values for each vehicle group. One can see that the impact of WBV exposure to the average index is much higher for earth moving machinery and forklift truck drivers.

3.5. Relation to outcome variables – descriptive results

Altogether 129 persons in ten companies participated, out of which 58 persons have been visited for WBV and posture measurements. There have been 27 drivers who participated in the exposure measurements, but have been unable to participate in the medical examination. However, their exposures are used for subjects in the same company without measured exposures. This leaves 102 drivers for further analysis of the questionnaire data.

Subjects are on average 43.9 years old (SD = 7.9), 18.6 years exposed to WBV (SD = 9.8) and 15.7 years in the current company. Thus, the requirements 1and 3 for the study population (Section 2) have also been met for the survey.

Individual and psychosocial factors do not differ significantly among vehicle groups. Also these factors do not show a significant effect on LBP. Only MMH data as an additional load factor are described and discussed in this article. Since it has not been possible to evaluate the questions concerning MMH with respect to the masses or exposure durations, Table 6 shows the results in the form of dichotomised answers (yes/no). The proportion of subjects with exposure to MMH is larger for the group 3 (earth-moving machinery) than for the other groups.

Table 7 reports on the proposed outcome variables with respect to the exposure groups. Group 1 of the bus and locomotive drivers shows the smallest proportions for the different outcome variables. Therefore, group 1 will act as the control group in this study population. The other groups are different to group 1 with respect to the exposures (particularly, WBV and posture) and the outcome variables. The extent to which the outcome variables are affected by the described exposure factors is impossible to perceive before the statistical regression analysis, which will be put forward in the next section. However, since a variation in WBV and postural exposure is present in the study population, it is possible to speculate that the postural exposure of group 2 will add to its LBP outcomes, and that the MMH and/or WBV (although not homogeneous within the group) are a decisive factor for group 3. There are no indicators so far for further relevant factors.

3.6. Relation to outcome variables – regression analysis

3.6.1. Univariate analysis

All factor variables (measured and questionnaire data) are subjected to a univariate analysis between the outcome variables and each factor variable. This will identify the important factor variables beyond the mere descriptive assessment of the preceding section.

In terms of WBV exposure, the only significant association is observed between the ten-fold daily vibration exposure $A(8)\times 10$ and 12 m-LBP: odds ratio (OR) is 1.33 (95 % confidence interval 1.03–1.72; $p < 0.05$). The daily exposure value $A(8)$, therefore, proves to be a suitable measure of vibrational workload and is chosen for further analysis with other cofactors. In order to equalise the range of the data from WBV and other factors, the ten-fold of $A(8)$ has been used. Thus, with an increase in 0.1 ms^{-2}, the OR for 12 m-LBP will increase by 1.33 in this study population. The OR for A(8), on the other hand, would be related to the increase in A(8) by 1 m/s^2, which would lead to very high ORs and difficult interpretations.

Concerning posture, there is no significant association between individual body angles and LBP. However, the risk for occurrence of sick leave tends to increase with an increasing R_{DOF}, the number of awkward body angles (OR = 1.72 CI 1.18–2.5 $p < 0.01$). This indicates that the correlation for R_{DOF} is a better variable for posture in the final regression analysis than the non-neutral percentages of single body angles.

Other findings are in line with the arguments of the preceding sections, e.g. the fact that age or psychosocial stress does not show a significant association with the outcomes. On the other hand, self-reported MMH is significantly associated with 12 m-LBP and sick leave ($p < 0.001$). The risk of occurrence of both outcomes increases with the incidence of lifting, carrying and pulling/pushing tasks.

3.6.2. Linear dependencies and regression analysis for a final model for 12 m-LBP and sick leave

In a next step, bivariate analyses have been used to identify factors that depend (linearly) on each other. Out of a group of interdepending factors, only one factor has been selected for the regression analysis. This procedure leaves the following factors for the further regression analysis: Age, weight, marital status, gardening, sports, smoking, professional training and shift remained in the group of individual factors. The psychosocial factors include job satisfaction, job demand control, social support from other persons and job uncertainty. As for MMH, only lifting has been selected for further analysis. Since non-neutral body angles are highly dependent on each other, the R_{DOF}-value has been selected to represent awkward posture. WBV is described by the tenfold daily vibration exposure $A(8)\times 10$.

Finally, a logistic regression analysis is started with this selection of factors. The factor vibration is entered in the model regardless of its significance. The selected independent variables are then added to the respective model. The regressions are calculated stepwise backwards (exclusion criteria: $p \geq 0.05$).

In the final model (Table 8), 12 m-LBP is described with the tenfold daily vibration exposure $A(8)\times 10$ and posture with the R_{DOF} value, both with negative effects. No other variable can contribute in a significant way. Sick leave in the final model is described with WBV as $A(8)\times 10$, the R_{DOF} value and lifting with negative effect, while the effect of WBV as $A(8)\times 10$ is marginal ($p > 0.05$). No other variables show a correlation to the two outcome variables. Finally, the results of interaction tests do not show an additive effect from the product of WBV and posture as $A(8)\times 10$ and R_{DOF}.

This hints at a linear relation between $A(8)$, R_{DOF} and the outcome variables. As a consequence, also the combined exposure of WBV and posture as expressed in $R_{WBV\text{-}P}$, which is a linear combination of those exposures, shows a very significant effect on sick leave (Table 8).

4. Discussion

The first aim of this study has been to collect measurement data of WBV exposure and postural stress for the study population. This aim has been achieved as shown in the preceding section, where the study population has been recruited in such a way that a reasonable variation with regard to WBV and posture exposure has been present. For example, the magnitude of RMS values differed for the different vehicles and they are similar to those published in other reports (Bovenzi et al. 2006), (Raffler et al. 2010), (Tiemessen, Hulshof, and Frings-Dresen 2008). Also for the postural workload a reasonable variation is discernible (Figure 2). The observed exposures can serve as a reference for studies which cannot measure the exposures, but have to resort to other assessment methods, such as questionnaires and observational techniques.

Due to the selections criteria of the study population it is not possible to deduce a causal dose–response relationship between the measured combined exposures and the outcome variables. However, it has been necessary to show, that it is possible to describe the outcome variables for LBP in terms of the measured quantities. The preceding section underlines that $A(8)$ and R_{DOF} are able to describe a relevant part of the outcome variables in this study. This finding has been the second aim of this study.

Other studies have found a correlation between age (Notbohm, Schwarze, and Albers 2009) or lifetime dose values (Bovenzi et al. 2006) (Bovenzi 2015) with outcome variables that describe LBP. Due to the selection process of the study population, age and lifetime dose values were out of scope in this study. The age distribution has been homogenous enough to suppress age effects, and since most of the exposure has been accumulated in the same company, the daily vibration dose $A(8)$ has been a better descriptor than lifetime dose quantities. There is also no conflict with (Notbohm, Schwarze, and Albers 2009) since only one subject has accumulated a lifetime dose which is attributed with a large risk for LBP in (Notbohm, Schwarze, and Albers 2009).

The body posture index R_{DOF} in equation (4) describing the adopted upper posture has led to a significant correlation with 12 m-LBP and sick leave in combination with WBV exposure. This is an a posteriori justification also of the underlying, quasi-static assessment scheme (Table 2). This correlation may be improved by considering dynamic properties (Rahmatalla and DeShaw 2011).

The fact that no other variables apart from MMH show a correlation in this regression analysis indicates that for this small study population no other effects have been overlooked. At the same time, it cannot be excluded that those other factors have a correlation with LBP: the small size of the study population and the fact that the factors other than WBV and posture have not been assessed with the same accuracy may have led to the absence of a statistically significant correlation. It has to be mentioned in this respect that other studies also failed to see a correlation with psychosocial factors (Bovenzi et al. 2006), while MMH has been attributed with LBP in the literature (Bovenzi et al. 2006) (Lotters et al. 2003).

The correlation of the posture index R_{DOF} and the $A(8)$ with LBP outcome variables shows that they have suitable quantities which can be used to describe the combined exposure of WBV and awkward posture in further studies. This correlation also allows the assessment of workplaces: the improvement of an exposure situation can be assessed by a decrease in R_{DOF}, $A(8)$. Since both quantities show a linear effect (no interaction terms in Table 8), it is readily understood that $R_{WBV\text{-}P}$ also shows a significant correlation to LBP since it depends linearly on both variables. In addition, it is very likely that other linear combinations of the two exposures (Schäfer et al. 2006) lead to a similar description.

5. Conclusion

In the multifactorial context of LBP, it is advantageous if not necessary to assess the relevant exposures on the same level of accuracy, and this study successfully used measurements to describe combined exposures to WBV and awkward postures. It has been shown, in addition, that quantities based on a quasi-static assessment of posture, especially R_{DOF}, are significantly associated with 12 m-LBP prevalence and sick leave in this context. Based on this, a proposal has been made to describe the effect of the combined exposures by only one quantity, which facilitates the assessment of workplaces.

This analysis contributes to the methodology of investigations of the combined exposure to WBV and posture. The assessment of a comprehensive, causal exposure–response relationship is clearly out of the scope of this study. However, it is reasonable to deduce that a decrease of R_{DOF}, $A(8)$ at a given workplace will lead to a decrease in the relevant exposure connected with LBP. This can assist the risk assessment. In addition, the authors hope that these findings will assist in the design of epidemiological studies, which will establish a causal exposure-response relationship or limit values for R_{DOF}, $A(8)$ in the future.

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