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Assessing Combined Exposures of Whole-body Vibration and Awkward Posture— Further Results from Application of a Simultaneous Field Measurement Methodology

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Abstract: The drivers of ten vehicles (tram, helicopter, saloon car, van, forklift, two mobile excavators, wheel loader, tractor, elevating platform truck) were studied with regard to the combined exposures of whole-body vibration and awkward posture during occupational tasks. Seven degrees of freedom (DOFs), or body angles, were recorded as a function of time by means of the CUELA measuring system (Computer-assisted registration and long-term analysis of musculoskeletal workloads) for the purpose of posture assessment. The vibrational exposure is expressed as the vector sum of the frequency-weighted accelerations in the three Cartesian coordinates; these were recorded simultaneously with the posture measurement. Based upon the percentage of working time spent under different workloads, a scheme is proposed for classification of the two exposures into three categories. In addition, a risk of adverse health effects classified as low, possible or high can be assigned to the combination of the two exposures. With regard to posture, the most severe exposure was measured for the drivers of the wheel loader and for the tractor driver, whereas the lowest exposure was measured for the helicopter pilots and van drivers. With regard to the combination of whole-body and posture exposures, the tractor driver and the elevating platform truck driver exhibited the highest workloads.

Key words: Combined exposures, Whole-body vibration, Awkward posture

Introduction

Awkward posture during whole-body vibration (WBV) exposure is one of the most important risk cofactors leading to musculoskeletal disease or permanent injury[1, 2]. For investigation of these two exposures, several measuring techniques and evaluation methods have been introduced for both laboratory and field measurements. Laboratory studies[3] show that a greater workload and a severe decrease in performance is experienced when subjects are seated in a twisted posture with no armrest support.

In field measurements, Tiemessen *et al.*[4] used a hand-held wireless system (Palm Trac) to observe and analyze the posture of ten drivers; the drivers' exposure to WBV was measured simultaneously. They also compared the results from this measurement procedure to those from self-administered questionnaires for estimation of the exposures, and concluded that although the Palm Trac system was time-consuming, it was a suitable method for the obtaining of specific information on the posture and the activities being performed.

In another study, driving postures and associated postural loading upon operators of load-haul-dumping vehicles were investigated by 3D match analysis of videotaped driving[5]. The exposure to WBV was not evaluated simultaneously with the posture. However, a total injury risk score was proposed which produces a quantification of the combined exposures to WBV and posture.

In a previous paper, the CUELA measuring technique was introduced for measurement and analysis of combined exposure to WBV and awkward posture[6, 7].

This study presents further applications of the methodology, yielding a comparative assessment of ten different driving tasks. For creation of an assessment tool by which the combined workloads may be compared, the results were presented in two different ways.

The aims of this study are (1) to compare the combined workloads of WBV and awkward exposure by means of the CUELA measuring technique for ten different vehicle drivers, and (2) to discuss the complications of measurement and evaluation of the posture exposure for seated subjects.

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Subjects and Methods

Subjects

The WBV and posture exposures of ten occupational drivers (male, mean age ± SD = 43 ± 6 yr; mean height ± SD = 181 ± 8 cm; mean weight ± SD = 82 ± 17 kg) were studied during their routine occupational tasks (Table 1). The subjects were required to have at least 5 yr' experience of work on the vehicle concerned. All subjects were in good health and were not suffering from noteworthy physical complaints at the time of the study. The durations of measurement depended upon the tasks and operational conditions and represent a whole one-day shift.

Videotaping was used in addition for analysis of the tasks and activities being performed and for monitoring of sensor alignment.

Whole-body vibration

The WBV measurements were conducted in three orthogonal axes (x fore and aft, y lateral and z vertical) on the seat surface and at the seat mounting point[6] (Fig. 1) in accordance with DIN EN 14253[8] and ISO 2631-1[9]. The acceleration measured at the seat mounting point was used to detect artifacts[8] and is not discussed in the present study.

The vector sum of the frequency-weighted acceleration values $a_{v1.4}(t)$ as a function of time t is calculated by:

$$a_{v1.4}(t) = \sqrt{1.4^2 a_{wx}(t)^2 + 1.4^2 a_{wy}(t)^2 + a_{wz}(t)^2} \quad (1)$$

where $a_{w\{x,\ y,\ z\}}$ represent the frequency-weighted acceleration values for each axis x, y, z at the seat surface[9]. The quantity $a_{v1.4}(t)$ was selected for the vibrational exposure because it includes all three axes in a single quantity and can thus be combined with the instantaneous posture. Furthermore, $a_{v1.4}(t)$ has also been shown in an epidemiological study[10] to be suitable for quantification of vibrational exposure that may lead to low back pain. In order to assess the vibrational exposure, three categories for $a_{v1.4}(t)$ are suggested as follows: Low ($a_{v1.4}(t) < 0.5$ m/s^2), middle (0.5 m/s$^2 \le a_{v1.4}(t) \le$ 1.0 m/s^2) and high ($a_{v1.4}(t) > 1.0$ m/s^2).

Body posture

The posture of the seated drivers was detected by the CUELA system[6, 7]. This system, which employs inertial/kinematic sensor technology, is attached to the subjects' clothing, and records the detected posture continuously as an angular measurement, whilst not hindering the subjects during their

Fig. 1. Whole-body vibration measuring equipment consisting of accelerometers for seat surface and seat mounting point.

Table 1. The vehicles studied, tasks/activities, duration of measurement and anthropometric data of the drivers/subjects

S/No	Vehicle data			Subject/driver data		
	Type	Task/activity	Duration of measurement	Age (yr)	Weight (kg)	Height (cm)
1	Tram	Driving forwards, stopping, waiting while stopped	01:50:35	32	83	180
2	Helicopter	Flight maneuvers idle, dive, auto rotation, climb, horizontal, cruise flights	00:54:34	49	93	182
3	Saloon car	Driving forwards on the highway, driving forwards in town, stopping	01:09:49	45	89	189
4	Van	Driving forwards on the highway, driving forwards in town, stopping	00:50:25	35	90	193
5	Forklift truck	Driving unladen, driving laden, engaging the fork	00:39:30	35	100	187
6	Mobile excavator 1	Excavating, driving unladen, driving laden	01:10:27	46	72	184
7	Mobile excavator 2	Sorting wood, emptying the boxes, loading conveyor	01:41:22	46	47	181
8	Wheel loader	Driving unladen, driving laden, loading, unloading	01:47:03	51	97	169
9	Tractor	Driving forwards, switching, driving backwards	00:38:09	46	64	171
10	Platform truck	Driving unladen, driving laden, loading, unloading	00:37:16	42	86	170

work. Figure 2 shows the sensor arrangement, the regions of the body, the locations of sensor attachment, and the respective DOFs and how they are calculated.

Movement sensors in the form of triaxial accelerometers (Analog Devices ADXL 103/203) and gyroscopes (muRata ENC-03R) record the movements directly on a flash memory card in a battery-driven logger at a sampling rate of 50 Hz. The analog output signal of each accelerometer is passed through a low-pass filter with a cut-off frequency of 10 Hz prior to digitization in order to prevent aliasing problems.

Owing to the sensitivity of the calculated angles (detected by accelerometers) to movements of low frequency and high amplitude, the signals from the gyroscopes are used to avoid these artifacts. Finally, the angle signals are low-pass filtered with cut-off frequencies which are optimized for sedentary workplaces. All body angles are initialized at the beginning of a measurement. The body posture during initialization (zero joint position) is an upright standing posture with the subject looking straight ahead. This eliminates subject-specific angle offsets and errors caused by the sensor attachment.

Overall, movement artifacts are less than ± 1° in low-vibration environments and ± 4° during shocks or rough vibrations with high amplitudes and low frequencies. Since the measurements are accompanied by videotaping of the subjects, these artifacts can also be verified by subsequent observance of the synchronized video.

With reference to the standards (ISO 11226 and DIN EN 1005-4), three categories were defined for classification of the body angles as neutral, moderate and awkward[11, 12]. For the upper body, seven degrees of freedom were specified in this study. Table 2 shows the description of the categories for all seven DOFs.

The percentage of the working time spent in each category can thus be shown for each DOF. If the observed duration of the *i*th DOF in the awkward category ($t_{a,i}$) is greater than 30% of the measured duration (T), the DOF in question is regarded as an "awkward" DOF. The awkward DOF (R_{DOF}) is quantified by:

$$R_{DoF} = \sum_{i=1}^{i=7} c_i \quad ; c_i = \begin{cases} 0 \ if \ \dfrac{t_{a,i}}{T} < 30\% \\ 1 \ if \ \dfrac{t_{a,i}}{T} \geq 30\% \end{cases} \tag{2}$$

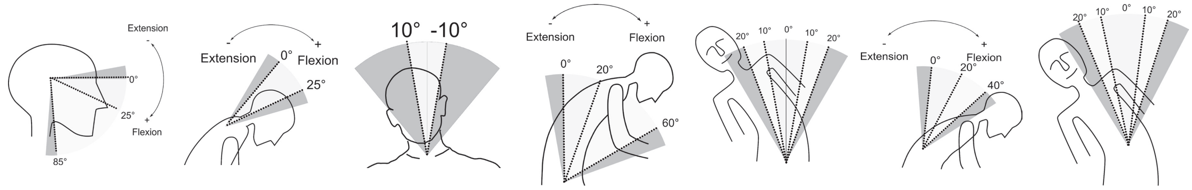
where c_i is the number of awkward DOFs, and $0 \leq R_{DOF} \leq 7$.

In order to emphasize the total duration of the awkward posture category, the percentages of the measured time in these categories are also summated for all measured DOFs. The minimum sum of the percentages of the measured time

Body region	Degree of freedom	Calculated as:mean value (M);differential (D)
Head	Head inclination (lateral/sagittal) Neck flexion (lateral/sagittal)	M of head (right and left) D of head and TS
Thoracic spine (TS) Lumbar spine (LS)	Trunk inclination (lateral/sagittal) Back flexion (lateral/sagittal)	M of the TS and LS D of TS and LS
Thigh	Hip flexion/extension	D of LS and thigh
Lower leg	Knee flexion/extension	D of thigh and lower leg

Fig. 2. CUELA posture measuring equipment, body regions for sensor attachment, degrees of freedom and their calculation.

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



Category	Body region						
	Head inclination (sagittal)	Neck flexion (sagittal)	Neck flexion (lateral)	Trunk inclination (sagittal)	Trunk inclination (lateral)	Back flexion (sagittal)	Back flexion (lateral)
Neutral	0°–25°,<0° full head support	0°–25°	–10°–10°	0°–20°, <0° full back support	0°–10°	0°–20°	0°–10°
Moderate	25°–85°			20°–60°	10°–20°	20°–40°	10°–20°
Awkward	< 0° or > 85°	< 0° or > 25°	< –10° or > 10°	< 0° or > 60°	<–20 or > 20°	< 0° or > 40°	<–20 or > 20°

spent in the awkward posture category is assumed to be 0 in the best case, in which no awkward posture was measured for any of the seven DOFs. The maximum sum is assumed to be 700, corresponding to a worst-case measurement result of all seven DOFs in the awkward posture category. The value for the sum may therefore range from 0 to 700.

Combination of whole-body vibration and posture

For the combination of the two exposures, the categories of WBV (low, middle and high) and posture (neutral, moderate and awkward) are plotted for each DOF in a 3 × 3 matrix scheme[6]. Figure 3 shows an example for the combination of lateral trunk inclination and WBV. The percentage of time spent in the respective categories for each combined form of the exposures is plotted in the matrix (e.g. neutral and high 3.3% in Fig. 3). The result is the definition, from the matrix fields showing the percentage of measured time, of three risk categories in accordance with the "traffic-light" principle:

- "Low" risk category, encompassing neutral and moderate posture at low vibration
- "Possible" risk category, encompassing medium-level vibration with the subject in a neutral or moderate posture
- "High" risk category, encompassing awkward posture and high vibration

If the observed duration of the *i*th combination (DOF and WBV) in the high risk category ($t_{h,i}$) is greater than 30% of the measured time (T), the combination in question is considered to be a high-risk combination.

The at-risk combinations ($R_{WBV\text{-}P}$) are quantified as follows:

$$R_{WBV\text{-}P} = \sum_{i=1}^{i=7} c_i \quad ; c_i = \begin{cases} 0 \; if \; \dfrac{t_{h,i}}{T} < 30\% \\ 1 \; if \; \dfrac{t_{h,i}}{T} \geq 30\% \end{cases} \tag{3}$$

where c_i is the the number of high-risk combinations, and $0 \leq R_{WBV\text{-}P} \leq 7$.

The percentages of this category for all seven combinations are also summated with an emphasis upon the duration of the high-risk combinations. In the best-case scenario, no combination of DOF and vibration in the high-risk category is observed; the summated value is therefore 0. For the worst case, in which all measured combinations are observed to be in the high-risk category, the summated value is 700.

Results

The WBV exposures observed for the ten vehicles are stated in Table 3. The WBV total values ranged from 0.16 m/s^2 for the tram driver to 1.24 m/s^2 for the elevating platform truck driver.

The respective percentages of the working time spent in a neutral, moderate and awkward posture for all seven DOFs studied is stated in Table 4. The combination of each DOF and WBV in terms of the measured working time is stated in Table 5. The last row in the tables indicates the sum of the percentages by time measured in an awkward posture/high risk category for all seven DOF combinations.

R_{DOF}, the awkward DOF exceeding 30% of the duration T, ranges from R_{DOF}= 0 for the van driver and helicopter co-pilot to R_{DOF}= 3 for the wheel loader driver and tractor driver (Fig. 4). Figure 4 also shows the combinations of DOF and WBV which exceeded 30% of the measured time T in high risk categories ($R_{WBV\text{-}P}$). The tractor driver and elevating platform truck driver exhibit the highest values: $R_{WBV\text{-}P}$ = 4 and $R_{WBV\text{-}P}$ = 7 respectively. The smallest number was observed for the helicopter co-pilot and the van driver ($R_{WBV\text{-}P}$ = 0).

Figure 4 also shows the sum of all percentages of measurement time spent in an awkward posture and in the high risk category for the combinations of WBV and posture. For the awkward posture, the tractor driver and the tram driver exhibit the highest values (244 and 249 respectively). The lowest values are observed for the van driver and for the mobile excavator driver 1 in construction work (21 and 55) respectively. The highest summated percentages of the duration spent in the high risk category are observed for the elevating platform truck driver and the tractor driver, at 298 and 300 respectively. The lowest values were measured for the helicopter co-pilot and the van driver, at 65 and 36 respectively.

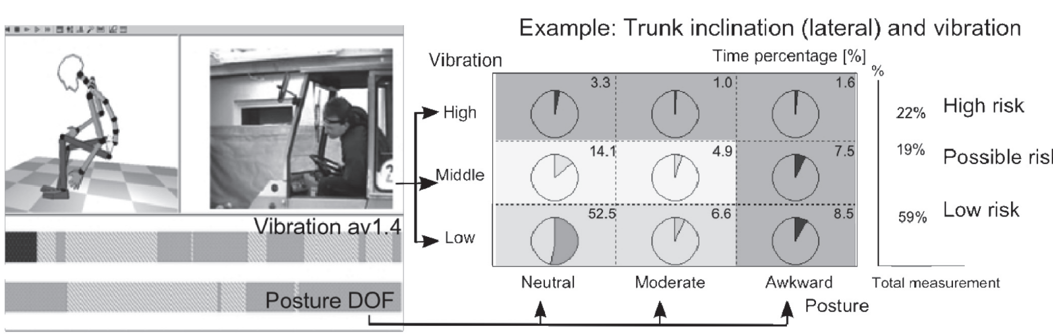


Fig. 3. Left: CUELA evaluating software, recording each category of whole-body vibration (as $a_{v1.4}(t)$, the vector sum of the frequency-weighted accelerations) and posture exposures (as DOF degree of freedom) simultaneously with the videotape and simulated dummy. Center: 3 × 3 matrix scheme with whole-body vibration categories on the vertical axis and posture categories on the horizontal axis. The matrix entries show the percentage of the measured duration spent in each combination of categories. Right: Three risk categories summarized from the matrix; where the working time spent in the high-risk category is greater than 30%, the combination for the given DOF is assumed to be 1, otherwise 0 in this study.

Table 3. Whole-body vibration data for ten investigated vehicles; $a_{w\{x,y,z\}}$ are the frequency-weighted, root-mean-square accelerations for the duration T of the measurement; $a_{v1.4}$ is the vector sum of a_{wx}, a_{wy} and a_{wz}

	Tram	Helicopter co-pilot	Saloon car	Van	Forklift	Mobile excavator 1	Mobile excavator 2	Wheel loader	Tractor	Elevating platform truck
Vector sum $a_{v\,1.4}$ [m/s^2]	0.16	0.37	0.44	0.53	0.45	0.74	0.81	0.76	1.17	1.24
a_{wx} [m/s^2]	0.06	0.06	0.15	0.34	0.24	0.38	0.42	0.31	0.81	0.69
a_{wy} [m/s^2]	0.08	0.10	0.10	0.14	0.12	0.29	0.34	0.34	0.17	0.38
a_{wz} [m/s^2]	0.08	0.33	0.35	0.14	0.23	0.31	0.28	0.41	0.22	0.56

Table 4. Posture data for ten vehicle drivers studied; the percentage of working time spent in each of the categories neutral (n), moderate (m) and awkward (a) is stated. R_{DOF} is the quantity of the awkward degrees of freedom

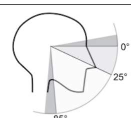
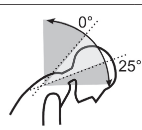
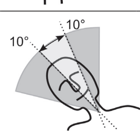
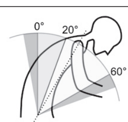
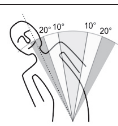
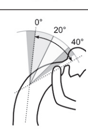
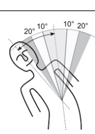
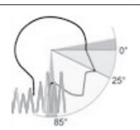
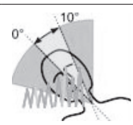
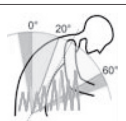
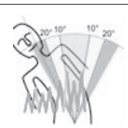
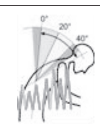
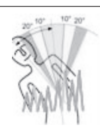
		Posture	Tram	Helicopter co-pilot	Saloon car	Van	Forklift	Mobile excavator 1	Mobile excavator 2	Wheel loader	Tractor	Elevating platform truck
Head inclination sagittal		n	77	93	60	98	84	70	87	61	89	79
		m	1	7	0	1	7	30	7	4	10	10
		a	**22**	**0**	**40**	**1**	**9**	**0**	**6**	**35**	**1**	**11**
Neck flexion sagittal		n	3	72	72	94	77	60	35	8	64	80
		m	0	0	0	0	0	0	0	0	0	0
		a	**97**	**28**	**28**	**6**	**23**	**40**	**65**	**92**	**36**	**20**
Neck flexion lateral		n	72	93	99	99	80	86	85	38	80	65
		m	0	0	0	0	0	0	0	0	0	0
		a	**28**	**7**	**1**	**1**	**20**	**14**	**15**	**62**	**20**	**35**
Trunk inclination sagittal		n	99	100	100	100	100	24	85	85	92	67
		m	0	0	0	0	0	76	15	15	8	4
		a	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**29**
Trunk inclination lateral		n	99	100	100	100	100	24	85	85	5	67
		m	0	0	0	0	0	76	15	15	0	4
		a	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**95**	**29**
Back flexion sagittal		n	0	0	0	0	94	0	0	7	0	92
		m	0	75	1	87	6	99	14	93	8	4
		a	**100**	**25**	**99**	**13**	**0**	**1**	**86**	**0**	**92**	**4**
Back flexion lateral		n	94	98	100	100	10	98	90	70	97	70
		m	6	2	0	0	49	2	9	30	3	19
		a	**0**	**0**	**0**	**0**	**41**	**0**	**1**	**0**	**0**	**11**
R_{DOF}			**2**	**0**	**2**	**0**	**1**	**1**	**2**	**3**	**3**	**1**
Σ of percentages by time measured in awkward posture (for all 7 DOFs)			**249**	**60**	**168**	**21**	**93**	**55**	**173**	**189**	**244**	**139**

Table 5. Combination of whole-body vibration and posture; the percentage of working time spent in each of the categories low risk (L), possible risk (P) and high risk (H) is stated. $R_{WBV\text{-}P}$ is the quantity of high-risk combinations of whole-body vibration and awkward posture

		Risk	Tram	Helicopter co-pilot	saloon car	Van	Forklift	Mobile excavator 1	Mobile excavator 2	Wheel loader	Tractor	Elevating platform truck
WBV & head inclination sagittal		L	77	84	47	77	71	61	52	47	53	37
		P	1	15	12	19	18	23	28	11	35	22
		H	**22**	**1**	**41**	**4**	**11**	**16**	**20**	**42**	**12**	**41**
WBV & neck flexion sagittal		L	3	62	57	73	60	38	18	7	34	29
		P	0	10	14	19	15	13	10	0	23	22
		H	**97**	**28**	**29**	**8**	**25**	**49**	**72**	**93**	**43**	**49**
WBV & neck flexion lateral		L	71	79	77	77	60	51	46	21	42	32
		P	1	13	20	20	18	21	26	10	27	16
		H	**28**	**8**	**3**	**3**	**22**	**28**	**28**	**69**	**31**	**52**
WBV & trunk inclination sagittal		L	98	84	77	78	77	61	56	62	3	36
		P	1	15	21	20	20	24	29	22	2	15
		H	**1**	**1**	**2**	**2**	**3**	**15**	**15**	**16**	**95**	**49**
WBV & trunk inclination lateral		L	99	84	77	78	76	61	56	62	53	42
		P	1	15	21	20	20	24	29	22	35	25
		H	**0**	**1**	**2**	**2**	**4**	**15**	**15**	**16**	**12**	**33**
WBV & back flexion sagittal		L	0	63	1	68	77	60	7	62	2	38
		P	0	12	0	17	20	24	4	22	3	25
		H	**100**	**25**	**99**	**15**	**3**	**16**	**89**	**16**	**95**	**37**
WBV & back flexion lateral		L	99	84	77	78	45	61	55	62	53	41
		P	1	15	21	20	12	24	29	22	35	22
		H	**0**	**1**	**2**	**2**	**43**	**15**	**16**	**16**	**12**	**37**
$R_{WBV\text{-}P}$			**2**	**0**	**2**	**0**	**1**	**1**	**2**	**3**	**4**	**7**
Σ of time percentages measured in high risk (for all 7 combinations)			**248**	**65**	**178**	**36**	**111**	**154**	**255**	**268**	**300**	**298**

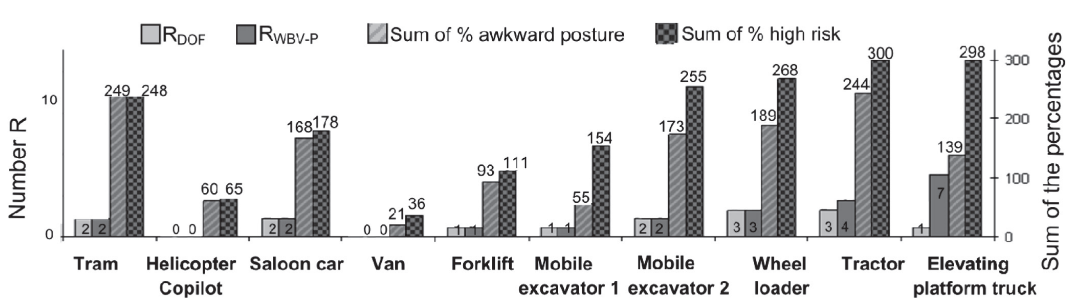


Fig. 4. Summated values for the percentages of the working time spent in awkward posture and high risk category; number of awkward DOFs (R_{DOF}) and high-risk combinations of WBV and DOF ($R_{WBV\text{-}P}$).

Discussion

The measured vector sum ($a_{v\ 1.4}$) represents the WBV values for the three orthogonal axes. An interesting observation is that most of the time, the values for the horizontal x axis are greater than those for the vertical z axis (Table 3).

The results for the awkward posture and the combination of the WBV and posture reveal two different findings. Whereas the figures for R_{DOF} and $R_{WBV\text{-}P}$ with respect to 30% of the measured time correlate very well to the generally anticipated workloads for the vehicles studied, the summated percentages do not demonstrate an appropriate distribution of the workloads. For example, in Fig. 4, the $R_{WBV\text{-}P}$ for the elevating platform truck driver is almost twice that of the tractor driver. However, the sum of the percentages for the high-risk category for the two drivers is virtually the same. This reflects the fact that the combined workload is evenly distributed over all DOFs in the case of elevating platform truck driver, whereas for the tractor driver fewer DOFs are associated with exposure, but for longer periods of time. In this respect, it is surprising that higher values for the summated percentages are also observed for the tram driver and the saloon car driver.

There are several explanations for the difficulties encountered during assessment of the WBV and awkward posture exposures, which have an influence on the results.

The back flexion, which generally describes the curvature of the trunk, is not defined by the standards and is currently evaluated with reference to the trunk inclination defined by ISO11226[11]. This evaluation[11] takes into account the effects of the full backrest only for the backward trunk inclination, which is then considered as neutral.

The use of the backrest cannot be measured yet by the CUELA system. It is not possible to take into account the effects of the backrest which result in high exposure in the cases of the saloon car and tram drivers. For future studies, a pressure sensor will be attached to the backrest or to the back of the subject and will yield data on the pressure on the back when the backrest is used. Furthermore, medical studies are needed for investigation of the effects of partially supported trunks in the lumbar spinal region, a situation frequently observed in the field measurements.

Also, according to ISO11226[11], any extension for head and neck posture is considered awkward. Since the sensor technology reports body angles very precisely, even small movements of the head lead to extensions, which in accordance with the standards are measured and evaluated as awkward in this case. More appropriate ranges for neck flexion and head extensions are therefore needed for descriptions of moderate and awkward posture for these DOFs.

Initialization of the posture at the beginning of the measurement could also be a source of error, owing to the standing posture of the subject during initialization outside the vehicle. Depending upon the size of the vehicle, the subjects must enter it very carefully, as the sensors may otherwise be displaced. This problem can be reduced by starting the measurement after the subject has entered and exited the vehicle several times with the sensors attached. Another potential solution is initialization within the vehicle in a seated posture; owing to the limited space within the vehicles, however, this would substantially complicate the initialization procedure. In addition, an upright seated reference posture for the purpose of initialization is harder for subjects to achieve than an upright standing posture. The synchronized video data permits observation of these errors. The initializing posture of the subject is recorded on video at the beginning, in the middle and at the end of the measurement; the alignment of the sensors is therefore monitored, and errors caused by displacement of the sensors are eliminated retrospectively in the software.

In summary, this work presents a comparative assessment study of combined exposure to WBV and awkward posture in ten different driving tasks. The results facilitate future epidemiological investigations, which are required for evaluation of the health and safety implications of the different postural behaviors in association with WBV. Even at this stage, the evaluation scheme yields valuable information for prevention activities. International standards describing the postural workload in more detail are also needed.

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