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ORIGINAL ARTICLE

Countering postural posteffects following prolonged exposure to whole-body vibration: a sensorimotor treatment

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Abstract Postural stability of bulldozer operators after a day of work is investigated. When operators are no longer exposed to whole-body vibration (WBV) generated by their vehicle, their sensorimotor coordination and body representation remain altered. A sensorimotor treatment based on a set of customized voluntary movements is tested to counter and prevent potential post-work accidents due to prolonged exposure to WBV. This treatment includes muscle stretching, joint rotations, and plantar pressures, all known to minimize the deleterious effects of prolonged exposure to mechanical vibrations. The postural stability of participants (drivers; $N = 12$) was assessed via the area of an ellipse computed from the X and Y displacements of the center-of-pressure (CoP) in the horizontal plane when they executed a simple balance task before driving, after driving, and after driving and having performed the sensorimotor treatment. An ancillary experiment is also reported in which a group of non-driver participants ($N = 12$) performed the same postural task three times during the same day but without exposure to WBV or the sensorimotor treatment. Prolonged exposure to WBV significantly increased postural instability in bulldozer drivers after they operated their vehicle compared to prior to their day of work. The sensorimotor treatment allowed postural stability to return to a level that was not significantly different from that before driving. The results reveal that (1) the postural system remains perturbed after prolonged exposure to WBV due to operating a bulldozer and (2) treatment immediately after driving provides a "sensorimotor recalibration" and a significant decrease in WBV-induced postural instability. If confirmed in different contexts, the postural re-stabilizing effect of the sensorimotor treatment would constitute a simple, rapid, inexpensive, and efficient means to prevent post-work accidents due to balance-related issues.

Keywords Proprioception · Stance · Aftereffect · Plantar pressure · Sensorimotor recalibration · Postural instability

Abbreviations

CoP	Center of pressure
FFT	Fast Fourier transform
WBV	Whole-body vibration

Introduction

Daily actions that seem as simple as maintaining upright stance, walking, avoiding an obstacle, or performing goal-directed actions involve complex sensorimotor patterns to be coordinated by the central nervous system. Each of these requires body configuration to be assessed and updated continuously with respect to the surrounding environment. This updating includes the integration of diverse information, visual, vestibular or somatosensory, that plays an important part in most sensorimotor and cognitive coordination tasks (Fuchs and Jirsa 2008; Gibson 1966; Latash and Lestienne 2006). In postural tasks, sensory messages originating from muscles and skin sensors throughout the

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body constitute a crucial source of information for accurate detection of body configuration, as well as for its interactions with the environment (Roll and Roll 1988).

Microneurographic studies have revealed how these muscle and cutaneous receptors are sensitive to mechanical vibration applied to the superficial and deep body tissues in a wide range of vibration frequencies (see Roll 1994 for a review). Moreover, these mechano-sensitive properties of muscles and cutaneous receptors make it possible to alter position sense and kinesthesia. In particular, applying vibrations to muscle tendons or to plantar soles induces sensations of illusory movement or involuntary motor responses (Eklund 1972; Goodwin et al. 1972; Kavounoudias et al. 1999; Roll et al. 2002; Roll and Roll 1988). For example, vibrating the muscle tendon of an individual standing upright leads to either an involuntary whole body leaning referred to as vibration-induced falling (VIF; e.g. Eklund 1972; Kavounoudias et al. 1999; Roll and Roll 1988) or an illusory sensation of body tilt, which is in the direction opposite to the side vibration was applied (Lackner and Levine 1979; Roll et al. 1998). Identical perceptual and motor effects have been described after plantar sole vibratory stimulations of standing humans (Kavounoudias et al. 1998; Roll et al. 2002). Also to be considered is the role played by the vestibular apparatus, as the aforementioned effects could also be induced by various vestibular stimulations (Gauthier et al. 1981; Dichgans and Diener 1989; Hlavacka et al. 1996).

Situations in daily or professional life perturb sensory modalities and can generate sensorimotor conflicts (Redding and Wallace 2000; Roll et al. 1998). Such a situation occurs while driving motorized vehicles for construction. Drivers can operate in an environment, such as the cab of a bulldozer, where they are exposed many hours each day to a large amount of mechanical whole-body vibration (WBV) with a wide spectrum of frequencies (from 1 to 100 Hz according to reports published by the *Direction Générale de l'Humanisation du Travail* (2005) and the European Commission (2007)). WBV spreads over the range of frequencies stimulating the skin and muscle mechanoreceptors along all three body axes (longitudinal, transverse, and sagittal) as they are delivered simultaneously at the back, hand, seat, and foot levels (for details see official reports from the European Commission, 2007). Drivers who are exposed to a substantial amount of WBV on a daily basis may have behavioral and health risks (Boileau and Scory 1986, 1990; Gauthier et al. 1981; Griffin 1978, 1990; Martin et al. 1984; Palmer et al. 2003; Roll et al. 1980). Chronic low back pain, vascular disorders, or postural perturbations are directly caused by prolonged exposure to WBV in the work environment (e.g. Carlsöö 1982; Seidel and Heide 1986; Tiemessen et al. 2007; Wasserman et al. 1997). Some cases of visual impairment or dizziness occur minutes or hours after work, including when employees are driving home, as reported by the *Organisme Professionnel de Prévention du Bâtiment et des Travaux Publics* (OPPBTP 2006).[1]

Most solutions developed to prevent, or at least minimize, WBV-related consequences have focused on how to improve vehicles in order to dampen their effects (Tiemessen et al. 2007). For example, particular attention has been placed on using seats and steering wheels that could diminish the transmission of mechanical vibrations to the human body (Bellmann 2002). Those solutions have not been efficient enough to eliminate WBV from some types of vehicles, including bulldozers. Therefore, operators have to deal with the effects of WBV during and even *after* work. For instance, it is known that, for vehicles with elevated cabs, about 75% of falls occur after the engine is stopped, and therefore after exposure to WBV, especially during egress (Fathallah 2006; Fathallah and Cotnam 2000; Heglund 1987; see also Haslam and Stubbs 2006 for an extensive overview on risks related to slips and falls in work environments). In addition, post-work incidents on construction sites are so frequent that they are an issue for a French institution in charge of monitoring the health of construction workers, the OPPBTP.

Such persisting sensorimotor effects following exposure to WBV are to be related to the so-called *posteffects* following sustained isometric contraction or exposure to mechanical vibration that have been observed in experimental studies on humans. Applying mechanical vibrations to various muscle groups —from neck to ankles— has proven to be an efficient way to modify human postural sway in both magnitude and direction (e.g. Martin et al. 1980). Interestingly, these alterations can persist several minutes after the vibratory stimulation is over (Duclos et al. 2007; Gilhodes et al. 1992; Martin et al. 1980; Wierzbicka et al. 1998). Wierzbicka and colleagues (1998) demonstrated that, after 30 s vibration of an ankle or cervical muscle group, involuntary whole-body leanings occur and last from 4 min up to several hours depending on the person tested. As proposed by various authors, these long-lasting posteffects of exposure to mechanical vibrations might originate from sustained artificial activation of the somesthetic mechanocaptors, resulting in a modification of the central integration of this sensory information (Duclos et al. 2007). One way to counter those so-called posteffects or at least to greatly diminish their magnitude is to ask participants to perform localized movements in order to voluntarily activate the muscles that have been vibrated (or contracted in an isometric way). This strategy can be considered a "sensorimotor resetting" of the postural system (Duclos et al. 2004, 2007; Hutton et al. 1987; Sapirstein 1937).

[1] Literally the "*Professional Organization for Prevention in Public Construction*". http://www.oppbtp.fr

Following preliminary work along this line (Oullier et al. 2007), the aim of the present study was to assess the level to which exposure to whole-body vibration generated by bulldozers affects postural balance and to investigate new procedures to minimize these posteffects. Bulldozer operators were therefore asked to perform, before and after driving, a simple postural task that was meant to reproduce what they experience during cab egress. After they drove, they were required to execute the postural tasks with or without performing a set of customized voluntary movements termed the *sensorimotor treatment.* This treatment including muscle contractions and stretching, joint rotations, and plantar pressures aimed at countering the effects of the exposure to WBV while driving. Two main hypotheses motivated the present study:

1. After a driving session, postural stability of operators is altered by prolonged exposure to mechanical vibrations generated by the bulldozer.
2. Postural stability is fully or at least partially restored by a customized set of voluntary movements performed at the end of work.

Materials and methods

Participants

A total of 24 male volunteers (between 17 and 20 years old) with normal or corrected-to-normal vision were tested. The *driver group* was composed of 12 apprentice bulldozer operators and the *non-driver group* included 12 participants. In both groups, the participants were right-handed. All of them gave prior informed consent to the procedure as required by the *Helsinki Declaration*. The experimental protocol received full approval from the local ethics committee (*Comité Consultatif de Protection des Personnes dans la Recherche Biomédicale: CCPPRB*).

Experimental design

Task

Participants stood on a force platform (50 cm × 50 cm × 3 cm; *Rematic Ltd*, Saint-Etienne, France). They wore shoes similar to those at work. Postural stability was assessed through three strain gauges in the platform (sampling frequency = 100 Hz), from which we computed the displacements of the participants center-of-pressure (CoP) in the medio-lateral (ML) and anterior-posterior (AP) axes. The precise position of the participants feet on the force platform was drawn after the experimenter had placed them in the first trial. Participants thereby had the same foot position for all subsequent trials. A simple postural task involving standing upright and transferring from bipedal to unipedal stance was used for the *driver* and the *non-driver* groups. Each experimental trial ($N = 4$ per experimental session) lasted for 20 s with a one-minute rest period between. Participants started with a comfortable bipedal upright stance position, arms along the body. After 8 s, they were verbally instructed by the experimenter to lift their right or left foot to finish the trial standing on one leg. To avoid the uncertainty effect and latency in transferring from two feet to one, participants were told which foot to lift prior to each trial. They were required to perform the trial with eyes either closed or open in order to match real work conditions where operators can climb down from their bulldozer under bad lighting conditions, for instance dim light or facing the sun. During the eyes-open conditions, participants were instructed to stare at a white uniform wall in front of them. For all trials, the experimenter stayed behind the participants to avoid falls due to loss of balance. Trials were counterbalanced across conditions. Overall, each of the three experimental sessions lasted for about 10 min.

Driver group

Data was collected on a construction worker training site. For trainees, a typical day of work included two driving periods (10 a.m. to 12 p.m. and 2 to 4 p.m.). This was of particular interest in the context of an experimental study as all trainees were exposed the same amount of time to WBV and did the same kind of work as part of their learning experience. Hence, all of them were exposed to similar multisensory stimulations throughout a work session. This would not have been the case if we had been using professional construction workers on an actual construction site. For instance, in real work conditions, the workers do not perform the same task and they can potentially switch from some equipment or vehicle to another, working with vibrating hand tools for 30 min and driving a bulldozer the following hours, for example, making between-subject comparisons difficult (if not impossible). During the 2 h work sessions, trainees were required to remain seated in their bulldozer and to keep the engine running for the purpose of the experiment. Drivers were tested three times the same day. The first experimental session (Session 1) took place before work started, i.e. around 9:30 a.m. At this time, they had not been exposed to bulldozer-induced vibrations yet. Session 2 occurred around noon, after participants stopped the engines. Postural stability was therefore measured after a two-hour exposure to WBV while driving. The final test (Session 3) took place at the end of the day of work, around 4 p.m., i.e. after working for another 2 h.

Sensorimotor treatment

Since previous results revealed that movements performed voluntarily can cancel vibration-induced posteffects (Duclos et al. 2007; Hutton et al. 1987), drivers were asked to execute a set of specific voluntary movements, referred to as the sensorimotor treatment, prior to having their postural oscillations recorded in Session 3. In fact, after the experimenter performed the movement sequence in front of them, drivers had to mimic it while still sitting in their cab as well as when on the ground. This treatment lasted for 3 min and included flexion-extension movements of the neck, shoulders, hands, hips, knees, and ankles in order to stretch their muscles and skin and to exert pressure against various body parts (see Fig. 1 for details).

In summary, for the driver group, Session 1 occurred before driving-induced exposure to whole-body vibration, hence without performing the sensorimotor treatment (*No WBV-No Treatment*). Session 2 took place after exposure, without performing the sensorimotor treatment (*With WBV-No Treatment*). Finally, Session 3 occurred after another 2 h long exposure and after performing the sensorimotor treatment (*With WBV-With Treatment*).

Non-driver group

To determine the effects of repetition and time of the day between trials performed in Sessions 1, 2, and 3, a non-driver group was tested three times a day with a 2 h gap between each experimental session in the laboratory. Therefore, participants from this group were neither exposed to WBV nor to sensorimotor treatment (*No WBV-No Treatment*). In addition, the non-driver participants were asked not to be involved in physical activity that could have influenced their postural stability in between sessions.

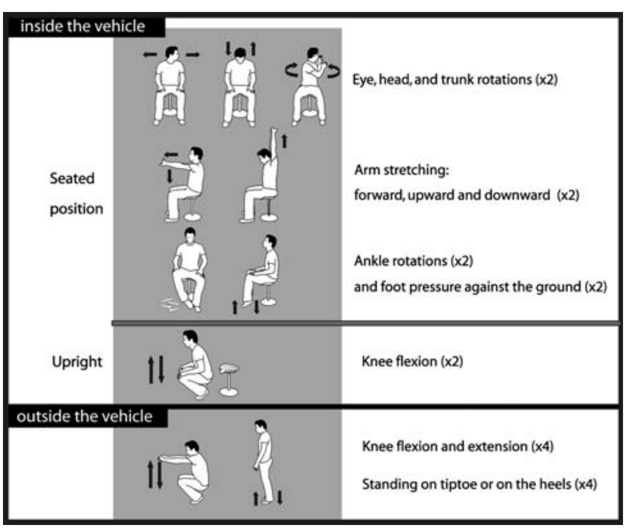

Fig. 1 Sensorimotor treatment. Sensorimotor recalibration treatment executed by bulldozer operators in their cab and after they left it

Data collection and analyses

Two-directional (AP and ML) displacements of the CoP in the horizontal plane were computed via a program specifically designed in *Labview* (*National Instruments,* Austin, TX). Prior to analysis, data was filtered using a FFT-based customized decomposition and reconstruction method. After decomposition, the signal was reconstructed within the 0–7 Hz frequency range to eliminate high frequency noise (Oullier et al. 2008).

The *CoP confidence ellipse* was used to assess postural stability (Duarte and Zatsiorsky 2002; Freitas et al. 2005; Suarez et al. 2003). The two main axes of the ellipse are determined using the eigenvalues of the covariance matrix between the CoP data, 85.35% of which end up inside the ellipse (Duarte and Zatsiorsky 2002; see Fig. 2 for an illustration of the computation method).

The variation of the CoP ellipse area from one condition to another is of greater interest than its absolute value. Therefore, the variation percentage of the area of the confidence ellipse across the conditions was computed for each participant. For this, a *reference ellipse area* (area = 100%; marked 'REF' on Figs. 3 and 4) served as a baseline for evaluating the percentage of change. This reference was measured when participants were standing on their two feet, with eyes open during the first session in both groups, i.e. driver and non-driver. In such conditions, stability is supposed to be maximal, as compared to other conditions (Edwards 1946; Gibson 1979). Hence, the CoP ellipse area for other conditions is reported as percentage of the area of this reference ellipse.

As illustrated in Fig. 2, two data segments were discriminated in the time series. In each 20 s trial, a bipedal (left column) and unipedal (right column) segment were isolated to focus on the difference between stability on two feet compared to one foot (either left or right).

The CoP ellipse area results presented were computed on the first 6 s of each experimental trial for the bipedal part and the 6 s following the transfer from two feet to one foot. To determine the moment at which the transfer terminated, the mean position of the medio-lateral displacement of the CoP (± 1 value of the standard deviation) was computed during the last 6 s of the trial (Bardy et al. 2002). When the medio-lateral displacement of the CoP entered the interval, the transfer was considered finished (see Fig. 2; top right panel).

Non-parametric Wilcoxon tests (corrected for multiple comparisons) were performed to compare results across conditions and to identify significant effects on postural sway for each independent variable: *Stance* (3 levels: bipedal,

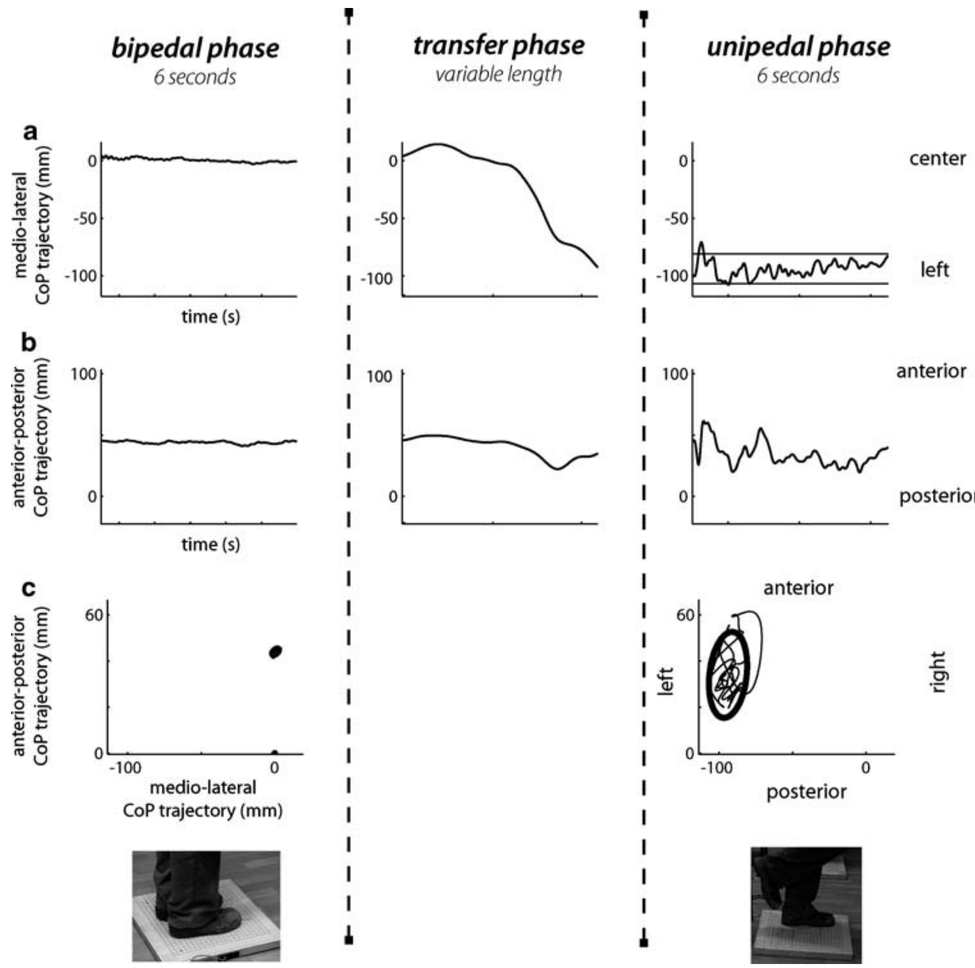

Fig. 2 Computation of the CoP ellipse area. Trajectory of the CoP and computation of the CoP ellipse area during the three periods of a representative trial: bipedal stance (*left column*), transfer phase after receiving the instruction to lift the right foot (*middle column*), and unipedal stance on the left foot (*right column*). **a** Displacement of the CoP along the medio-lateral axis. **b** Displacement of the CoP along the anterior-posterior axis. **c** Displacement of the CoP in the horizontal plane and its confidence ellipse (85% of the CoP displacements) in the bipedal (*left column*) and the unipedal periods (*right column*)

unipedal right or unipedal left), *Vision* (2 levels: eyes open or eyes closed) and *Session* (3 levels: Session 1, Session 2, Session 3). Note that this *Session* variable represents the time of day at which the testing occurred and that it differed for each group of participants, as the non-driver group was not exposed to vibrations and did not perform the sensorimotor treatment.

Results

Effects of two hours of bulldozer driving on postural stability

After 2 h of being exposed to whole-body vibration while operating a bulldozer, the magnitude of postural oscillations of the drivers was significantly higher (Session 2) than before work (Session 1). This effect was found in both vision and no vision conditions.

As illustrated in Fig. 3 and Table 1, the CoP area was always significantly larger after driving alone, i.e. after exposure to WBV but without sensorimotor treatment (grey bars) when compared to the reference (REF; black bar). This effect was observed for all three stance conditions analyzed [*bipedal* (eyes open: $P = 0.002$, eyes closed: $P = 0.028$); unipedal left (eyes open: $P = 0.002$, eyes closed: $P = 0.028$); and unipedal right (eyes open: $P = 0.028$, eyes closed: $P = 0.003$)] independently of the availability of visual information (see Fig. 3b and Table 1 for details).

As classically observed in the literature, for all comparisons but one (see Table 2 for details), removing vision had a destabilizing effect on posture: it significantly increased the size of the *CoP area* (Fig. 3b). The only comparison that did not reach significance was the one between conditions of bipedal stance after exposure to vibrations but without treatment (2 feet: Session 2 eyes open versus Session 2 eyes closed).

Effect of voluntary movements on stabilizing posture

To determine the potential role of the sensorimotor treatment on diminishing postural perturbations induced by driving, performances in postural tasks in Sessions 1 (*No WBV-No Treatment*) and 3 (*With WBV-With Treatment*) were compared for the driver group.

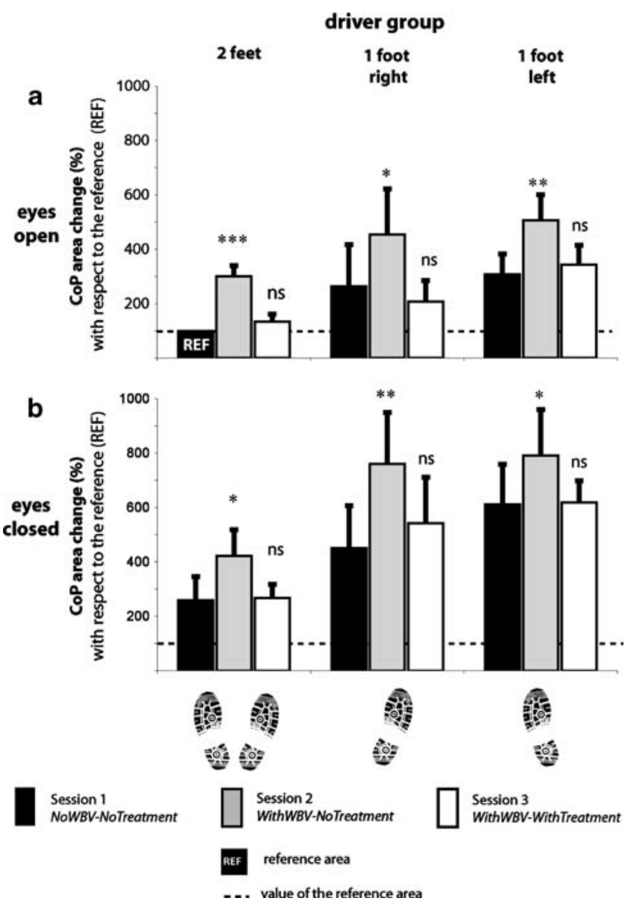

Fig. 3 Driver experiment percentages of CoP area changes computed with respect to a reference area (REF = 100%) in the *driver* experiment when participants have their eyes open (**a**) or closed (**b**). For each stance modality (two feet, one foot right, and one foot left), the average CoP area percentage of change ($N = 12$) is plotted for each experimental session (Session 1: *black*, Session 2: *grey*, and Session 3: *white*). The *error bars* represent the standard error for each condition. The statistical indices above the *grey* and the *white bars* represent the levels of significance when Session 2 and Session 3 are compared to Session 1 respectively (*ns* non significant, *significant for $P < 0.05$, **significant for $P < 0.01$ and ***significant for $P < 0.005$)

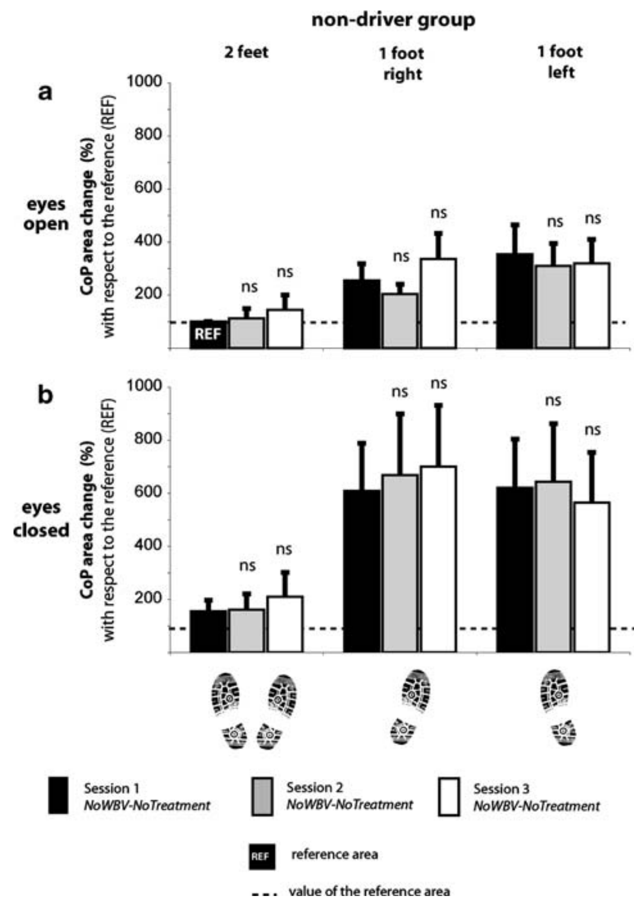

Fig. 4 Non-driver experiment percentages of CoP area changes computed with respect to a reference area (REF = 100%) in the *non-driver* experiment when participants have their eyes open (**a**) or closed (**b**). For each stance modality (two feet, one foot right, and one foot left), the average CoP area percentage of change ($N = 12$) is plotted for each experimental session (Session 1: *black*, Session 2: *grey*, and Session 3: *white*). The *error bars* represent the standard error for each condition. The statistical indices above the *grey* and the *white bars* represent the levels of significance when Session 2 and Session 3 are compared to Session 1 respectively (*ns* non significant, $P > 0.05$)

As illustrated in Table 3 and Fig. 3, voluntary movements executed in and after leaving their bulldozer cab were useful to counter the effects of WBV. Performing the sensorimotor treatment clearly reduced WBV-induced postural alterations. Regardless of *Vision* and *Stance* conditions, no significant differences were found between Sessions 1 and 3 (black and white bars, respectively, on Fig. 3; *bipedal* (eyes open: $P = 0.18$, eyes closed: $P = 0.07$); unipedal left (eyes open: $P = 0.20$, eyes closed: $P = 0.81$); and unipedal right (eyes open: $P = 0.38$, eyes closed: $P = 0.05$)) in spite of the strong effect of WBV on postural stability between Sessions 1 and 2 reported earlier.

Effects of trial repetition on stabilizing posture

In the non-driver group, while participants were not exposed to whole-body vibration, their postural stability did not change across sessions. For instance, comparisons between Sessions 1 and 2 and between Sessions 1 and 3 revealed no significant differences (Fig. 4; see also Tables 1 and 3, bottom parts for details).

In all sessions, postural stability decreased when vision was removed except when non-driver participants adopted bipedal stance (Figs. 3, 4). In the latter, areas of the CoP ellipse did not significantly differ between the eyes open and the eyes closed conditions (Table 2).

Table 1 Effect of vibrations

Group	Stance	Comparison	*N*	*T*	*Z*	*P*	Significance
Driver	2 feet	Session 1 eyes open versus Session 2 eyes open	12	0	3.0594	0.0022	***
		Session 1 eyes closed versus Session 2 eyes closed	12	11	2.1965	0.0281	*
	1 foot right	Session 1 eyes open versus Session 2 eyes open	12	11	2.1965	0.0281	*
		Session 1 eyes closed versus Session 2 eyes closed	12	2	2.9025	0.0037	**
	1 foot left	Session 1 eyes open versus Session 2 eyes open	12	0	3.0594	0.0022	**
		Session 1 eyes closed versus Session 2 eyes closed	12	11	2.1965	0.0281	*
Non-driver	2 feet	Session 1 eyes open versus Session 2 eyes open	12	30	0.7060	0.4802	ns
		Session 1 eyes closed versus Session 2 eyes closed	12	38	0.0784	0.9375	ns
	1 foot right	Session 1 eyes open versus Session 2 eyes open	12	26	1.0198	0.3078	ns
		Session 1 eyes closed versus Session 2 eyes closed	12	29	0.7845	0.4328	ns
	1 foot left	Session 1 eyes open versus Session 2 eyes open	12	26	1.0198	0.3078	ns
		Session 1 eyes closed versus Session 2 eyes closed	12	39	0.0000	1.0000	ns

Comparisons of the CoP area between Sessions 1 and 2 for each group

Driver group Session 1: No WBV-No Treatment

Driver group Session 2: With WBV-No Treatment

Non-driver group all sessions: No WBV-No Treatment

ns non significant

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.005$

Discussion

Results show that prolonged exposure to WBV alters the upright stance of bulldozer drivers and that the execution of the sensorimotor treatment constitutes an efficient re-stabilization procedure.

Postural alterations after prolonged exposure to WBV

In this study, classical posturographic tools and methods were employed to assess to what extent bulldozer operators' upright stance was disturbed after several hours of driving. The results of the driver group showed that perturbations resulting from exposure to WBV last even after exposure. In a day of work for bulldozer operators, a critical moment is when they stop the engine and egress the vehicle as, according to reports from OPPBTP, a large proportion of accidents occur. At this moment, drivers are in a transient period during which they must shift abruptly from a vibratory environment to a more usual context with no vibrations.

The present results illustrate the destabilizing effects of WBV on upright stance and when operators transfer from bipedal to unipedal posture to climb down from their bulldozer (Boileau and Scory 1986, 1990). These findings, although obtained over trials of short duration, corroborate the vast literature reporting postural modifications during and after prolonged exposure to vibration (Duclos et al. 2007; Eklund 1972; Gilhodes et al. 1992; Kavounoudias et al. 1999; Martin et al. 1980; Wierzbicka et al. 1998). Indeed, several studies have revealed that after a muscle is vibrated for several seconds (minimum ≈30 s), an involuntary contraction of the previously vibrated muscle often occurs and can last for minutes, even hours (Duclos et al. 2007). This involuntary contraction can be accompanied by movements of a limb (Gilhodes et al. 1992). Wierzbicka and colleagues (1998) clearly showed that after the ankle or neck muscles are vibrated, long-lasting dynamical changes are observed in postural stability, such as increases in postural oscillations. Similar results were found when seated people were exposed experimentally to whole-body, head-trunk, leg, or head alone vibrations (Martin et al. 1980). The present results strengthen previous observations on construction workers that prolonged exposure to whole-body mechanical vibrations, when driving construction-devoted motorized vehicles, constitutes a potential source of accidents during or after the end of the workday (Griffin 1990).

Interestingly, prolonged sustained isometric voluntary contractions also provoke *a posteriori* alterations of posture very similar to those described after vibration of a muscle (Craske and Craske 1986; Duclos et al. 2004; Gilhodes et al. 1992; Kluzik et al. 2005). For instance, when one has to control a vibrating and/or unstable object, one tends to voluntarily increase the intensity of muscle contraction. When driving a bulldozer, operators are exposed to the aforementioned situations (i.e. vibration and sustained muscle activity); it could therefore be expected that these well known locomotor and postural posteffects would occur. That muscle fatigue contributes to postural alteration

Table 2 Effect of vision

Group	Stance	Comparison	*N*	*T*	*Z*	*P*	Significance
Driver	2 feet	Session 1 eyes open versus Session 1 eyes closed	12	5	2.6672	0.0077	**
		Session 2 eyes open versus Session 2 eyes closed	12	24	1.1767	0.2393	ns
		Session 3 eyes open versus Session 3 eyes closed	12	10	2.2749	0.0229	*
	1 foot right	Session 1 eyes open versus Session 1 eyes closed	12	11	2.1965	0.0281	*
		Session 2 eyes open versus Session 2 eyes closed	12	11	2.1965	0.0281	*
		Session 3 eyes open versus Session 3 eyes closed	12	0	3.0594	0.0022	**
	1 foot left	Session 1 eyes open versus Session 1 eyes closed	12	1	2.9810	0.0029	**
		Session 2 eyes open versus Session 2 eyes closed	12	1	2.9810	0.0029	**
		Session 3 eyes open versus Session 3 eyes closed	12	0	3.0594	0.0022	**
Non-driver	2 feet	Session 1 eyes open versus Session 1 eyes closed	12	19	1.5689	0.1167	ns
		Session 2 eyes open versus Session 2 eyes closed	12	20	1.4905	0.1361	ns
		Session 3 eyes open versus Session 3 eyes closed	12	21	1.4120	0.1579	ns
	1 foot right	Session 1 eyes open versus Session 1 eyes closed	12	0	3.0594	0.0022	**
		Session 2 eyes open versus Session 2 eyes closed	12	8	2.4318	0.0150	*
		Session 3 eyes open versus Session 3 eyes closed	12	0	3.0594	0.0022	**
	1 foot left	Session 1 eyes open versus Session 1 eyes closed	12	0	3.0594	0.0022	**
		Session 2 eyes open versus Session 2 eyes closed	12	0	3.0594	0.0022	**
		Session 3 eyes open versus Session 3 eyes closed	12	0	3.0594	0.0022	**

Comparisons of the CoP area with eyes open or closed in all conditions for each group

Driver group Session 1: No WBV-No Treatment

Driver group Session 2: With WBV-No Treatment

Driver group Session 3: With WBV-With Treatment

Non-driver group all sessions: No WBV-No Treatment

ns non significant

*$P < 0.05$; **$P < 0.01$; ***$P < 0.005$

Table 3 Effect of sensorimotor treatment

Group	Stance	Comparison	*N*	*T*	*Z*	*P*	Significance
Driver	2 feet	Session 1 eyes open versus Session 3 eyes open	12	22	1.3336	0.1823	ns
		Session 1 eyes closed versus Session 3 eyes closed	12	16	1.8043	0.0712	ns
	1 foot right	Session 1 eyes open versus Session 3 eyes open	12	28	0.8629	0.3882	ns
		Session 1 eyes closed versus Session 3 eyes closed	12	14	1.9612	0.0499	ns
	1 foot left	Session 1 eyes open versus Session 3 eyes open	12	23	1.2551	0.2094	ns
		Session 1 eyes closed versus Session 3 eyes closed	12	36	0.2353	0.8139	ns
Non-driver	2 feet	Session 1 eyes open versus Session 3 eyes open	12	38	0.0784	0.9375	ns
		Session 1 eyes closed versus Session 3 eyes closed	12	30	0.7060	0.4802	ns
	1 foot right	Session 1 eyes open versus Session 3 eyes open	12	24	1.1767	0.2393	ns
		Session 1 eyes closed versus Session 3 eyes closed	12	22	1.3336	0.1823	ns
	1 foot left	Session 1 eyes open versus Session 3 eyes open	12	23	1.2551	0.2094	ns
		Session 1 eyes closed versus Session 3 eyes closed	12	21	1.4120	0.1579	ns

Comparisons of the CoP area between Sessions 1 and 3 for each group

Driver group Session 1: No WBV-No Treatment

Driver group Session 3: With WBV-With Treatment

Non-driver group all sessions: No WBV-No Treatment

ns non significant

$P > 0.05$

cannot be ruled out (Adamo et al. 2002; Park and Martin 1993); however, motor posteffects are generally considered of central origin (e.g. Craske and Craske 1986; Duclos et al. 2004, 2007; Gurfinkel et al. 1989). This view is supported by recent neuroimaging studies showing that proprioceptive signals induced by vibration or voluntary contraction reach the cortex and activate sensorimotor-related cortical networks (Casini et al. 2006; Naito and Ehrsson 2001; Radovanovic et al. 2002; Romaiguère et al. 2003) and that these cerebral networks remain activated after the end of the stimulations (Duclos et al. 2007). Therefore, this persistent brain activation, of proprioceptive origin, might be responsible for the motor posteffects observed (Gurfinkel et al. 1989; Ivanenko et al. 2006). Interestingly, this remnant cerebral activity no longer reaches significance when the participants are asked to voluntarily contract the previously vibrated, or durably contracted, muscles (Duclos et al. 2007).

Simple treatment for minimizing WBV-induced postural instability: a potential tool for sensorimotor recalibration

Adaptation of action to conflicting sensory information is thought to reflect a global sensorimotor recalibration process involving limb proprioception and the motor commands (Baraduc and Wolpert 2002) as well as postural and environmental constraints (Feldman and Latash 1982; Roll et al. 1980). Long-lasting postural posteffects of muscle contraction or vibration are thought to result from an updating of the postural reference frame that is altered by the sustained proprioceptive inflow (Duclos et al. 2004). Contrary to the classically observed VIF responses (Eklund 1972), the postural posteffects are not compensatory reactions but, rather, they correspond to a body realignment along a new postural frame of reference. As shown by Wierzbicka and colleagues (1998), the involuntary postural deviations observed after the stimulation of only one muscle group were specifically oriented, and the direction of these deviations was linked to the mechanical function of the stimulated muscle. That motor posteffects were not found to be specifically oriented in the case of the bulldozer drivers is consistent with these previous works, since they might result from multi-directional co-activations of somesthetic receptors distributed throughout the body.

The present work introduces a re-stabilizing method that involves performing simple voluntary movements to counter vibration-induced posteffects (Duclos et al. 2007) or those induced by isometric muscle contraction (Hutton et al. 1987). Here, the set of voluntary movements involving joint rotations, muscle contractions and stretching, and plantar pressure could operate as a recalibration process allowing the somesthetic parameters to be reset. The sensorimotor treatment leads the CNS to interrogate the system state and to make somesthetic sensory input coincide with the central motor commands for adaptation to a new environmental context (Baker et al. 2006).

Overall, although our study focused on the contribution of skin and muscle inputs to erect stance, exposure to whole-body vibration, including their low-frequency components, dramatically changed the complementary influence of the vestibular messages (Gauthier et al. 1981; Suarez et al. 2003; Suvorov et al. 1989). Along this line, one can assume that the vestibular inputs contribute to re-stabilizing posture via the sensorimotor treatment, especially the participants voluntary head movements (Abercromby et al. 2007; Bovenzi 2006). This would be worth studying specifically especially when considering how head movements lead to recalibrating both the vestibulo-oculomotor and the vestibulo-collic systems (Borel et al. 1988; Leigh and Brandt 1993).

Finally, in light of the results of the non-driver group, it seems unlikely that the re-stabilizing effect found after the sequence of voluntary movements performed was due to repeating the postural task. Repeating the task several times the same day had no significant stabilizing effect. Hence, one could assume that the stabilizing effect found in the driver experiment was mainly due to the sensorimotor treatment.

On a more practical note, the sensorimotor treatment could be available to all employees to prevent the occurrence of post-work accidents such as slips and falls. The applicability of the present results remains quite narrow as our population of interest was not constituted of professional bulldozer drivers but individuals in a learning process. Before the present results can be generalized, further investigations are needed on other construction vehicles, different kinds of equipment and/or work. If the re-stabilizing effect of the sensorimotor treatment proves efficient in various work environments, it would complement existing programs seeking to change the behavior of people exposed to WBV at work (Tiemessen et al. 2007).

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