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Published in:
Clinical Neurophysiology

DOI:
10.1016/j.clinph.2007.10.058

2008

Clinical Neurophysiology 119 (2008) 617–625

www.elsevier.com/locate/clinph

Effects of proprioceptive vibratory stimulation on body movement at 24 and 36 h of sleep deprivation ☆

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Accepted 30 October 2007

Abstract

Objective: To investigate whether postural stability and adaptation differed after a normal night of sleep, after 24 h (24 SDep) and 36 h (36 SDep) of sleep deprivation while subjected to repeated balance perturbations. Also, to determine whether there was any correlation between subjective alertness scores and objective posturographic measurements. Lastly, to investigate the effects of vision on the stability during sleep deprivation.

Methods: Body movements at five locations were recorded in 18 subjects (mean age 23.8 years) using a 3D movement measurement system while subjected with eyes open and closed to vibratory proprioceptive calf stimulation after a normal night of sleep, 24 and 36 SDep.

Results: The clearest sleep deprivation effect was reduced ability to adapt head, shoulder and hip movements, both with eyes open and eyes closed. Additionally, several near falls occurred after being subjected to balance perturbations for 2–3 min while sleep deprived. Unexpectedly, postural performance did not continue to deteriorate between 24 and 36 h of sleep deprivation, but showed some signs of improvement. Subjective scores of sleepiness correlated poorly with actual changes in postural control performance.

Conclusions: Sleep deprivation might affect postural stability through reduced adaptation ability and lapses in attention. Subjective alertness might not be an accurate indicator of the physiological effects of sleep deprivation.

Significance: Sleep deprivation could increase the risk of accidents in attention demanding tasks. There is a need for objective evaluation methods to determine actual performance capacity during sleep deprivation.

Keywords: Postural control; Proprioceptive vibratory stimulation; Attention; Sleep deprivation

1. Introduction

In the modern society, large fractions of the population report daily sleep below the recommended 8 h per night (National Sleep Foundation, 2005). This can induce tiredness and affect daily activities such as driving (Cummings et al., 2001). Sleep deprivation can drastically increase the risk of accidents and has been revealed as one of the main causes of some high-profile catastrophic disasters (Mitler et al., 1988). The features of sleep deprivation include fatigue, a decrease in sustained attention and reduced alertness. Sleep loss may therefore result in a higher risk for accidents and errors particularly where high levels of attention are required (Zils et al., 2005). Recent findings have also indicated that postural stability (Liu et al., 2001; Nakano et al., 2001; Avni et al., 2006) and motor control (Frey et al., 2004) are affected by sleep deprivation, though the mechanisms have yet to be determined. Some consider that the motor deficits are caused by alterations in the attentional state of the brain (Schlesinger et al., 1998; Fabbri et al., 2006). Other authors have proposed that detrimental postural effects are the result of daily circadian changes involving alertness (Nakano et al., 2001; Gribble and Hertel, 2004). Although levels of sleepiness can be measured subjectively, such assessment may not reflect the objective

☆ The authors acknowledge the invaluable contributions from Janeth Lindblad and Per Almbladh in assisting the data collection.

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1388-2457/$32.00
doi:10.1016/j.clinph.2007.10.058

performance of the tired person, due to motivation, personal factors, experience, training, etc., (Avni et al., 2006).

In order to explore the effects of sleep deprivation on postural control, we have used the archetypal quiet standing posture as an experimental model. The standing position is often described in terms of an inverted pendulum where the feet act as the point of 'anchorage' and the 'free, movable' end is the head with both extremes joined by a 'single rod' provided by the rest of the body. However, the pendulum model of standing might, in some cases, be oversimplified because the human body is multi-segmented with a number of points where pivoting can occur (i.e., neck, hip, knees and ankles). In order to quantify the standing position of the body, positional markers were placed at the main points of pivot in order to record the more subtle movement changes along the body.

An extension to the methodology was to investigate the standing position during balance perturbations. One method of perturbing the body is vibratory proprioceptive stimulation of postural muscles or tendons. Vibratory stimulation increases the afferent signals from the muscle spindles (Eklund, 1973) and creates a proprioceptive illusion that the vibrated muscle is being stretched (Matthews, 1986). Tonic stretch reflexes are subsequently induced which return the vibrated muscle to its perceived original length (Goodwin et al., 1972) resulting in a change of posture and increased postural sway (Fransson et al., 2000). When repeated, muscle vibration can evoke postural adaptation which enhances postural performance (Horak and Nashner, 1986; Keshner et al., 1987; Fransson et al., 2002) and markedly reduce the likelihood of imbalance and prevent falls (Pai and Iqbal, 1999; Pavol and Pai, 2002).

In one of the few hitherto studies of postural control stability while subjected to vibratory proprioceptive calf stimulation during sleep deprivation, Uimonen et al. found no effects of sleep deprivation on stability (Uimonen et al., 1994). However, Uimonen et al. assessed postural stability for only 55 s and only exposed the subjects to five vibratory perturbations, whereas we intend to record for 235 s and expose subjects to 64 vibratory perturbations in each of our tests. Furthermore, Uimonen et al., did not investigate whether postural adaptation or the actual body movements were changed by sleep deprivation.

The first aim of this study was to investigate whether postural stability and postural adaptation differed between tests after a normal night of sleep (Control), after 24 h and after 36 h of sleep deprivation while subjected to proprioceptive vibratory stimulation with eyes open and eyes closed. The second aim was to determine whether there was any correlation between subjective alertness scores (VAS) and objective posturographic measures. The third aim was to investigate whether postural control and adaptation differed with eyes open and eyes closed during sleep deprivation.

Our main hypothesis was that sleep deprivation would increase body movement both with eyes open and eyes closed. However, because the maintenance of postural stability is regulated by visual, vestibular and somatosensory information, the destabilizing effects of sleep deprivation might be larger with eyes closed. In addition, as the duration of sleep deprivation has been shown to increase cerebral deactivation (Thomas et al., 2003), another possibility was that body movement would be larger at 36 hours of sleep deprivation compared with 24 h.

2. Methods and materials

2.1. Subjects

Tests were performed on eighteen (ten male and eight female) healthy subjects (mean age 23.8 years, range 17–38 years; mean height 1.77 m, range 1.55–1.90 m; mean weight 78 kg, range 54–117 kg) with no history of balance problems, central nervous disease or injury to the musculoskeletal system. The participants were instructed not to consume any alcohol, medication, drowsiness-inducing or revitalizing products, such as caffeine, for a period of 48 h before and during testing, and all signed consent forms. The experiments were performed in accordance with the Helsinki Declaration of 1975 and approved by the local Ethics Committee.

2.2. Equipment

The proprioceptive stimulators had a vibration amplitude of 1.0 mm and frequency of 85 Hz and were 6 cm long and 1 cm in diameter. The vibrators were placed over the gastrocnemius muscles and secured by elastic straps.

An ultrasonic 3D-Motion Analysis system (Zebris™) measured the linear movements of five markers positioned at anatomical landmarks. The first marker ('Head') was attached to the subject's cheekbone (os zygomaticum), the second ('Shoulder') to tuberculum majus, the third ('Hip') to the crista iliaca, the fourth ('Knee') to the lateral epicondyle of femur, and the fifth ('Ankle') to the lateral distal fibula head, see Fig. 1. Each marker was tracked in three directions, i.e., anteroposterior, lateral and vertical. The measurement resolution in all dimensions was 0.4 mm. A customized computer program controlled the vibratory stimulation, and sampled the kinematic data at 50 Hz.

2.3. Procedure

To investigate the effects of sleep deprivation, testing was performed on two consecutive days. On day 1, subjects were asked to wake up at 7am or 8am (depending on the recording schedule) to begin their sleep deprivation session. The subjects were instructed to stay awake, without using stimulants, and go about their daily routines as usual. Subjects came to the laboratory 12 h later when they were fitted with a portable EEG recording device (Embletta™) to monitor their alertness during the experimental period.

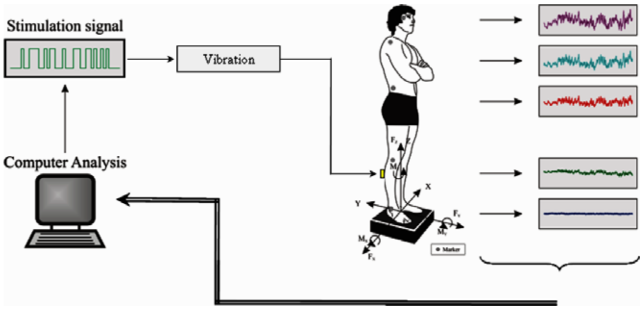

Fig. 1. Schematic picture of the measurement setup and placement of the five Zebris markers attached on a subject. The marker locations are shown by small circles.

Signs of sleep were monitored with an unilateral electrode measurement setup using routine electrodes. The EEG equipment comprised three electrodes; an active electrode positioned on the upper temple; a reference electrode positioned on the upper mastoid bone on the opposite side to the active electrode; and a ground electrode positioned on the mid-forehead. During the night of sleep deprivation, subjects reported that they remained awake by, for example, reading, watching television and taking long walks. The subjects returned on day 2 at 7am, 24 h into sleep deprivation (denoted 24 SDep), then again that evening at 7pm, 36 h into sleep deprivation (denoted 36 SDep) for their final posturographic assessment. The EEG equipment was removed prior to testing in order to avoid any possible interference from tactile information from EEG electrodes, the recording device and EEG cables. Additionally, it was appraised that correct EEG recordings could not be assured during the tests due to the electrical noise produced by the posturography equipment. The EEG data were stored for off-line analysis before re-attachment. Scoring of wakefulness/sleep was carried out according to Rechtschaffen and Kales (1968). Uninterrupted sleep stage II for more than 2 min was considered sleep.

Before the posturographic measurements at 24 SDep and before the measurements at 36 SDep, the subjects provided a subjective score of alertness ranging from "completely alert" to "exhausted and near sleep" using a Visuo-Analogue sleepiness Scale (VAS). Each subject's analogue score was converted into a number ranging from 1 to 10, where 1 = "completely alert" and 10 = "exhausted to near sleep". The subjective VAS score was collected before the posturographic measurements in order to avoid, for example, experiences of poor performance during the posturographic measurements influencing the VAS score given.

A Control posturography test following a normal night of sleep was performed either 1 week prior to sleep deprivation tests or 1 week after, in a randomized order. No VAS scores were obtained prior to the Control posturography tests as this was regarded as the normal state.

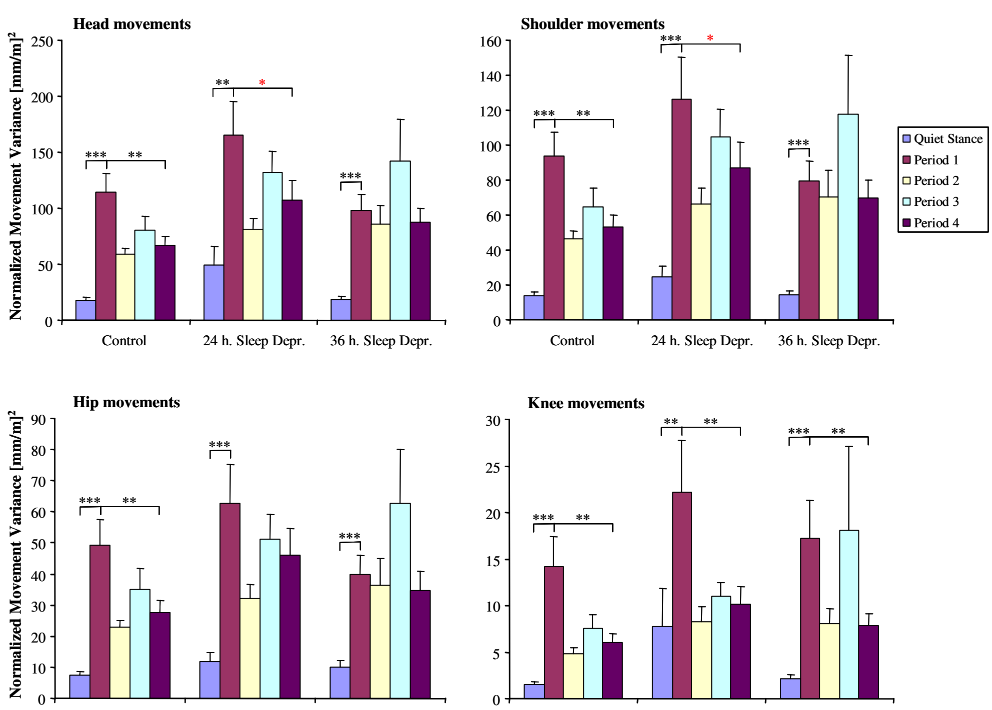

Fig. 2. Variance values for anteroposterior linear head, shoulder, hip and knee movements with eyes closed (mean and standard error of mean (SEM)). The presented values have been normalized using the subject's height. The statistical differences found between Quiet Stance and Period 1 of vibration, and between Periods 1 and 4 are marked with asterisks, where $^{*}p < 0.05$, $^{**}p < 0.01$ and $^{***}p < 0.001$. At Period 1, there was a clear increase in variance values in all tests and at all recording sites compared with Quiet Stance. Indications of adaptation were only apparent in all body segments in the Control test, whereas adaptation was poor in the upper body segments during sleep deprivation tests, particularly after 36 SDep. Note the differences in scale of Movement Variance axes indicating the different extents of sway for each segment of the body.

2.4. Posturography assessment

The five Zebris markers were attached on the right side of the subject facing the Zebris transmitter. Each subject was then instructed to stand barefoot on a force platform, relaxed and with arms folded across the chest. Subjects focused on a target 1.5 m in front of them at eye level or closed their eyes, depending on the test condition.

Tests were performed during three different test conditions: (I) after a normal night of sleep, (II) after 24 h of sleep deprivation (24 SDep) and (III) after 36 h of sleep deprivation (36 SDep). During each of these test conditions the following two posturography tests were performed by all subjects in a randomized order using a Latin Square design.

- Vibration of the calf muscles with eyes closed (EC).
- Vibration of the calf muscles with eyes open (EO).

The subjects were allowed to rest for five minutes between tests. Before vibration, a 30-s period of Quiet Stance was recorded. The vibratory stimulation pulses were activated using a pseudorandom binary sequence (PRBS) schedule (Johansson, 1993) over 205 s making each test 235 s long. Each pulse had random durations from 0.8 to 6.4 s, yielding an effect bandwidth of the vibratory stimulation within 0.1–2.5 Hz.

2.5. Analysis

Vibratory calf muscle stimulation induces body movement mainly in the anteroposterior direction, therefore, only linear movement in this plane is considered here (Fransson et al., 2000). Postural sway was analyzed in terms of the variance of the head, shoulder, hip and knee movements recorded by the Zebris™ system (Fransson et al., 2007). Furthermore, EC/EO quotient values showing the proportional differences in body movements between eyes open and eyes closed tests for each marker position were calculated for all three test conditions.

Each test was divided into five periods: Quiet Stance (QS) (0–30 s), and four 50-s stimulation periods (Period 1: 30–80 s; Period 2: 80–130 s; Period 3: 130–180 s; Period 4: 180–230 s).

2.6. Statistical analysis

Anteroposterior linear movement variance values were normalized using the subject's squared height before the statistical analysis to account for anthropometric differences between the subjects (Johansson et al., 1988). The squared nature of the variance algorithm made it necessary to use normalization with squared parameters to achieve unit agreement with the standardization.

The Wilcoxon matched-pairs signed-rank test (Exact sig. 2-tailed) (Altman, 1991) was used to statistically compare results between the test conditions and for the analysis of quotients. The movement variance changes between Quiet Stance and Period 1 were evaluated to determine how the assessed parameters were initially affected by the balance perturbations evoked by vibratory proprioceptive stimulation compared to the activity during Quiet Stance. The movement variance changes between Periods 1 and 4 were evaluated to determine how the assessed parameters were affected by repeated vibratory stimulation, quantifying possible effects of adaptation to vibratory proprioceptive stimulation. The EC/EO quotient changes were analyzed between all periods in order to monitor periodic changes in body movement pattern. In addition, a GLM univariate ANOVA (General Linear Model univariate Analysis of Variance) statistical test on log-transformed values (Altman, 1991) was used to determine whether vision or sleep deprivation significantly affected results and whether there was an interaction between the two factors on measured linear body movement. The GLM model accuracy was evaluated by testing the model residual for normal distribution. Correlation analysis was performed between subjective VAS scores and movement variance using Spearman correlation test.

Non-parametric statistics were used because the values were not normally distributed. The statistical analysis was carried out with Bonferroni correction for multiple comparisons with no more than four matched-pair analyses performed on each single data set. In the analysis, *p*-values <0.01 were considered statistically significant, except for the GLM analysis and Spearman's correlation analysis where *p*-values <0.05 were considered significant (Altman, 1991). However, we present the *p*-values <0.05 in the figures (in red) for consistency.

3. Results

Average subjective VAS sleepiness scores increased from 5.2 at 24 SDep to 6.8 at 36 SDep ($p < 0.001$), where the VAS range was defined as 1 = "completely alert" and 10 = "exhausted to near sleep".

3.1. Linear head, shoulder, hip and knee movements

3.1.1. Effect of 24 and 36 h of sleep deprivation on Quiet Stance (QS)

During QS with eyes open (EO), there was a progressive increase in variance of movement from the knee towards the head in the Control test, see Fig. 3. This is characteristic of the movement associated with the single-link, pendulum model. This pattern of body movements was largely retained in the 24 and 36 SDep tests, only the amplitudes were larger than in the Control test. With eyes closed (EC), QS during the Control test and sleep deprivation tests showed a similar pattern to that of EO, though there were indications that the hip movements increase was proportionally smaller compared with the other body movements at 24 SDep, see Fig. 2.

3.1.2. Effect of balance perturbations with eyes closed

During the first vibratory stimulation period (Period 1) with eyes closed there was a significant increase in body movement variance at all marker positions compared to Quiet Stance in the Control test ($p < 0.001$), see Fig. 2. Head, shoulder and hip movements increased by 560% and knee movement by about 800%. Between Periods 1 and 4, there was a decrease in head, shoulder, and hip movement variances by about 35% ($p < 0.01$) and 60% at the knee ($p < 0.01$). In Period 1 of 24 SDep there was a rise in movement variance from Quiet Stance by about 240% at the head ($p < 0.01$), 420% at the shoulder ($p < 0.001$) and hip ($p < 0.001$) and 190% at the knee ($p < 0.01$). Between Periods 1 and 4, there was a reduction and leveling off in the body movements, though the reduction only reached a significant level at the knee. The decrease in knee movement variance was about 50% ($p < 0.01$).

In Period 1 of 36 SDep, the body movement variance increased similarly to Control test values, and the movement variance changes were smaller than the movement variance changes found at 24 SDep. Head and shoulder movement variances increased by about 440% ($p < 0.001$), hip by 300% ($p < 0.001$), and knee movements by about 700% ($p < 0.001$). Like at 24 SDep, only the knee movement variance reduced significantly between Periods 1 and 4, by about 55% ($p < 0.01$).

3.1.3. Effect of balance perturbations with eyes open

In the Control test, body movement variance increased during the first vibratory stimulation period at the shoulder, hip and knee by about 320% ($p < 0.001$) compared to Quiet Stance, whereas the head movement increased by about 200% ($p < 0.001$) with eyes open, see Fig. 3. With repeated vibration, there was a significant reduction in head and shoulder movement variance by about 35% ($p < 0.01$) between Periods 1 and 4. Knee and hip movement variance also decreased, but the changes did not reach the appropriate level of significance.

In Period 1 of 24 SDep, body movement variance increased by 355% at the head, 465% at the shoulder, 390% at the hip and 290% at the knee ($p < 0.001$) compared to Quiet Stance. However, during the repeated vibrations movement variance only decreased at the knee by about 55% ($p < 0.01$) between Periods 1 and 4.

Similarly, in Period 1 of 36 SDep, body movement variance increased by 240% at the head ($p < 0.001$), by 165% at the shoulder ($p < 0.001$), by 100% at the hip ($p < 0.001$) and by 50% at the knee ($p < 0.01$) compared to Quiet Stance. However, there was no significant reduction of movement variance at any marker position between vibration Periods 1 and 4.

3.2. GLM analysis of linear body movements

Sleep deprivation significantly affected all body movement variances in Period 3 ($p < 0.05$), see Table 1. The analysis also showed that vision influenced almost all body movements, the variances being significantly lower with EO in all periods, particularly at the head and shoulder. In addition, we found that there was no interaction of vision and sleep deprivation.

3.3. Analysis of EC/EO quotient values

The EC/EO quotient values at all recorded body positions were proportionally the same in all periods in the Control test, see Fig. 4. However, the EC/EO quotient values for 24 SDep showed differing movement amplitudes at the body levels in QS and in Periods 2 and 3. During QS, there were proportionally larger knee and head movement variance differences compared to the hip and shoulder between EC and EO, though some changes were only determined at significant level ($p < 0.05$). In Periods 2 and 3, there were proportionally larger head and shoulder movement variance differences compared to the knee and hip ($p < 0.05$). In Period 3, there were proportionally larger head movement variance differences compared to the knee ($p < 0.01$) between EC and EO tests. Like the Control test, the QS EC/EO quotient values for 36 SDep showed an equal reduction in movement with EO and EC. However, in Period 2, head movement variance differences were proportionally larger than hip and shoulder movement variance differences between EC and EO ($p < 0.05$). Also, during Period 3, shoulder movement variance differences were proportionally larger than hip movement variance differences ($p < 0.01$).

3.4. Correlation between subjective sleepiness and anteroposterior body movement

There was an indication of a negative correlation between subjective sleepiness VAS scores and hip movement only at 24 SDep in Period 3 with eyes closed ($p < 0.05$, $R = -0.547$) and in Period 1 with eyes open ($p < 0.05$, $R = -0.494$).

4. Discussion

Most people have had first hand experience of sleepiness. However, by using recordings of movement from multiple articulation points, this study has provided some new insights into how balance control and the movement strategies are affected by 24 and 36 h of sleep deprivation. In previous sleep deprivation studies on postural control, the investigations have been limited to center of pressure measurements using force platforms. However, the findings presented in the present study suggest that body movement variance and the movement pattern are also affected in sleep deprived subjects. Although some evidence showed that sleep deprivation affected unperturbed standing, the most prominent effects were found when sleep deprived subjects were exposed to proprioceptive vibratory stimulation, illustrated for example, by a decreased ability to adapt to balance perturbation. Furthermore, our findings suggested that postural performance might be partially

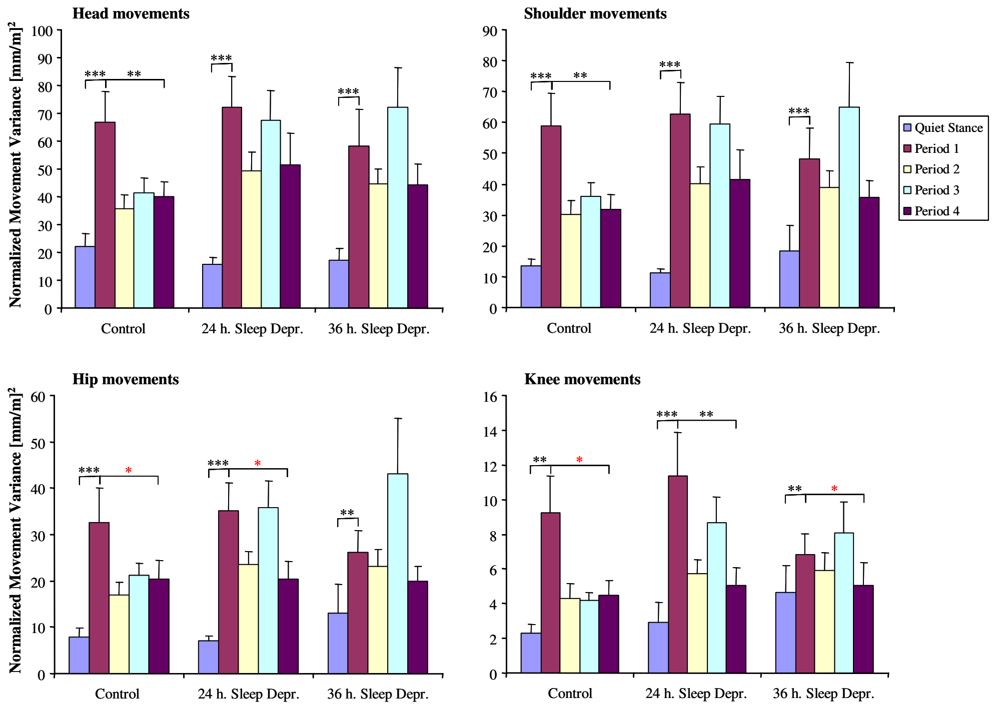

Fig. 3. Variance values for anteroposterior linear head, shoulder, hip and knee movements with eyes open (mean and standard error of mean (SEM)). At Period 1, there was a clear increase in variance values in all tests and at all recording sites compared with Quiet Stance. Indications of adaptation were only apparent in the Control test in the upper body segments, whereas adaptation was poor during sleep deprivation tests.

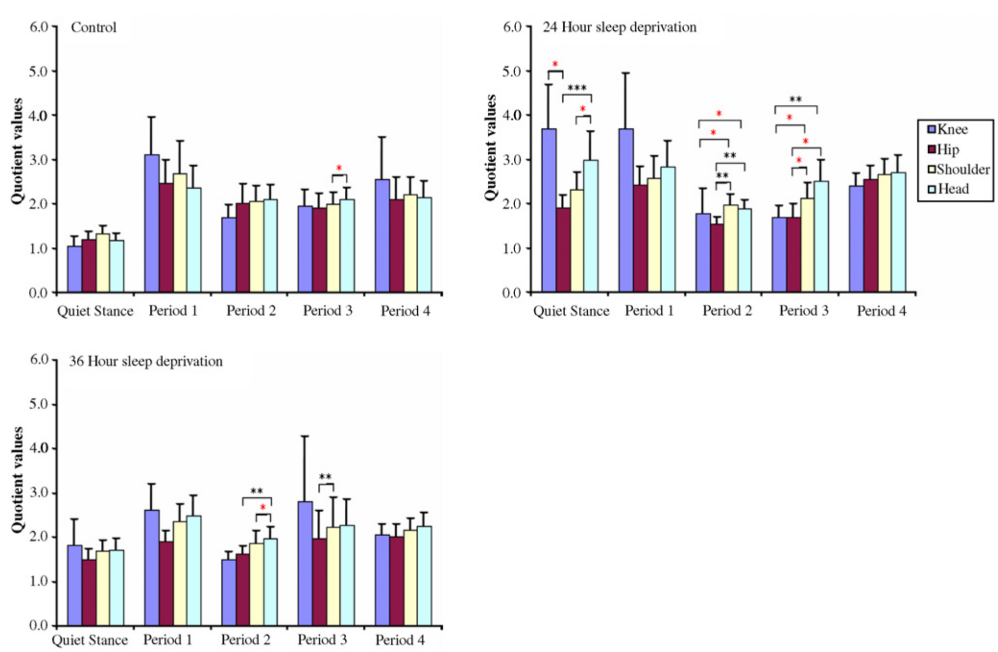

Fig. 4. EC/EO quotients (mean and (SEM)) showing the average body movement values for each test.

affected by circadian rhythm effects and not only by the length of sleep deprivation.

4.1. Postural control and sleep deprivation

Although it is generally accepted that sleep deprivation has a destabilizing effect on posture (Schlesinger et al., 1998; Liu et al., 2001; Nakano et al., 2001; Avni et al., 2006; Fabbri et al., 2006), our study showed that body movement only markedly increased when balance was perturbed by calf vibration. This might be related to the level of attention of sleep deprived subjects. Previous findings have shown that sleep loss results in a higher risk of accidents and errors when high levels of attention are required

Table 1
Statistical evaluation of the linear body movement values using the GLM univariate ANOVA method

	Position	*p*-Value		
		Sleep deprivation	Visual influence	Sleep deprivation × visual influence
Linear body movements				
Quiet Stance	Head	ns	0.041	ns
	Shoulder[a]	ns	0.040	ns
	Hip[a]	ns	ns	ns
	Knee	ns	ns	ns
Period 1	Head	ns	<0.001	ns
	Shoulder	ns	<0.001	ns
	Hip	ns	<0.001	ns
	Knee	ns	0.002	ns
Period 2	Head	ns	<0.001	ns
	Shoulder	ns	<0.001	ns
	Hip	ns	0.007	ns
	Knee	ns	ns	ns
Period 3	Head	0.013	<0.001	ns
	Shoulder	0.015	0.001	ns
	Hip	0.048	0.047	ns
	Knee[a]	0.024	ns	ns
Period 4	Head	ns	<0.001	ns
	Shoulder	ns	<0.001	ns
	Hip	ns	<0.001	ns
	Knee	ns	<0.001	ns

The notation "<0.001" means that the *p*-value is smaller than 0.001, and "ns" signifies no significant difference. Vision had a clear effect on all body movement, especially at the head and shoulder, during all periods. Sleep deprivation only had significant effect on the body movements in Period 3. The combined effect was non-significant. [a]The GLM model residual was not normally distributed. These statistical values may therefore be somewhat less accurate.

(Zils et al., 2005; Fabbri et al., 2006). Attention has long been thought to play a vital role in processing sensory information to maintain postural stability (Woollacott and Shumway-Cook, 2002; Fabbri et al., 2006), especially when sensory information from at least one source is unreliable (Redfern et al., 2001). In this study, calf vibration provided the stimulus to give a false perception of movement. As such, the sensory information from the proprioceptors was 'unreliable' in terms of accurately portraying the actual movement of the body. Under normal conditions, the attentional state of the subject is sufficiently high to re-weight the different sensory inputs and place greater importance on the more reliable receptors (Schlesinger et al., 1998; Woollacott and Shumway-Cook, 2002). This ability to prioritize sensory input may be lost during calf vibration in sleep deprived individuals as evidenced by the larger body movement variances.

Another finding was that the most prominent effects of sleep deprivation were found in Period 3 of stimulation, i.e., during the 100- to 150-s period of vibratory stimulation. During this period, several subjects exhibited a sudden and severe movement so that they almost fell, despite having experienced the effects of vibratory stimulation over the previous 100 s. One explanation could be that these near-falls were caused by lapses of attention as the length of the tests increased, which would be in line with the "Lapse hypothesis" (Wilkinson, 1965). Of note, evaluations of the real-time recordings showed no visible large changes of the capacity to handle the balance perturbations prior to or after the near-fall event, so our conclusion is that the large values in Period 3 are not a sign of poor adaptation but rather another representation of how sleep deprivation may momentarily affect postural control.

These findings might have significant implications for tired workers, especially in the transport industry, as a lapse in attention could lead to an increased risk of an accident. It is possible that these marked events of near-falls, represented by substantially increased body movements during Period 3, may have made the subjects more aware of the instability hazard caused by their sleep deviation and thereby to become more stable for the remainder of the test.

It should be noted that total sleep deprivation, as investigated in this study, and chronic sleep restrictions may not have identical effects on motor control and postural stability (Haslam, 1984). However, decreased postural stability has also been reported among subjects after chronic restricted sleep (Karita et al., 2006). Therefore, it is reasonable to assume that our findings might also be relevant for patients with severe sleep disorders such as obstructive sleep apnea syndrome (OSAS) which is characterized by a stoppage or decrease in breathing, resulting in inadequate sleep.

The present study also showed an unexpected result in that the initial deterioration of postural stability at 24 h of sleep deprivation was not followed by a further deterioration in performance at 36 h of sleep deprivation. Instead, in most cases, the body movement variances were similar, and in several cases even clearly smaller at 36SDep (Figs. 2 and 3). One explanation for this could be that performance follows a circadian rhythm (Nakano et al., 2001; Gribble and Hertel, 2004; Avni et al., 2006). A way of confirming this would be to re-assess subjects after a further 24-h period of sleep deprivation.

4.2. Adaptation and sleep deprivation

Adaptation is an important function of postural control which results in decreased body movement and a reduced risk of falling (Eccles, 1986; Pai and Iqbal, 1999; Pavol and Pai, 2002; Fransson et al., 2003). As expected, after a normal night of sleep, subjects responded to the balance perturbations with an initial increase in body movement variance followed by a gradual reduction in movement variance when repeatedly perturbed by calf vibration. However, sleep deprivation seemed to compromise this mechanism, and in fact the clearest effect of sleep deprivation was found to be a lack of adaptation of the body movement variances at the head, shoulder and hip. One possible reason for this might be that the initiation and maintenance of an adaptive response may require a certain amount of attention. The integration of information from the visual, vestibular and somatosensory receptors and motor coordination are processes known to require attention (Schlesinger et al., 1998; Fabbri et al., 2006), especially when information from any of the sensory systems is not reliable (Redfern et al., 2001). Hence, sleep deprivation and the accompanying decrease in attention may lead to slower or inappropriate sensory integration, which also affected the ability to choose the most appropriate motor response to enhance balance stability.

4.3. Subjective VAS scores and postural control

Previous research has shown that sleep deprivation can decrease subjective alertness (Harma et al., 1998; Liu et al., 2001). However, in the present study, high subjective sleepiness scores did not correlate with increased body movement variances. Instead, in the only two comparisons in which we found a significant correlation, body movement was actually lower among the subjects that subjectively regarded themselves as the sleepiest. This suggests that subjective sleepiness may not be a reliable indicator of actual postural control performance (Fabbri et al., 2006). These findings therefore highlight the value of implementing regulations for work durations, particularly in attention demanding occupations, such as long distance driving, because subjective sleepiness may not reflect actual performance decrease, which potentially could cause safety hazards and traffic accidents. Although sleepiness and fatigue can be subjectively assessed, such evaluations may not reflect the objective physiological status of the tired person, because subjective scores can be biased by motivation, personal factors, experience, training, etc (Avni et al., 2006). Additionally, the mere act of performing a test might momentarily enhance attention and motivation (Avni et al., 2006). Therefore, there is a need for objective evaluation methods to determine actual performance capacity during sleep deprivation.

4.4. Vision and sleep deprivation

Our findings support evidence from Edwards showing that vision can provide information to assist postural control (Edwards, 1946), as sleep deprivation had less effect on body movement variance with eyes open compared with eyes closed in the anteroposterior direction. In most cases, head and shoulder movement variances were significantly larger in tests conducted with eyes closed compared with eyes open. However, although the EC/EO quotients suggested that the body movement pattern was different while sleep deprived, we were unable to find statistical evidence showing that vision was more important while sleep deprived. Additionally, the near-falls and decreased adaptation occurred both in tests with eyes open and eyes closed. Hence, although visual information provided enhanced stability, this additional information seemed not to be sufficient to compensate fully for the deterioration of performance caused by sleep deprivation.

4.5. EC/EO quotients and sleep deprivation

In normal conditions, unperturbed stance induces continual body movements that resemble an inverted pendulum, with proportionally larger movements at the head and shoulder than at positions closer to the support surface. Consistent with this body movement strategy, we found that the proportional changes of the EC/EO quotients were the same in all body segments after a normal night of sleep both during Quiet Stance and during balance perturbations.

However, at 24 h of sleep deprivation, the Quiet Stance body movement pattern was different, reflected by the finding that knee, shoulder and head movements were proportionally changed more between eyes closed and eyes open tests than hip movements. This finding suggests that the subjects used a more precautious hip movement strategy during Quiet Stance while standing with eyes closed. Some data values suggest that this movement pattern was maintained during the first stimulation period, though the latter observation could not be statistically confirmed. After about 150s of balance perturbations the subjects appeared to have returned to using a single-link pendulum movement strategy though with larger body movements. This finding suggests that while sleep deprived, the segmental movement pattern during Quiet Stance and in response to repeated balance perturbations is changed, and that the ability to select an appropriate movement pattern appears to be slower than in normal conditions (Maki and Whitelaw, 1992; Chong et al., 1999).

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