Effects of Sleep Deprivation on Human Postural Control, Subjective Fatigue Assessment and Psychomotor Performance

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This study aimed to investigate the effects of sleep deprivation on postural control, subjective fatigue assessment and psychomotor performance, and to assess the efficiency of an objective posturographic test as an indicator of mental fatigue. Postural sway using static posturography (Romberg’s test), subjective fatigue assessment (Stanford Sleepiness Scale) and psychomotor performance (Sternberg dual-task test) were assessed in 12 subjects before and after 24 h of sustained wakefulness. After sustained wakefulness, the Romberg test parameters of circumference area and rectangle area with the eyes-closed, and standard deviation in the anterior–posterior direction with the eyes-open were significantly higher compared with baseline values (before sustained wakefulness). Subjective fatigue assessment scores were also significantly increased, while psychomotor performance was unchanged. Sleep deprivation can arouse a feeling of fatigue and can affect postural stability, hence an objective posturographic test score may be useful as an indicator of mental fatigue.

KEY WORDS: Postural control; sleep deprivation; mental fatigue; psychomotor performance

Introduction

Mental fatigue has become a major concern in occupational activities that require optimal vigilance and attention over an extended time span, e.g. during night shifts. Mental fatigue is a functional state that can lead either to sleep or to a relaxed, restful state, both of which are likely to reduce attention and alertness.1 Mental fatigue is believed to be a gradual and cumulative process and is thought to be associated with a disinclination to exert any effort, reduced efficiency and alertness, and impaired mental performance.2 Fatigue and weakened vigilance are considered to be main causes of both aviation and ground
Mental fatigue can be subjectively assessed. It has, however, been shown that such an evaluation does not fully reflect the objective, physiological status of a tired person, mainly because subjective reports are biased by motivation, personal factors, experience and training. Physiological parameters, such as an electrocardiogram, electroencephalogram and rectal temperature have not been popular in the assessment of fatigue because of their inherent drawbacks, such as inconvenience of use and difficulties in interpretation of the data. There is, therefore, an urgent need to find a practicable, non-invasive but objective method to measure mental fatigue, particularly in its early stages.

Balance is an important function of the human body. The body’s postural control depends on co-ordination of the central nervous system (CNS) with visual sense, proprioceptive sense and vestibular information, and regulation of the CNS to exercise the effector organs. Any change in these processes will influence postural control. In this context, the objective, computerized assessment of postural control, known to be intimately linked with neurophysiological processes affected by fatigue, appears to be a promising method of fatigue assessment.

It has been shown that postural stability and motor control are affected by > 19, 24 or 48 h of sleep deprivation, although the mechanism by which sleep deprivation exerts these effects has yet to be determined. The effect of sleep deprivation on postural sway is correlated with reduced levels of alertness, peaking when the body temperature reaches its minimum. The efficiency of a short, objective posturographic test as an indicator of the early stages of mental fatigue is, however, still unclear.

The objective of the present study was to use a mental fatigue model of 24 h of sustained wakefulness (i.e. sleep deprivation) to evaluate the efficiency of a short, objective posturographic test as an indicator of the early stages of mental fatigue. Postural sway with both eyes-closed and with both eyes-open using static posturography, subjective fatigue assessment and the psychomotor performance was tested before and after a period of sleep deprivation.

Subjects and methods

SUBJECTS
Male senior college students with regular sleeping habits, i.e. sleeping between 22:30 h and 06:30 h, were enrolled into the study. Subjects were included if they did not report any sleep disorders, mental or nervous system diseases, did not gamble and were not using any medication. The study protocol was approved by the Ethics Committee for Human Research of the Fourth Military Medical University, Xi’an, China. Each subject provided written informed consent to participate 2 days before they started the study.

EXPERIMENTAL PROCEDURE
All participants rested for 2 days before the experiment and were asked to refrain from smoking, drinking alcohol, tea or coffee, or consuming any other central stimulant or suppressive drug. They were also asked to refrain from heavy exercise. During the daytime of the 2-day period prior to the start of the study, they were taught to operate a psychomotor performance test on a computer.

On the morning of the experiment, after a normal full night’s sleep, the subjects were required to stay awake for 24 h consecutively at the laboratory from 08:00 h to 08:00 h the following day (sleep deprivation for one
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night). At the beginning (08:00 h – 08:50 h on the first morning) and the end of the experiment (08:00 h – 08:50 h on the following day), each subject completed static posturographic examinations (Romberg’s test), underwent subjective assessment of fatigue, using the Stanford Sleepiness Scale questionnaire, and psychomotor performance, assessed by the Sternberg dual-task test.

ROMBERG’S TEST
Static postural control was measured using the EAB-100 balance examination system (Anima, Tokyo, Japan) before and after a 24-h period of sustained wakefulness. The equipment consisted of an examining table 1200 mm (width) × 760 mm (diameter) × 110 mm (height), a customized computer program, a display subsystem and a print subsystem. Each subject was asked to stand on the platform and stare at a black dot 3 m away, with feet together and hands placed at the sides of the body. In a static posturograph, Romberg’s test was activated for a 30 s recording with the eyes-open. There was then a 1 min break before a 30 s recording with the eyes closed, performed in the same position.

The following parameters of postural sway were calculated:7,15 whole path length (WPL); total path length of centre-of-pressure (COP) changes during quiet standing, which represents the mean speed of displacement of centre of mass (COM); circumference area (CA) that encloses all recorded COP points (CA was established using an algorithm that constructs a smooth closed curve of irregular shape); and rectangle area (RA), defined as the product of the maximum displacement values of COP in lateral and anterior–posterior directions. RA is a global measure that allows estimation of the overall postural performance generally associated with fall risk.16 The following additional measurements were also recorded: unit area path length (UAPL = WPL/CA), which represents proprioceptive sense posture control; standard deviation in the lateral direction (SDx) and anterior–posterior direction (SDy), which reflects variability of COP movement around the mean COP position in lateral and anterior–posterior directions;17 mean displacement of COP on the lateral axis (Mx) and on the anterior–posterior axis (My), which represents the general sway condition in the lateral and anterior–posterior direction, respectively; and Romberg’s index, which is the ratio of WPL, UAPL, CA, RA, SDx, SDy, Mx, My with the eyes open and the eyes closed. This represents the differences between when the eyes are open and when they are closed and, therefore, reflects the contribution that vision makes to maintain posture.11

SUBJECTIVE ASSESSMENT OF FATIGUE
Subjective assessment of fatigue was performed using the Stanford Sleepiness Scale (SSS) questionnaire before and after a 24-h period of sustained wakefulness. In this questionnaire, which has been validated for its sensitivity to fatigue,3 subjects ranked their feelings of fatigue, vigilance and sleepiness according to a scale of seven statements describing a gradually increasing feeling of sleepiness ranging from ‘feeling active and vital; alert; wide-awake’ (score 1) to ‘almost in reverie; sleep onset soon; lost struggle to remain awake’ (score 7).

STERNBERG DUAL-TASK TEST
Psychomotor performances were assessed by the Sternberg dual-task test before and after a 24-h period of sustained wakefulness. The dual-task test combined a complex reaction time test and an unstable tracking test.
simultaneously for 3 min. Subjects sat in a quiet room facing a computer monitor at a distance of about 0.5 m. A randomly moving target square in a 17.8 × 24.8 mm viewing area was presented on a screen. A series of four English characters were presented in the moving target square for 1 s, followed 1 s later by two ‘probe’ characters. The subject’s task was to determine, as quickly as possible, whether one of the ‘probe’ characters was among those initially presented and to press the ‘yes’ or ‘no’ key on the joystick with their right thumb and index fingers, respectively. In total, 40 trials were presented to each subject. When the target square moved randomly, subjects were required to use the same joystick to control cursor (2 × 2 mm) movement, keeping the ‘+’ cursor within the centre (15 × 15 mm) of the target square. The ‘+’ cursor and moving target square with four English characters are shown in Fig. 1. Dependent measures were complex response time, number of correct responses and the root-mean squared (RMS) tracking error measured from the central target square.

STATISTICAL ANALYSES

All data were expressed as mean ± SD. Statistical analysis was performed using the SPSS® software package, version 8.0 (SPSS Inc., Chicago, IL, USA) for Windows®. For the stabilometric parameters and repeated measures, analysis of variance was carried out with time (the beginning and the end of the experiment) and visual input (eyes-open and eyes-closed conditions) as within-subject
factors. A comparative analysis between the first set of tests (before sleep deprivation) and the second set of tests (after sleep deprivation) was performed using the paired t-test for the Stanford Sleepiness Scale data and Sternberg dual-task data. A P-value < 0.05 was considered to be statistically significant.

**Results**

Sixteen male senior college students with a mean ± SD age of 20.75 ± 1.18 years, height of 174.00 ± 3.70 cm and body mass of 64.61 ± 4.63 kg, were enrolled into the study.

Compared with when the eyes were open, postural sway parameters (WPL, CA, RA, SDx) when the eyes were closed increased significantly both before and after a period of 24 h sustained wakefulness ($P < 0.05$ or $P < 0.01$). The SDy when the eyes were closed was only significantly higher than when they were open before sustained wakefulness ($P < 0.05$), whereas UAPL decreased significantly with the eyes closed compared with the eyes open both before and after 24 h of sustained wakefulness ($P < 0.05$; Table 1). After sustained wakefulness, CA and RA with the eyes closed were significantly higher compared with before sustained wakefulness ($P < 0.05$). The SDy with the eyes open was also significantly higher after sustained wakefulness compared with before ($P < 0.05$). Other postural sway parameters, including Romberg’s index, showed no significant differences after versus before sustained wakefulness (Table 1).

The effects of sleep deprivation (24 h of sustained wakefulness) on the subjective feeling of fatigue, as reflected by the Stanford Sleepiness Scale, are presented in Fig. 2. The scores obtained after sleep deprivation were significantly higher than those recorded at the beginning of the 24-h period of sustained wakefulness ($P < 0.01$).

Table 2 provides the results of the psychomotor performance assessment with the Sternberg dual-task test before and after a 24-h period of sustained wakefulness. No significant differences were obtained in the complex response time, the number of correct responses and the RMS of tracking error between the two conditions.

**Discussion**

The human postural control system integrates various mechanisms that prevent the human body from falling. The postural system is highly complex and includes feedback loops from several sensory inputs (e.g. superficial and deep tactile sense, proprioception from joints, tendons and muscles, vision and the vestibular system). Accordingly, major parts of the CNS are involved in the maintenance of balance. The vestibular system plays a central role in maintaining postural control, especially when vision, proprioception and tactile sense give little useful information. When body equilibrium becomes upset, impulses originating in sensory receptors activate reflex contractions in the muscular fibres to restore equilibrium. Thus, reflex contractions in the musculature cause continuous body oscillations that maintain the dynamic equilibrium of the upright posture. The neuromuscular response to imbalance of the COM generates a COP trajectory when a person stands on top of a force platform.

Static posturography is a curve reflecting the relationship of time and projection on a plate, with information recorded by a pressure sensor when people are standing with a static posture, and is analysed by a computer. The COP response depends on the COM movements and on the motor control of other muscles, including those in the ankles. The postural sway parameters (WPL,
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### TABLE 1: Posturography parameters in Romberg’s test in 12 healthy male subjects with the eyes open or closed before and after 24 h of sustained wakefulness (sleep deprivation)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Status</th>
<th>Before sustained wakefulness</th>
<th>After sustained wakefulness</th>
</tr>
</thead>
<tbody>
<tr>
<td>WPL (mm)</td>
<td>Eyes-open</td>
<td>569.04 ± 43.22</td>
<td>545.58 ± 34.90</td>
</tr>
<tr>
<td></td>
<td>Eyes-closed</td>
<td>655.22 ± 85.79a</td>
<td>609.14 ± 59.47a</td>
</tr>
<tr>
<td></td>
<td>Romberg’s index</td>
<td>1.16 ± 0.16</td>
<td>1.13 ± 0.10</td>
</tr>
<tr>
<td></td>
<td>UAPL (l/mm)</td>
<td>Eyes-open</td>
<td>6.46 ± 2.71</td>
</tr>
<tr>
<td></td>
<td>Eyes-closed</td>
<td>4.90 ± 1.88a</td>
<td>4.04 ± 2.89a</td>
</tr>
<tr>
<td></td>
<td>Romberg’s index</td>
<td>0.79 ± 0.22</td>
<td>0.78 ± 0.32</td>
</tr>
<tr>
<td></td>
<td>CA (mm²)</td>
<td>Eyes-open</td>
<td>105.99 ± 56.49</td>
</tr>
<tr>
<td></td>
<td>Eyes-closed</td>
<td>159.53 ± 65.41a</td>
<td>222.60 ± 71.85b,c</td>
</tr>
<tr>
<td></td>
<td>Romberg’s index</td>
<td>1.59 ± 0.60</td>
<td>1.93 ± 1.31</td>
</tr>
<tr>
<td></td>
<td>RA (mm²)</td>
<td>Eyes-open</td>
<td>295.69 ± 152.77</td>
</tr>
<tr>
<td></td>
<td>Eyes-closed</td>
<td>433.30 ± 180.11a</td>
<td>643.09 ± 210.99b,c</td>
</tr>
<tr>
<td></td>
<td>Romberg’s index</td>
<td>1.58 ± 0.76</td>
<td>2.05 ± 1.71</td>
</tr>
<tr>
<td></td>
<td>SDx (mm)</td>
<td>Eyes-open</td>
<td>3.50 ± 1.33</td>
</tr>
<tr>
<td></td>
<td>Eyes-closed</td>
<td>4.02 ± 1.35a</td>
<td>5.09 ± 2.61a</td>
</tr>
<tr>
<td></td>
<td>Romberg’s index</td>
<td>1.21 ± 0.40</td>
<td>1.44 ± 0.70</td>
</tr>
<tr>
<td></td>
<td>SDy (mm)</td>
<td>Eyes-open</td>
<td>3.30 ± 0.59</td>
</tr>
<tr>
<td></td>
<td>Eyes-closed</td>
<td>4.10 ± 1.03a</td>
<td>4.78 ± 1.37</td>
</tr>
<tr>
<td></td>
<td>Romberg’s index</td>
<td>1.26 ± 0.25</td>
<td>1.23 ± 0.52</td>
</tr>
<tr>
<td></td>
<td>Mx (mm)</td>
<td>Eyes-open</td>
<td>7.31 ± 3.14</td>
</tr>
<tr>
<td></td>
<td>Eyes-closed</td>
<td>8.25 ± 4.05</td>
<td>7.45 ± 6.10</td>
</tr>
<tr>
<td></td>
<td>Romberg’s index</td>
<td>1.17 ± 0.49</td>
<td>1.70 ± 1.87</td>
</tr>
<tr>
<td></td>
<td>My (mm)</td>
<td>Eyes-open</td>
<td>7.02 ± 5.29</td>
</tr>
<tr>
<td></td>
<td>Eyes-closed</td>
<td>10.35 ± 7.22</td>
<td>6.52 ± 4.48</td>
</tr>
<tr>
<td></td>
<td>Romberg’s index</td>
<td>1.71 ± 0.93</td>
<td>1.66 ± 1.42</td>
</tr>
</tbody>
</table>

Data shown are mean ± SD. 

a \( P < 0.05 \), b \( P < 0.01 \), for eyes closed versus eyes open; c \( P < 0.05 \), for after versus before sustained wakefulness. 

WPL, whole path length; UAPL, unit area path length; CA, circumference area; RA, rectangle area; SDx, standard deviation in the lateral direction; SDy, standard deviation in the anterior–posterior direction; Mx, mean centre displacement in the lateral direction; My, mean centre displacement in the anterior–posterior direction. 

Romberg’s index, the ratio between eyes closed and eyes open for each parameter.

### TABLE 2: Psychomotor performance assessed with the Sternberg dual-task test before and after 24 h of sustained wakefulness in 12 healthy male subjects

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Before sustained wakefulness</th>
<th>After sustained wakefulness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of correct responses</td>
<td>33.88 ± 4.88</td>
<td>31.63 ± 5.34</td>
</tr>
<tr>
<td>Complex reaction time (ms)</td>
<td>372.5 ± 49.7</td>
<td>393.3 ± 73.2</td>
</tr>
<tr>
<td>Root-mean square of tracking error (mm)</td>
<td>56.43 ± 9.93</td>
<td>62.90 ± 13.51</td>
</tr>
</tbody>
</table>

Data shown are mean ± SD. 

No statistically significant differences \( P > 0.05 \).
CA, RA, SDx, SDy) with open or closed eyes can sensitively and reliably identify the equilibrium function of the subject.¹⁸

There is an emerging recognition that a state of sleepiness/mental fatigue contributes to deterioration in performance, which may lead to errors and increase the risk of accidents.¹ Numerous studies have demonstrated that sleep deprivation has many effects on the human body, such as increased lapses in concentration, cognitive slowing, decrease in vigilance and operation performance, and memory impairment.¹⁹ – ²¹ Nardone et al.²² demonstrated that fatigue affected body swing and the study by Fabbri et al.¹¹ revealed that, after a night without sleep, there is a slower processing of visual inputs when maintaining postural control. Other studies have shown that reduction in nocturnal human postural control is related to sleepiness and biological rhythms (e.g. body temperature) and can affect balance.⁴,⁹

A decrease in vigilance results in neurophysiological alterations and slow processing of visual inputs.¹² Sleep deprivation of 24 h slows the cortex–thalamus network system and results in functional changes in the attention system and pre-frontal cortex.²³,²⁴

The objective of the present study was to evaluate the efficiency of a short, objective posturographic test as an indicator of the early stages of mental fatigue. The results revealed that, when the eyes were closed, WPL increased significantly both before and after a period of 24 h sustained wakefulness compared with WPL when the eyes were open. After 24 h of sustained wakefulness (sleep deprivation), the WPL was lower (although this was not statistically significant), compared with before sustained wakefulness in both the eyes-closed and eyes-open conditions, indicating that COP displacement is decreased and displacement speed is reduced after sleep deprivation. In contrast, compared with before sustained wakefulness,
CA and RA were significantly increased after sleep deprivation in tests with the eyes closed, indicating that the scope of COP movement in the force plate surface changes greatly, and that postural control without sensory integration of visual input is decreased after sleep deprivation. As the UAPL is affected by WPL and CA indices, changes in either of these will also alter UAPL. The results showed that UAPL was decreased (although this was not statistically significant) by sleep deprivation in tests with open or closed eyes compared with before sustained wakefulness, which corresponds to the decrease seen in WPL and the increase seen in CA.

The changes in WPL after sleep deprivation in the present study were not consistent with the results of an earlier study by Fabbri et al. In general, their results showed that postural sway (statokinesigram length) increased after a sleepless night, performing the recording with eyes open and eyes closed. Static posturography in their study was, however, tested at 22:00 h and 08:00 h, neglecting the influence of circadian rhythms on functional state, sleepiness and fatigue, as well as on postural control. Circadian rhythms are biological clocks and normally cover a period of about 24 h. Balance exhibits a circadian rhythm: it has a nadir in the early morning (06:00 h – 07:00 h) and again in the afternoon (13:00 h – 16:00 h). The pattern is consistent with that of circadian sleepiness, i.e. balance correlates with physiological, manifested and perceived sleepiness. Disruption to circadian rhythms can upset physiological factors, such as motor activity, body temperature, sleep, wakefulness, hormonal secretions, blood pressure, and work performance and should, therefore, be an important consideration in the study of postural sway and the measurement of fatigue. To avoid any confounding effects of circadian rhythm in the present study, postural sway, subjective fatigue assessment and psychomotor performance were measured at the same time before and after 24 h of sustained wakefulness.

Compared with when eyes were open, postural sway parameters (WPL, CA, RA, SDx) with the eyes closed increased significantly both before and after a period of 24 h sustained wakefulness ($P < 0.05$ or $P < 0.01$), indicating that vision plays an important role in the balance control system. Balance control is greatly weakened by a lack of visual clues, which is consistent with the results of an earlier study on the influence of vision on balance control of the human body. Moreover, no obvious differences were found in Romberg's index before versus after sleep deprivation, suggesting that postural sway parameters with eyes open or closed exhibit consistent changes with those after sleep deprivation, and visual input still integrates the postural control system after sleep deprivation.

Mean displacement of COP on the lateral axis ($M_x$) and on the anterior–posterior axis ($M_y$), which represent general sway in the lateral and anterior–posterior directions, respectively, cannot reflect elaborate changes of COP in these directions, SDx and SDy. Mean displacement of COP on Mx and My can, however, can reflect variability of COP movement around the mean COP position in the lateral and anterior–posterior directions, respectively. Compared with related indexes such as WPL, CA, RA and UAPL, SDx and SDy are more stable and provide better indicators of mental fatigue. After 24 h sustained wakefulness, SDy in the eyes-open condition was significantly increased compared with before sustained wakefulness and SDy in the eyes-closed condition was slightly increased (not statistically significant), which is consistent
with the changes in CA and RA, and indicates attenuation in postural control when the body equilibrium becomes upset after sleep deprivation.

The subjective scores of feeling fatigued that were obtained after sleep deprivation in the present study were significantly higher than those recorded at the beginning of the 24 h period of sustained wakefulness ($P < 0.01$). The result confirmed the occurrence of mental fatigue after sleep deprivation, although such a subjective evaluation does not fully reflect the objective, physiological status of a tired person. There was, however, no significant difference in psychomotor performance (complex response time, number of correct responses and RMS of tracking error), assessed by the Sternberg dual-task test before and after the 24-h period of sustained wakefulness. An explanation for this finding may be the presence of an ‘end spurt effect’. The authors propose that participants were aware in the later stages of the deprivation period that only a few hours separated them from the end of the experiment and it is postulated that this awareness might have facilitated motivation, positive mood and an increase in expenditure of effort until the end of the experiment when they could go to sleep.27 The combination of the subjective scores of feeling fatigued together with the objective psychomotor performance tests in this study probably indicated that subjects were in the early stages of mental fatigue state after 24 h of sustained wakefulness.

The results from the present study imply that the contributions of somatosensory, visual and vestibular information for postural control are altered following sleep deprivation. This investigation cannot, however, conclude which part of the postural system becomes affected and any attempt to explain the mechanism behind the observed change in postural control would be conjecture. Since the visual system and vestibular–cerebellar part of the balance system play a central role in the total regulation of postural control, one may speculate that these systems could be the main sites of disturbance following sleep deprivation. Studies in larger samples with physiological measurements, such as electromyography and electroencephalography, may provide further insight into the effect of sleep deprivation on postural control.

In conclusion, the present study showed that one night of sleep deprivation can arouse a feeling of fatigue and might affect postural stability. Fatigue caused by sleep deprivation can be objectively assessed by a short, non-invasive, postural sway test. Posturography has potential for the detection of mental fatigue. The technique is, therefore, worthy of further investigation and development.

**Conflicts of interest**
The authors had no conflicts of interest to declare in relation to this article.

- Received for publication 18 April 2009 • Accepted subject to revision 29 April 2009
- Revised accepted 6 September 2009

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