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Regular Article

Brief posturographic test as an indicator of fatigue

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Abstract The purpose of the present paper was to analyze the efficiency of an abbreviated, albeit objective posturographic test as an indicator of fatigue. Posturography was measured in 10 healthy adults (age 18–33 years, male/female 7/3). Baseline posturographic measurements were taken for each subject. Later, a shorter (3-min) posturographic test was administered 12 times during 25 h of sleep deprivation. This was correlated with subjective assessment of fatigue using a questionnaire and cognitive performance assessed with a reaction time test (Psychomotor Vigilance Test). Although showing significant individual differences, the score of the abbreviated posturographic examination, normalized to each subject's baseline performance ('fatigue index') had a pronounced circadian pattern with a peak of instability in the early morning hours. Fatigue index was highly correlated with the cognitive test ($r = 0.80$–0.90). A substantial, albeit weaker correlation was found between the fatigue index and the subjective fatigue scores ($r = 0.59$–0.75). Fourier spectral analysis showed that low median sway (0.10–0.50 Hz), considered to be an expression of vestibular control, was most affected by fatigue. The study demonstrates that cognitive deterioration caused by fatigue can be objectively predicted by an abbreviated postural test of ≤3 min. This test is promising to be valid, reliable, and practicable, while being significantly correlated with physiological markers and validated cognitive measures of fatigue obtained by substantially more time-consuming and less convenient methods.

Key words fatigue, performance, posturography, sleep deprivation, vigilance.

INTRODUCTION

In contemporary technological society, fatigue has become a problem of central importance in occupational activities requiring vigilance and attention over an extended stretch of time, often involving late evening and night shifts. It is considered to be one of the main causes of work accidents, as well as air and surface traffic accidents.[1–7]

Although levels of fatigue can be subjectively assessed, it was shown that such an evaluation does not reflect the objective, physiological status of the tired person, mainly because subjective reports are biased by motivation, personal factors, experience, training etc. Hence it is obvious that fatigue must be measured with objective methods. There are several autonomic parameters that are influenced by fatigue. Such methods have been used, such as electrocardiogram (ECG), electroencephalogram (EEG),[8,9] rectal temperature,[10,11] blood pressure[8] etc. However, none of these assessment methods has gained popular use. This is due to several drawbacks such as inconvenience of use, difficulties in interpretation of data, impractical use in field settings and other causes that eventually made all these methods non-cost-effective. In light of this, there is an urgent need to find practicable, non-invasive, but reliable tools to measure fatigue, and especially the critical levels involving high risk for accidents.

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 avenue of approach to the problem. Several studies, done by our group and by others have shown that postural control is influenced by changes in vigilance.[7,9,12,13]

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The objective of the present study was to validate a short posturographic examination, using the Tetrax Interactive Balance System, described here, to predict fatigue in healthy subjects. In light of this purpose the following hypothesis were tested: (i) the posturographic measures will be sensitive to circadian changes; (ii) the method will detect individual differences in the circadian pattern of fatigue; (iii) the posturographic scores will correlate with external criteria of fatigue (i.e. with results of cognitive tests known to be influenced by fatigue; with physiological markers of fatigue; and with subjective assessment of fatigue); (iv) the posturographic parameters will be reveal differences in the susceptibility of the visual, vestibular and somatosensory postural subsystems to the impact of fatigue; and (v) positions assumed by the subjects that involve greater postural stress will be more sensitive to fatigue.

METHODS

Instruments

Postural control was measured using the Tetrax Interactive Balance System (Tetrax, Ramat Gan, and Sunlight Medical, Tel-Aviv, Israel). This method of posturography is based on the assessment of the vertical pressure fluctuations on four independent force plates, each placed beneath the two heels and toe parts of the subject while standing in an upright position. The software of the system elaborates four basic parameters, obtained by standing in eight positions. The parameters are as follows.

(1) Stability, which is an indicator of the amount of sway. It is calculated as the square root of the sum of the squared differences between adjacent pressure fluctuation signals, sampled at a rate of 32 Hz. The higher the score, the greater the sway and instability.

(2) Weight distribution, which is calculated by the percentage of weight put on each of the four platforms.

(3) Synchronizations, which are mathematical expressions of the interactions between paired traces obtained by comparing the six possible combinations of the four outputs, that is, heel and toe of each foot (2), the two heels (1), the two toes (1) and the diagonals (2; heel and contralateral toe part). Synchronizations reflect the quality and efficiency of coordination movements of the agonist and antagonist muscle system of the lower extremities.

(4) Intensity of sway, which is measured by Fourier transformation across a spectrum of sway frequencies ranging from 0.01 to 3.00 Hz. This spectrum is broken down into four frequency bands designated as low (0.01–0.1 Hz), medium-low (0.1–0.5 Hz), medium-high (0.5–1.00 Hz) and high (1.00–3.00 Hz). As shown in previous studies, the power of the low frequencies is linked with visual control, the medium-low frequency band is sensitive to vestibular stress and disturbances, the medium-high frequencies reflect somatosensory input from the lower extremities, while bursts of high frequencies are signs of postural tremor caused by muscular stress or central nervous dysfunctions.[14–17]

The standard examination protocol includes standing for 32 s in each of the eight positions as follows: (i) head straight, eyes open, support solid; (ii) head straight, eyes closed, support solid; (iii) head straight, eyes open, support soft (foam rubber); (iv) head straight, eyes closed, support soft; (v) head turned to the right, eyes closed support solid; (vi) head turned to the left, eyes closed support solid; (vii) head up, eyes closed, support solid; and (viii) head down, eyes closed, support solid.

For a more comprehensive and detailed description of the Tetrax System see 13,18,19.

Cognitive performance was measured by the Psychomotor Vigilance Test (PVT, Ambulatory Monitoring, NY, USA). This is a widely used device that assesses cognitive performance during fatigue.[20] It consists of a battery-operated set of pressure buttons mounted on a box held in the hands of the subject. The machine emits successive auditory and/or visual signal at random intervals. Subjects are asked to respond to the signal as quickly as possible by pressing a button with their dominant hand during 10 min. The device measures speed of response, speed of average response and the number of times the subject responded later than 500 ms ('lapses'). For statistical analysis we used the median response time and the number of lapses in each session.

Subjective assessment of fatigue was done using the Stanford Sleepiness Scale (SSS) questionnaire. In this questionnaire, which was validated for its sensitivity to fatigue,[21] subjects rank their feeling of vigilance according to a scale of seven statements describing raising levels of fatigue.

Sample

Ten subjects (three female, seven male) aged 16–33 participated in the study. All were healthy and did not take any medication, as verified by medical check up. Additional exclusion criteria were postural problems, minor orthopedic abnormalities and suspected sleep disorders, as assessed by a special questionnaire.[22] As result of this criteria four subjects were excluded from the original sample of 14. Subjects were also instructed not to drink alcohol or drinks containing caffeine on the morning prior to and during the experiment.

Procedure and protocol

In order to control individual differences in postural control, the experiment was conducted in two stages. During stage 1 a baseline of static balance ability was assessed by administering the full Tetrax protocol described here. This was done four times on different days. Later, during the fatigue experiment, a shortened modified protocol was used. This consisted of three positions, each sustained for 48 s: (i) head straight, eyes open, support solid; (ii) head straight, eyes closed, support solid; and (iii) eyes open, head down, on soft support and platforms tilted 10° toes up. The third position was specially designed for the study, aimed at creating maximal stress on the postural system.

At stage 2, that is, on the day of the experiment, approximately 2–4 days after the baseline session, subjects arrived in the morning, again after a normal, full night's sleep and were required to stay awake for 25 h. Starting at 9 am and terminating at 10 am the next day, they were given the battery of the three tests, that is, the short version of the Tetrax test, the PVT test and the Fatigue Questionnaire 12 times, according to a circadian schedule shown in Tables 1–3.

Statistical analysis'

The postural measure of fatigue was defined as the fatigue index, which was the calculated ratio between

Table 1. Fatigue index during 25 h of sleep deprivation: Position 1 (head straight, eyes open, support solid)

	Subject									
Time	1	2	3	4	5	6	7	8	9	10
09:00	102	102	115	**127**	119	82	96	92	82	105
13:00	87	92	**131**	102	**121**	100	99	101	117	**135**
15:00	74	**130**	92	113	93	**127**	79	98	112	114
18:00	93	109	115	93	85	104	79	86	112	**123**
21:00	102	**120**	**128**	107	85	119	79	98	102	102
23:00	84	98	**161**	87	110	97	88	**129**	**122**	105
01:00	**121**	87	110	**120**	119	**134**	70	**142**	92	105
03:00	**121**	76	**147**	**127**	**127**	**142**	79	111	102	105
05:00	112	87	**193**	113	76	**127**	88	**135**	**214**	**149**
07:00	**140**	87	**211**	**120**	**254**	**134**	79	**148**	**235**	**342**
09:00	**130**	87	**124**	113	**136**	**127**	70	117	112	**281**
10:00	84	119	115	107	119	119	70	**123**	**153**	**123**

Bold, values above the median of 120 (20% above the baseline of 100) estimated to be indicators of fatigue.

Table 2. Fatigue index during 25 h of sleep deprivation: Position 2 (head straight, eyes closed, support solid)

	Subject									
Time	1	2	3	4	5	6	7	8	9	10
09:00	102	109	109	**131**	119	**122**	90	103	62	115
13:00	94	77	**137**	97	109	83	75	106	78	**128**
15:00	86	91	119	119	104	**128**	103	108	96	101
18:00	86	100	100	**131**	112	**140**	77	87	75	115
21:00	109	**127**	**200**	102	90	110	64	118	116	88
23:00	78	82	110	108	97	116	83	97	96	101
01:00	102	64	**126**	108	97	116	71	118	82	81
03:00	117	73	**219**	108	97	116	64	**133**	89	**149**
05:00	86	**125**	**215**	**125**	75	**134**	77	**138**	**192**	101
07:00	**188**	82	**207**	**125**	**231**	**134**	83	**144**	**199**	**284**
09:00	**149**	73	**159**	**153**	**149**	**165**	83	108	82	**230**
10:00	102	73	148	97	82	104	71	113	68	142

Bold, values above the median of 120 (20% above the baseline of 100) estimated to be indicators of fatigue.

Table 3. Fatigue index during 25 h of sleep deprivation: Eyes open, head down, on soft support and platforms tilted 10° toes up

	Subject									
Time	1	2	3	4	5	6	7	8	9	10
09:00	**129**	**120**	100	**137**	107	118	**135**	88	**121**	**144**
13:00	99	82	110	114	115	118	99	94	110	80
15:00	**147**	110	110	115	89	113	108	88	114	78
18:00	112	107	**122**	**126**	**131**	**124**	**122**	88	**121**	**122**
21:00	**121**	115	**178**	**132**	**143**	**129**	101	94	86	111
23:00	112	98	99	99	95	97	115	114	**121**	94
01:00	**164**	82	**174**	**148**	**143**	**145**	115	**130**	114	94
03:00	**138**	90	**174**	99	**185**	97	95	**187**	**121**	94
05:00	**147**	**147**	**197**	**154**	77	**151**	**1**115	**125**	**193**	94
07:00	**147**	74	**155**	**165**	**244**	**161**	88	**156**	**200**	**244**
09:00	**129**	**129**	83	**154**	107	**151**	88	99	**157**	**194**
10:00	86	90	**155**	**121**	83	118	81	119	107	106

Bold, values above the median of 120 (20% above the baseline of 100) estimated to be indicators of fatigue.

the postural scores obtained during the 25-h study and the average of the four baseline trials obtained at the first stage of the experiment. Tentatively a fatigue index of 120 (i.e. a ratio of ≥1.2) was considered to be a sign of fatigue. This score was the median value of the distribution of the 120 scores of 10 subjects on the 12 experimental tests, indicating a 20% decrease of postural fitness in comparison to the base line. In the context of this pilot investigation the fatigue index was elaborated solely for the parameters of stability and Fourier intensities (latter not tabulated), because previous studies had shown that the parameters of synchronization and weight distribution, described in detail here, are sensitive to circadian changes only when administering all the eight positions of the complete Tetrax protocol.[12,13] Hence, these parameters were not included in the elaboration of the fatigue index based on the abbreviated version of the Tetrax testing procedure.

Individual differences and positions on the postural fatigue index were the assessed using a general, linear model of three-way ANOVA for repeated measurements. Effects of circadian time, and the circadian performance on each of the three instruments (Tetrax, PVT, Questionnaire) were compared by computing Spearman rank correlations.

Table 4. Three-way ANOVA showing the effects of circadian rhythm, individual differences and positions on fatigue index

Source	d.f.	F	*P*
Time	11	12.53	<0.001
Subjects	9	9.93	<0.001
Position	2	2.78	0.064
Time × Position × Subject	30	0.79	NS

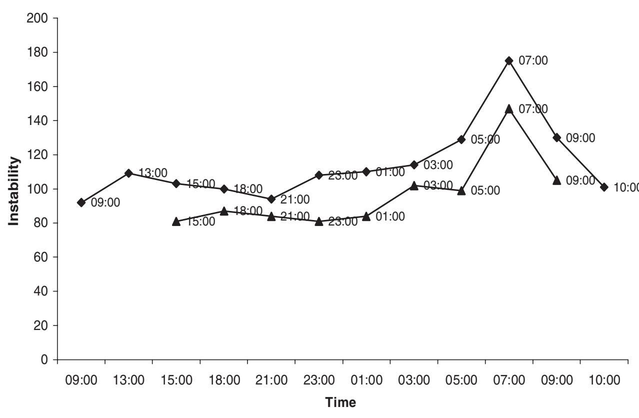

Figure 1. Comparison of circadian patterns in stability (position 1) in the (◆) present study and the (▲) Nakano *et al.* study.[23]

RESULTS

As presented in Tables 1–3 and Fig. 1 the fatigue index of postural stability on the three experimental positions shows a circadian pattern with a consistent elevation after midnight and a definitive peak towards 5–7 am. As shown in Table 4, the effect of time is highly significant ($P < 0.001$). In turn, the effect of individual differences is also considerably significant, which is visible on closer inspection of Tables 1–3 and Table 5. Subject 7 was remarkably alert during the whole experimental period, while subject 2 becomes only mildly tired and exclusively on the stressful position 3. Sub-

Table 5. Effect of circadian rhythm and position on individual subjects

Subject	1	2	3	4	5	6	7	8	9	10
Time	0.003	0.01	0.001	0.02	0.000	0.05	0.12	0.001	0.000	0.000
Position	0.008	NS	NS	0.01	NS	NS	0.000	NS	0.006	0.056

Table 6. Correlation coefficient (r)

	PVT Median	PVT Lapses	Questionnaire
Position 1			
Fatigue index	0.85	0.87	0.63
PVT Median		0.97	0.74
PVT Lapses			0.75
Position 2			
Fatigue index	0.79	0.82	0.59
PVT Median		0.97	0.74
PVT Lapses			0.75
Position 3			
Fatigue index	0.67	0.65	0.76
PVT Median		0.97	0.74
PVT Lapses			0.75

PVT, Psychomotor Vigilance Test.

Table 7. Effect of circadian time on different frequency ranges of postural sway

Frequency range	Hz	F	*P*
Low	0.01–0.2	0.24	**NS**
Low-medium	**0.2–0.5**	**4.34**	**0.002**
High-medium	0.5–1.0	3.77	0.05
High	1.0–3.0	2.05	0.05

The low-medium range of the Furrier frequency appears to be most influenced by circadian changes (bold).

jects 5 and 10 appear to resist fatigue throughout the night, but break down abruptly at 7 am. The alertness of the remaining examinees weakens after 1 am and seems to shape the circadian pattern of the sample. The effect of postural position is only marginal ($P = 0.065$) and the comparison of Tables 1–3 does not reveal any dramatic raise of the fatigue index on the stressful third position in comparison with simple standing with open eyes on solid surface (position 1).

Effects of time, but not of individual differences, were similar for the PVT and the Questionnaire (data not tabulated).

As evident in Table 6 the fatigue index has a conspicuously high correlation with the PVT measurements, while correlating still significantly but to a lesser degree with the Questionnaire.

Calculating time effects for discrete Fourier frequency ranges revealed that the medium-low range of 0.1–0.5 Hz, appears to be the most intensively affected by circadian change ($P = 0.002$, Table 7).

DISCUSSION

The results of the present study are supported by the results of several previous studies. In a study done by Nakano *et al*. postural sway (standing on solid surface, with eyes open and closed, respectively), and rectal temperature were measured in eight subjects kept awake during 19 h.[23] In addition, ECG, and EEG were monitored. Every hour subjects were required to assess their level of fatigue. It was found that fatigue correlated positively with the intensity of sway, which reached its peak when rectal temperature was minimal, that is, between 6 and 7 am. Plotting the circadian pattern of our fatigue index against the results of the Nakano *et al*. study (Fig. 1), shows a striking, almost complete overlap, cross-validating the findings of the present study. The validity of the fatigue index is further indirectly supported by another finding of the Japanese investigation, which demonstrates the parallel circadian pattern of postural stability and rectal temperature.[23]

In anther study the performance of seven technical employees of the aviation industry on a flight simulator was compared to postural response assessed by the Tetrax Interactive Balance System. Subjects were not allowed to sleep for 36 consecutive hours and were tested every 2 h with both devices. Results showed that circadian changes in postural parameters of weight distribution and high-frequency sway overlapped almost exactly with the performance pattern on the flight simulator, showing a typical 12-h rhythm.[12] In another study eight young medical doctors were given posturographic tests before and after work on morning, afternoon and night shifts, respectively, in the emergency room of a large medical center in Tel Aviv.[13] Results revealed deterioration of postural stability on the test given at 7 am, following the night shift, as well as a clear-cut circadian pattern of fatigue.

It can be argued that the deterioration in postural measurements described in the present study and previous investigations was due not to fatigue but to sleep deprivation. Although it is well-established that sleep deprivation per se can cause deterioration in cognitive performance,[24–27] which is our main concern in the clinical setting, the latter study proved that postural indices are also influenced by fatigue, which is not sleep deprivation related. In the present study postural indices deteriorated not only after 24 h of sleep deprivation, but also after 8 h of regular shift work from 7 am to 3 pm.[13]

The findings of the present study fully support the hypotheses made, that is, a brief postural measure of postural control, normalized for individual differences (i) objectively predicts fatigue; (ii) reveals individual differences in circadian fatigue patterns; and (iii) significantly correlates directly with validated behavioral tests of fatigue and indirectly with a physiological marker of the latter, that is, body temperature.

Calculating time effects for discrete Fourier frequency ranges revealed that the medium-low range of 0.1–0.5 Hz, appears to be the most intensively affected by circadian change ($P = 0.002$, Table 7). According to current posturographic literature, this frequency range has been shown to be linked with the vestibular mechanisms of postural control.[14–17] Hence the results seem to indicate that the vestibular system, relative to the visual and somatosensory functions, is more vulnerable to the impact of fatigue. This validates our fourth hypothesis.

One of our hypotheses, however, was not confirmed: we did not find a more pronounced effect of deterioration in postural control in the third, more stressful position. This latter negative finding might be of pragmatic significance in that screening tests that are designed to assess fatigue must not be necessarily complex, stressful or unfriendly to the examinee.

In conclusion, the present study has demonstrated that the deterioration in cognitive function caused by fatigue could be predicted by a short posturographic test. Although the present results, cross-validated by the Nakano *et al*. study, appear to be satisfactory, further research is needed to verify them on a larger scale. Also from the practical point of view, reliable cut-off points of the fatigue index must be established, predicating a high risk of failure to function which, eventually, may lead to accidents. This again requires systematic exploration on extensive, well-selected, samples

If further validated, the application of this short posturographic test as an indicator of fatigue might be found to be of considerable practical value, when applied in clinics and laboratories in the field of pharmacology (assessing decrease of vigilance due to side-effect of drugs), industrial medicine (screening workers before manipulating dangerous equipment or mounting on elevated platforms), aviation medicine (testing pilots before take off) etc. The importance of these applications in the context of public heath service needs is obvious.

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