Postural Stability Change Under Sleep Deprivation and Mental Fatigue Status

Shan Cheng; Jinghua Yang; Miao Su; Jicheng Sun; Kaiwen Xiong; Jin Ma; Wendong Hu

BACKGROUND: Based on posturography parameters during sleep deprivation (SD), a mental fatigue index (MFI) was constructed for healthy male cadets.

METHODS: There were 37 young male subjects who volunteered for two successive days of SD. Their posturography balance, profile of mood status (POMS), and heart rate variability (HRV) were measured at four different times (10:00 and 22:00 of day 1, 10:00 and 22:00 of day 2). According to the methods used in our previous research, similar MFIs based on posturography parameters were computed. Then, correlations of MFIs with POMS scores and HRV values were evaluated by linear and nonlinear methods including quadratic, S-curve, growth, and exponential analyses.

RESULTS: MFI continued to increase during SD and MFI as the independent variable had quadratic relationships with fluster (R^2= 0.057), depression (R^2= 0.067), and anger (R^2= 0.05) scores of POMS. A linear correlation was found between MFI and the depression score (R^2= 0.045) and MFI correlated linearly (R^2= 0.029) and nonlinearly (R^2= 0.03) with heart rate. Similarly, MFI reflected changes in the time and frequency domain parameters of HRV, with linear (R^2range: 0.029–0.082) or nonlinear (R^2range: 0.030–0.082) relationships.

DISCUSSION: The increase of MFI was linked with amplification of personal negative moods and an imbalance of autonomic nervous system activity. The findings suggest that MFI might be a potential indicator of mental fatigue and provide a method to prevent driving fatigue and human errors.

KEYWORDS: postural control, sleep deprivation, curve estimation, heart rate variability, mood status.

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Military flight tasks with complicated human-machine interactions produce a mental load on pilots, with insufficient sleep being an important risk factor for pilot fatigue,[27] which clearly decreases their flight ability.[14] Sleep deprivation (SD) is well known to have negative effects on cognitive, neurobehavioral, and physiological functions. During SD, heart rate decreases, while the power of heart rate variability (HRV) increases significantly at different frequencies,[26] which suggests that the autonomic balance of sympathetic and parasympathetic tone is disturbed.[20] SD further impairs stimulus detection of visual processing,[23] working memory ability,[10] and reaction time,[5] which can result in a decrease of task performance.[12]

It has been reported that normal postural control is mainly maintained by vestibular, visual, and proprioceptive functions.[8] After the signals are processed by the central nervous system, upright posture is controlled and modulated in a timely manner.[17] SD impairs the ability to adapt sensorimotor coupling between visual information and body sway in young adults' postural control when a perturbation occurs.[1] Though the body sway of young adults increases significantly during SD, whether in the eyes open or closed state,[19] studies have reported that postural performance was significantly reduced

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after 24 h SD, but interestingly to a lesser extent after 36 h.[22] These results were noted in the study of Gomez et al., in which postural performance did not continue to deteriorate between 24 and 36 h of SD.[15] The high accuracy and positive predictive value of posturography parameters suggested further research was necessary to develop posturographic sleepiness monitoring,[12,13,16] and significant correlations were found between postural parameters and subjective feeling scales.[21] Avni et al. reported that the scores of posturography examinations were highly correlated with cognitive tests and subjective fatigue scores in sleep deprived healthy adults.[3] In our previous research, a mental fatigue index was computed based on postural parameters sensitive to SD measured on subjects with their eyes closed,[6] and this index was linked with HRV.[7] In the current study, an eyes open condition was adopted to explore the relationships of the postural performance derived mental fatigue index (MFI), which was evaluated during SD and with Profile of Mood States (POMS) scores as well as heart functions.

METHODS

Subjects

This study is a follow-up part of our previous research,[6,7] thus the subjects were the same. There were 37 male cadets who were involved, with ages 23.3 ± 2.0 yr, a mean height of 1.74 ± 0.05 m, and bodyweight 64.87 ± 11.11 kg. All subjects were free of known muscle injuries, vestibular dysfunction, or other diseases that could have affected postural control in the last 3 mo, evaluated by a self-reported questionnaire. The subjects were familiar with the experimental procedures and provided written informed consent. The study was supported by the Ethics Committee of Beijing Military Region General Hospital and conformed to the declaration of Helsinki.

Procedures

All subjects were enrolled 12 d before the SD period, during which they agreed to sleep at least 6 h per night, get up at 06:00 in the morning, and refrain from consuming any medications, stimulants, caffeine, or alcohol during the entire 2-wk enrollment period. On day 13, the fatigue states were induced by 40 h SD over 2 successive days from 06:00 on the first day (Day 1) to 22:00 on the second day (Day 2). Before 08:00 on Day 1, cadets arrived at the laboratory in Beijing Military Region General Hospital. During SD, subjects' posturography balance, POMS, and HRV were measured four times at 10:00 of Day 1, 22:00 of Day 1, 10:00 of Day 2, and 22:00 of Day 2.

As previously described,[2,19] the EAB-100 Balancer (Sakai Medical, Tokyo, Japan) and Tetrax (Sunlight Medical, Tel Aviv, Israel) force-platform systems were used to assess postural stability. Based on our previous research, normal standing on the force platform with eyes open (NEO) was more sensitive to SD than the other two upright postures, comprising standing on solid or foam-padded platforms with eyes closed.[6] Therefore, in the present study a NEO condition was adopted to measure postural control. The posturographic parameters used included body sway intensity on eight band frequencies, including F1 (0.01–0.1 Hz), F2 (0.1–0.25 Hz), F3 (0.25–0.35 Hz), F4 (0.35–0.5 Hz), F5 (0.5–0.75 Hz), F6 (0.75–1.0 Hz), F7 (1.0–3.0 Hz), and F8 (3.0 Hz) and center of body pressure.[2,19]

Based on previous research, the mood states of sleep-deprived subjects in this study were assessed by POMS,[24] while HRV parameters related to mental fatigue were measured using an analyzer (SA-3000P; Medicore, Sungnam-Si, South Korea) based on the pulse beat in the middle finger, including heart rate (HR), standard deviation of normal to normal beats (SDNN), square root of the mean differences of successive NN intervals (RMSSD), total power of the HRV spectrum, very low frequency power of the HRV spectrum (VLF), low frequency power of the HRV spectrum (LF), high-frequency power of the HRV spectrum (HF), and LF/HF.[7]

Statistical Analysis

The statistical analysis was performed using SPSS version 16.0 (IBM, Armonk, NY, USA). According to the algorithm of balance score that was constructed in our previous research,[6] the MFI of sleep-deprived subjects at different times could be computed. Next, repeated measures analysis of variance was used to compare the changes in the MFI during SD. Then potential correlations of MFI as an independent variable with mental fatigue related indicators such as POMS and HRV were analyzed by curve estimation using regression analysis. The linear, quadratic, and exponential, as well as S-curve and growth-curve relationships, are presented as the magnitude of statistical probability (F) and degrees of freedom (df) for intersubject and intrasubject comparisons. A P-value < 0.05 was considered to be a statistically significant difference.

RESULTS

During SD, the mean MFI of the subjects continued to increase [$F(3,34) = 13.745$, $P < 0.001$], and the linear trend of the change was obvious [$F(1,36) = 13.436$, $P = 0.001$] (**Fig. 1**). There were similar circadian MFI changes during the SD period with increasing MFI values from the morning at 10:00 to the evening on both days at 22:00 [$F(1,36) = 22.056$, $P < 0.001$] (**Fig. 2**). However, though there was a circadian fluctuation of MFI on day 1, SD led to constantly higher degrees of mental fatigue, which were particularly reflected in circadian MFI changes without significant difference on Day 2. **Table I** shows that the MFI as the independent variable had a quadratic relationship with the fluster (r = 0.239, $P = 0.028$) and anger (r = 0.224, $P = 0.044$) scores of the POMS. Apart from the linear correlation found between the MFI and depression score (r = 0.212, $P = 0.018$), there was also a quadratic relationship (r = 0.259, $P = 0.016$).

During SD, MFI correlated linearly with HR (r = −0.170, $P = 0.040$) and a nonlinear correlation was also found between them such as growth (r = −0.173, $P = 0.036$). There were also linear and nonlinear (quadratic, S, growth, and exponential) relationships between the MFI and the SDNN and RMSSD of

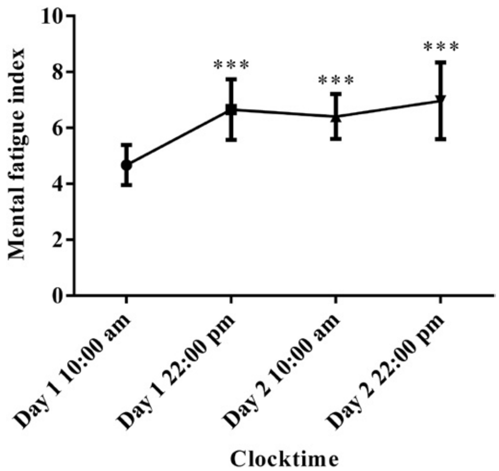

Fig. 1. Linear trend of subjects' MFI during sleep deprivation. Compared with basic data (10:00 a.m. of Day 1), ****P* < 0.001. Error bars represent the 95% confidence interval (CI).

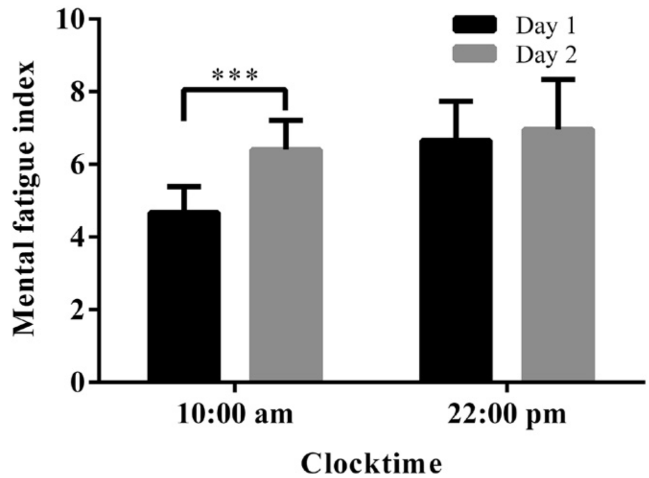

Fig. 2. Circadian MFI changes. ****P* < 0.001. Error bars represent the 95% confidence interval (CI).

the HRV (**Table II**). **Table III** shows that with an increase of MFI during SD, the total power of HRV also increased linearly (r = 0.255, *P* = 0.002) and nonlinearly (quadratic; r = 0.259, *P* = 0.008). Thus, MFI could reflect the changes of VLF, LF, and LF/HF linearly or nonlinearly. Regardless of the correlations of MFI with mood status and HRV which were linear or nonlinear, the change trends suggested that the negative feeling and HRV of subjects increased, while HR decreased as the MFI increased.

DISCUSSION

The findings demonstrated that the MFI increased during SD, which showed the feasibility of using the mental fatigue assessment model based on postural control parameters. Our previous research had demonstrated that body sway with eyes open continued to increase during SD, while this change of postural balance was not obvious when the eyes were closed. Based on the postural parameters that changed significantly in the NEO condition, a mental fatigue assessment model was constructed by using principal component analysis.[6] The analysis suggested that the score of this model (MFI) should increase with continuing SD, with the current results favoring this hypothesis. According to the data of Forsman et al., the new balance score, which was quantified using principal component analysis from different features of computerized posturography, was more sensitive to the small sleepiness-related balance decrements during SD.[11] Therefore, the MFI measured during our study may well be a sensitive parameter providing an early warning of mental fatigue.

Table I. Curve Estimation of MFI with Subscale Scores of POMS (*N* = 124).

		MODEL SUMMARY				PARAMETER ESTIMATES		
SUBSCALES & EQUATIONS	R^2	*F*	DF1	DF2	*P*	CONSTANT	B1	B2
Fluster								
Linear	0.001	0.099	1	122	0.754	3.400	−0.030	
Quadratic	0.057	3.677	2	121	0.028	−0.190	1.401	−0.122
S	0.004	0.503	1	122	0.479	1.013	−0.418	
Growth	0.002	0.251	1	122	0.617	1.006	−0.015	
Exponential	0.002	0.251	1	122	0.617	2.734	−0.015	
Depression								
Linear	0.045	5.744	1	122	0.018	1.384	0.255	
Quadratic	0.067	4.313	2	121	0.016	−1.170	1.273	−0.087
S	0.042	5.322	1	122	0.023	0.998	−1.474	
Growth	0.032	4.080	1	122	0.046	0.313	0.066	
Exponential	0.032	4.080	1	122	0.046	1.368	0.066	
Anger								
Linear	0.024	2.999	1	122	0.086	1.268	0.198	
Quadratic	0.050	3.213	2	121	0.044	−1.734	1.394	−0.102
S	0.029	3.688	1	122	0.057	0.715	−1.221	
Growth	0.017	2.104	1	122	0.150	0.190	0.047	
Exponential	0.017	2.104	1	122	0.150	1.209	0.047	

MFI, mental fatigue index; POMS, Profile of Mood States.

MFI was taken as the independent variable. During sleep deprivation, six subjects missed some items of the POMS as a result of low arousal level, and the data were therefore excluded or null.

Table II. Curve Estimation of MFI with Time-Domain Parameters of HRV (N = 147).

		MODEL SUMMARY				PARAMETER ESTIMATES		
INDICES & EQUATIONS	R^2	*F*	DF1	DF2	*P*	CONSTANT	B1	B2
HR								
Linear	0.029	4.291	1	145	0.040	73.239	−0.751	
Quadratic	0.033	2.439	2	144	0.091	69.165	0.858	−0.137
S	0.016	2.391	1	145	0.124	4.190	0.160	
Growth	0.030	4.460	1	145	0.036	4.286	−0.011	
Exponential	0.030	4.460	1	145	0.036	72.697	−0.011	
SDNN								
Linear	0.082	12.978	1	145	< 0.001	41.564	2.499	
Quadratic	0.082	6.460	2	144	0.002	39.833	3.183	−0.058
S	0.059	9.039	1	145	0.003	4.121	−0.735	
Growth	0.081	12.803	1	145	< 0.001	3.717	0.044	
Exponential	0.081	12.803	1	145	< 0.001	41.139	0.044	
RMSSD								
Linear	0.043	6.483	1	145	0.012	33.343	1.667	
Quadratic	0.043	3.272	2	144	0.041	36.370	0.471	0.102
S	0.022	3.294	1	145	0.072	3.792	−0.527	
Growth	0.039	5.936	1	145	0.016	3.478	0.035	
Exponential	0.039	5.936	1	145	0.016	32.398	0.035	

HR, heart rate; HRV, heart rate variability; MFI, mental fatigue index; RMSSD, square root of the mean differences of successive NN intervals; SDNN, standard deviation of normal to normal beats.
MFI was taken as the independent variable. During sleep deprivation, one parameter of HRV was wrongly recorded by the machine, and these data were therefore null.

The correlation of MFI with subjective feelings and HRV suggested that the new MFI could detect the mental fatigue status. Scott et al. reported that SD could cause the change of mood status measured by POMS,[24] which showed that the score of subscales in POMS was a good indicator of mental fatigue. The change of HRV mainly controlled by activity of the autonomic nervous system was also an important symptom caused by mental fatigue.[30] It has been noted that HRV increased[28] and was correlated with the sleepiness-related increase in lapses of psychomotor vigilance tasks.[9] Different HRV characteristics can distinguish between rest, physical, and mental condition.[25] A linear correlation of MFI with mental fatigue status was found in our previous research, but the nonlinear correlation between them was not clear.[7] The current

Table III. Curve Estimation of MFI with Frequency-Domain Parameters of HRV (N = 144).

		MODEL SUMMARY				PARAMETER ESTIMATES		
INDICES & EQUATIONS	R^2	*F*	DF1	DF2	*P*	CONSTANT	B1	B2
TP								
Linear	0.065	9.926	1	142	0.002	7.068	0.092	
Quadratic	0.067	5.056	2	141	0.008	6.862	0.174	−0.007
S	0.053	7.963	1	142	0.005	2.068	−0.217	
Growth	0.066	10.089	1	142	0.002	1.951	0.012	
Exponential	0.066	10.089	1	142	0.002	7.038	0.012	
VLF								
Linear	0.062	9.378	1	142	0.003	5.867	0.120	
Quadratic	0.062	4.676	2	141	0.011	5.756	0.164	−0.004
S	0.041	6.029	1	142	0.015	1.930	−0.305	
Growth	0.060	9.075	1	142	0.003	1.758	0.019	
Exponential	0.060	9.075	1	142	0.003	5.802	0.019	
LF								
Linear	0.045	6.743	1	142	0.010	6.087	0.088	
Quadratic	0.046	3.396	2	141	0.036	5.939	0.147	−0.005
S	0.041	6.007	1	142	0.015	1.929	−0.255	
Growth	0.045	6.679	1	142	0.011	1.798	0.014	
Exponential	0.045	6.679	1	142	0.011	6.035	0.014	
LF/HF								
Linear	0.040	5.831	1	141	0.017	1.856	0.165	
Quadratic	0.044	3.189	2	140	0.044	1.118	0.457	−0.025
S	0.047	6.909	1	141	0.010	1.098	−1.387	
Growth	0.030	4.405	1	141	0.038	0.481	0.057	
Exponential	0.030	4.405	1	141	0.038	1.617	0.057	

MFI, mental fatigue index; HRV, heart rate variability; TP, total power of the HRV spectrum; VLF, very low frequency power of the HRV spectrum; LF, low frequency power of the HRV spectrum; LF/HF, low frequency/high frequency ratio.

study mainly focused on nonlinear regression analysis, such as quadratic and exponents. Thus, our results further demonstrated that MFI was a good potential indicator of mental fatigue status.

Our study had a number of limitations. First, the self-controlled study design may produce a correlation coefficient between the MFI and mental fatigue status that was statistically significant, but might not truly reflect the reality that repeated measurements of postural control ability during 40 h of SD might produce learning effects, which may compromise the adverse effects of mental fatigue on postural control. In addition, mental fatigue status is a complex phenomenon and involves many physiological and psychological functions, while posturography balance testing is only one method which might serve as part of multimodal information for assessing fatigue status.[18] Furthermore, though the analysis of test-retest reliability demonstrated an excellent reliability of speed measurements and a moderate reliability of area measurement,[4] Whitney et al. reported that the test-retest reliability of using center of body pressure for the measurement of normalized path length varied from 0.42 to 0.81.[29] Improving the posturographic balance method might further improve the validity of the MFI in assessing mental fatigue status.

In conclusion, SD leads to an increase in the MFI based on postural parameters and the increase in MFI was also related to the amplification of personal negative emotions and imbalance of autonomic nervous system activity. Our results have shown that a change in posture stability can accurately indicate the state of mental fatigue, which should play a pivotal role in providing an early warning of human errors.

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