Posturographic Balance's Validity in Mental and Physical Fatigue Assessment Among Cadet Pilots

Shan Cheng; Jicheng Sun; Jin Ma; Weitao Dang; Mengjun Tang; Duoduo Hui; Lili Zhang; Wendong Hu

BACKGROUND: Postural control is adversely affected by mental and physical fatigue, but its validity in fatigue assessment has not been investigated systemically among pilots. We explored the correlations of posturographic balance with physiological and psychological signals among cadet pilots.

METHODS: In experiment 1, 37 cadet pilots performed a posturographic balance test, heart rate variability (HRV), and profile of mood states (POMS) during 40 h of sleep deprivation. For experiment 2, physiological signals of 60 subjects, including breathing rate (BR), systolic blood pressure (SBP), and heart rate (HR) were measured under the effects of physical fatigue. Then correlations with a mental and physical fatigue index based on effective posturographic parameters with those subjective and objective methods were analyzed by linear regression.

RESULTS: The mental fatigue index correlated linearly with the depression score of the POMS ($r = 0.212$), standard deviation of normal to normal beats ($r = 0.286$), and square root of the mean differences of successive beat intervals ($r = 0.207$). Meanwhile, linear correlations with frequency-domain parameters of HRV such as total power, low frequency power, and high frequency power were also statistically significant. With the increase in the physical fatigue index, physiological signals such as SBP ($r = 0.300$), HR ($r = 0.349$), and BR ($r = 0.266$) increased linearly.

CONCLUSIONS: Impairment of postural stability can reflect the aggravation of mental and physical fatigue among cadet pilots, which provides a potential method for assessing fatigue level before flight tasks and preventing errors by pilots.

KEYWORDS: posturographic balance, mental fatigue, physical fatigue, correlation analysis, human factors.

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Ever increasingly complex human-machine interaction has progressively brought higher mental and physical workload to pilots. And pilots' fatigue status following these loads has become one of the main human factors that may be attributed to the substantial decline in mission performance,[12] and even lead to air accidents.[9] Moreover, though both mental and physical fatigue status contribute to flight fatigue, there are not effective measures to prevent human errors and accidents.

More effective measures should be implemented to assess the fatigue status of pilots. Usually, subjective methods such as fatigue rating scales can be used,[8] but these methods do not objectively reflect the real functional status of tired personnel.[11] In addition, some objective methods are problematic. For example, electroencephalogram and electrocardiogram,[28] though very popular among professionals, may not be easily explained to those who have limited knowledge in the field.[17] A posturographic balance test has been widely used for fatigue assessment by more and more researchers in recent years because of its reliability and effectiveness.[21] This method can measure changes of whole-bodyweight distribution on the feet with pressure sensors, which shows changes in postural stability.[22] This is the basis on which posturographic balance can assess fatigue status.

Postural control is mainly supported by cues from visual, vestibular, and proprioceptive organs,[1] with the motor center processing those cues and modulating the organs for locomotion.[14] Any adverse factors, such as mental and physical fatigue, will affect this pathway, decrease the efficacy of postural control, and change the center of body pressure (COP). For example, mental fatigue induced by sleep deprivation has been reported

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to impair the ability to adapt sensorimotor coupling related to abnormal visual and proprioceptive stimulation, which would reduce the efficiency of postural control.[2] Sway of COP is significantly increased by general physical fatigue caused by physical training, for example, hiking[25] and marathons.[7] Moreover, local fatigue induced by special experimental procedures, such as gastrocnemius muscle exercise,[18] also produced effects on postural stability similar to the above general fatigue.

Previous studies have shown that time-domain[24] and frequency-domain analysis[28] of heart rate variability (HRV) significantly changed under the effects of sleep deprivation; HRV was one of the important predictors of mental fatigue.[4] Additionally, emotional states like depression, anxiety, and anger, measured using the Profile of Mood States (POMS), were adversely affected by mental fatigue due to sleep deprivation.[23] Thus, mood states could also be an indicator of mental fatigue. Muscular exercise could consume much more energy than usual, which would accelerate the flow of body fluids, increase the input of oxygen, and speed up the beating of the heart.[19] Therefore, these physiological parameters, such as heart rate (HR) and breathing rate (BR), would be considered indicators of physical fatigue status.

Although decline in postural stability correlates with sleepiness level[10,17] and task performance,[20] whether posturographic balance correlates with these indicators of mental and physical fatigue states among pilots remains unclear. The purpose of this study was to investigate the relationship between posturographic balance and these fatigue indicators among cadet pilots, to test the validity of the posturographic balance test in fatigue assessment and prevention of human errors among pilots.

METHODS

Subjects

Male cadet pilots, all free of known bone fractures, muscle injuries, vestibular dysfunction, or other diseases affecting upright posture in the 3 mo preceding our study, were recruited from a military aviation academy in Beijing, China. In experiment 1, 37 male cadets (age: 21.3 ± 2.0 yr, height: 1.73 ± 0.04 m, weight: 64.9 ± 1.1 kg, and BMI: $21.4 \pm 3.0\ \mathrm{kg \cdot m^{-2}}$) were recruited. In experiment 2, 60 male cadets (age: 20.5 ± 1.9 yr, height: 1.75 ± 0.04 m, weight: 67.5 ± 6.4 kg, and BMI: $22.0 \pm 2.0\ \mathrm{kg \cdot m^{-2}}$) were randomly divided into two groups (control and pedaling groups). There was no significant difference in the basic anthropological data between the two groups.

This study was conducted in accordance with the declaration of Helsinki and received approval from the Ethics Committee of Beijing Military Region General Hospital. Written informed consent was obtained from all subjects, and any subject who felt dysfunctional was given medical help and an exemption for leaving the study.

Equipment and Materials

Static posturographic balance was measured by the EAB-100 (Anima, Tokyo, Japan)[16] and the Tetrax (Tetrax, Sunlight Medical Ltd., Israel).[3] Based on this COP trajectory, time-domain and frequency-domain parameters of static posturography can be computed automatically, including the circumference area (CA) and mean displacement of COP in the anteroposterior and lateral directions and its SD (MD_x, MD_y, SD_x, and SD_y),[16] and the Fourier frequency parameters on eight different frequency bands (0.01–3.0 Hz).[3] Because of the potential compensatory responses of postural control caused by sleep deprivation,[13] the easier task of normally standing on the stable foreplate[15] was adopted in our study to decrease this effect. The dynamic postural task is similar to the delayed visual feedback paradigm in the work by Yeh et al.[26] Subjects were asked to drive their COP close to the target by swaying their body, and the mean distance and SD that were based on the distances between each COP coordinate and the target showed their ability of dynamic postural control.

In experiment 1, subjective feelings of the subjects during sleep deprivation was measured using POMS.[23,27] HR and HRV related to mental fatigue were measured using SA-3000P (Medicore, Sungnam-Si, South Korea) based on the pulse beats of the middle finger. Through this apparatus, the following parameters could be acquired: HR, SD of normal to normal beats (SDNN), square root of the mean differences of successive NN intervals (RMSSD), total power of the HRV spectrum (TP), 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. In experiment 2, the newly developed questionnaire for work-related fatigue feelings[27] (2002, Chinese version; WRFFQ) was used to assess subjective feelings after pedaling training procedures. Besides HR and BR, blood pressure (BP), systolic BP (SBP), diastolic BP (DBP), and mean BP (MBP) were also measured using a patient monitoring subsystem (PM6750; Berry, Shanghai, China).

Procedure

The mechanisms of mental and physical fatigue were different. For example, mental fatigue refers to changes in psychophysiological state, which is limited solely to the mental state.[28] Therefore, the two fatigue states should be induced by different experimental procedures.

In experiment 1, the mental fatigue state of cadets was induced by 40 h sleep deprivation over 2 successive days from 06:00 during the first day (Day 1) to 22:00 on the second day (Day 2). Before 08:00 of Day 1, cadets arrived at the laboratory in Beijing Military Region General Hospital. During the sleep deprivation, subjects' posturographic balance, POMS, and HRV were measured four times at 10:00 of Day1, 22:00 of Day 1, 10:00 of Day 2, and 22:00 of Day 2. During the testing days, the subjects agreed to get at least 6 h of sleep per night and also refrain from consuming any medications such as stimulants.

In experiment 2, the physical fatigue status of cadets in the pedaling group was induced by the pedaling training schedule. This pedal task was the simplified anti-G straining maneuver of the lower extremity, which is the main source of physical load among military flights. The cadets in the pedaling group had to successively perform five stages of pedaling tasks with loading values of 80, 100, 120, 140, and 160 kg. For each loading value, the cadets were instructed to repeat it five times with 30-s intervals for each value for 5 min. Their BR, HR, and BP were recorded automatically during the experiment. Moreover, their

Table I. Change of Static Postural Control During Sleep Deprivation (Mean ± SD, $N = 37$).

PARAMETERS	10:00 DAY 1	10:00 DAY 2	22:00 DAY 1	22:00 DAY 2
F_1 (0.01–0.1 Hz)	0.91 ± 0.39	1.07 ± 0.48*	1.09 ± 0.58	1.09 ± 0.51
F_2 (0.1–0.25 Hz)	0.38 ± 0.18	0.46 ± 0.16**	0.46 ± 0.18	0.40 ± 0.17
F_3 (0.25–0.35 Hz)	0.24 ± 0.09	0.31 ± 0.10†	0.32 ± 0.13	0.32 ± 0.16
F_4 (0.35–0.5 Hz)	0.17 ± 0.07	0.22 ± 0.07**	0.24 ± 0.11	0.27 ± 0.14
F_5 (0.5–0.75 Hz)	0.11 ± 0.05	0.14 ± 0.06*	0.14 ± 0.08	0.15 ± 0.10
F_6 (0.75–1.0 Hz)	0.09 ± 0.04	0.11 ± 0.04**	0.11 ± 0.06	0.11 ± 0.06
F_7 (1.0–3.0 Hz)	0.03 ± 0.01	0.04 ± 0.01**	0.04 ± 0.02	0.04 ± 0.02
F_8 (3.0 Hz)	0.02 ± 0.01	0.02 ± 0.01**	0.02 ± 0.01	0.02 ± 0.01
CA (10^{-3})	3.00 ± 1.65	4.57 ± 2.49†	4.92 ± 3.93	5.49 ± 5.71
MD_x	0.49 ± 0.04	0.50 ± 0.04	0.49 ± 0.04	0.50 ± 0.04
MD_y	0.56 ± 0.12	0.57 ± 0.12	0.55 ± 0.11	0.56 ± 0.13
SD_x	0.01 ± 0.01	0.01 ± 0.00	0.01 ± 0.01	0.01 ± 0.01
SD_y	0.02 ± 0.01	0.03 ± 0.01**	0.03 ± 0.01	0.03 ± 0.01

The frequency domain parameters (F_1–F_8) in this table respectively show the intensity of body sway at corresponding frequency bands. By comparison of the posturographic data with similar biological rhythms (10:00 day 1 vs. 10:00 day 2; 22:00 day 1 vs. 22:00 day 2); statistical significance: *$P < 0.05$; **$P < 0.01$; $^\dagger P < 0.001$.

posturographic data and WRFFQ were also collected immediately after the experimental procedures.

Statistical Analysis

All data in this study were analyzed using SPSS 16.0 for Windows. In experiment 1, posturographic data, subjective feelings, and HRV at different times during sleep deprivation were compared using analysis of variance for repeated measures. In experiment 2, the independent sample *t*-test was used to compare data such as posturographic balance, HR, BR, and SBP between the two groups.

Based on the effective parameters of posturographic balance, the Mental Fatigue Index (MFI) and Physical Fatigue Index (PFI) were calculated by principal component analysis (PCA), which has been proven in previous work.[10] Then correlations of the two fatigue indices as independent variables with fatigue indicators such as HRV, BR, and SBP were analyzed by linear regression. The statistical probability (P) of < 0.05 was considered statistically significant.

RESULTS

During experiment 1, six subjects missed some items of the POMS as a result of low arousal level. In experiment 2, important personal information was not found in the WRFFQ of one subject, and physiological data of two subjects in the pedaling group were not recorded by the patient monitoring subsystem, so these data were excluded or null.

Compared with similar biological rhythm, the intensity of body sway in different frequencies, the circumference area of the COP, and SD of the sway distance in the anteroposterior direction increased (**Table I**). However, dynamic postural control was not affected by mental fatigue. According to Table I, 10 effective parameters of static posturography during sleep deprivation were analyzed by PCA. The first five components with a cumulative contribution rate of variance of up to 91.95% were further included in the calculation of the MFI. In experiment 2, compared with the control group, the intensity of body sway on medium- and high-frequency bands that was linked with muscular dysfunction[25] and SD increased significantly (**Table II**). However, static postural stability did not decrease statistically. Then, the seven effective parameters of dynamic posturography in experiment 2 were analyzed by PCA. Based on the PCA results, the first four components with a cumulative contribution rate of variance of up to 90.92% were further included in the calculation of PFI.

Compared with basic data (Day 1, 10:00), the emotional stability and HRV of cadets noticeably got worse on Day 2 at 10:00. Specifically, negative feelings of the subjects, such as fatigue [$F(1,30) = 93.471$, $P < 0.001$], anger [$F(1,30) = 14.387$, $P = 0.001$], and depression [$F(1,30) = 24.528$, $P < 0.001$] increased, while their positive feelings, such as vigor [$F(1,30) = 109.049$, $P < 0.001$], decreased. The RMSSD of HRV [$F(1,36) = 11.429$, $P = 0.002$] also noticeably decreased in the early period of sleep deprivation, but HR [$F(1,36) = 27.624$, $P < 0.001$] and LF/HF [$F(1,36) = 4.257$, $P = 0.047$] significantly increased on Day 2 at 22:00. These results show that significant changes in the subjective feelings and HRV could be indicators of mental fatigue. As the MFI increases, the depression score of the POMS also linearly increases [$r = 0.212$, $F(1,122) = 5.744$, $P = 0.018$]. Moreover, MFI could also reflect the change in physiological signals related to mental fatigue, such as HR [$r = -0.170$, $F(1,145) = 4.291$, $P = 0.040$], SDNN [$r = 0.286$, $F(1,145) = 4.291$, $P < 0.001$], RMSSD [$r = 0.207$, $F(1,145) = 6.483$, $P = 0.012$], TP [$r = 0.255$, $F(1,142) = 9.926$, $P = 0.002$], VLF [$r = 0.249$, $F(1,142) = 9.378$, $P = 0.003$], LF [$r = 0.212$, $F(1,142) = 6.743$, $P = 0.010$], and LF/HF [$r = 0.200$, $F(1,141) = 5.831$, $P = 0.017$]

Table II. Comparison of Dynamic Postural Control Between Two Groups (Mean ± SD, $N = 30$ in Each Group).

PARAMETERS	CONTROL GROUP	PEDALING GROUP	*t*	df	SIGNIFICANCE
F_1	5.12 ± 1.13	5.31 ± 1.24	−0.614	58	0.542
F_2	1.84 ± 0.45	2.01 ± 0.56	−1.301	58	0.198
F_3	0.94 ± 0.26	1.16 ± 0.39	−2.658	58	0.010
F_4	0.70 ± 0.20	0.97 ± 0.34	−3.772	58	<0.001
F_5	0.47 ± 0.12	0.59 ± 0.26	−2.492	58	0.016
F_6	0.33 ± 0.11	0.41 ± 0.17	−2.279	58	0.026
F_7	0.15 ± 0.04	0.19 ± 0.08	−2.794	58	0.007
F_8	0.08 ± 0.02	0.09 ± 0.02	−2.235	58	0.029
MD	0.02 ± 0.01	0.03 ± 0.01	−1.557	58	0.125
SD	0.009 ± 0.003	0.013 ± 0.009	−2.292	58	0.026

Independent sample *t*-test.

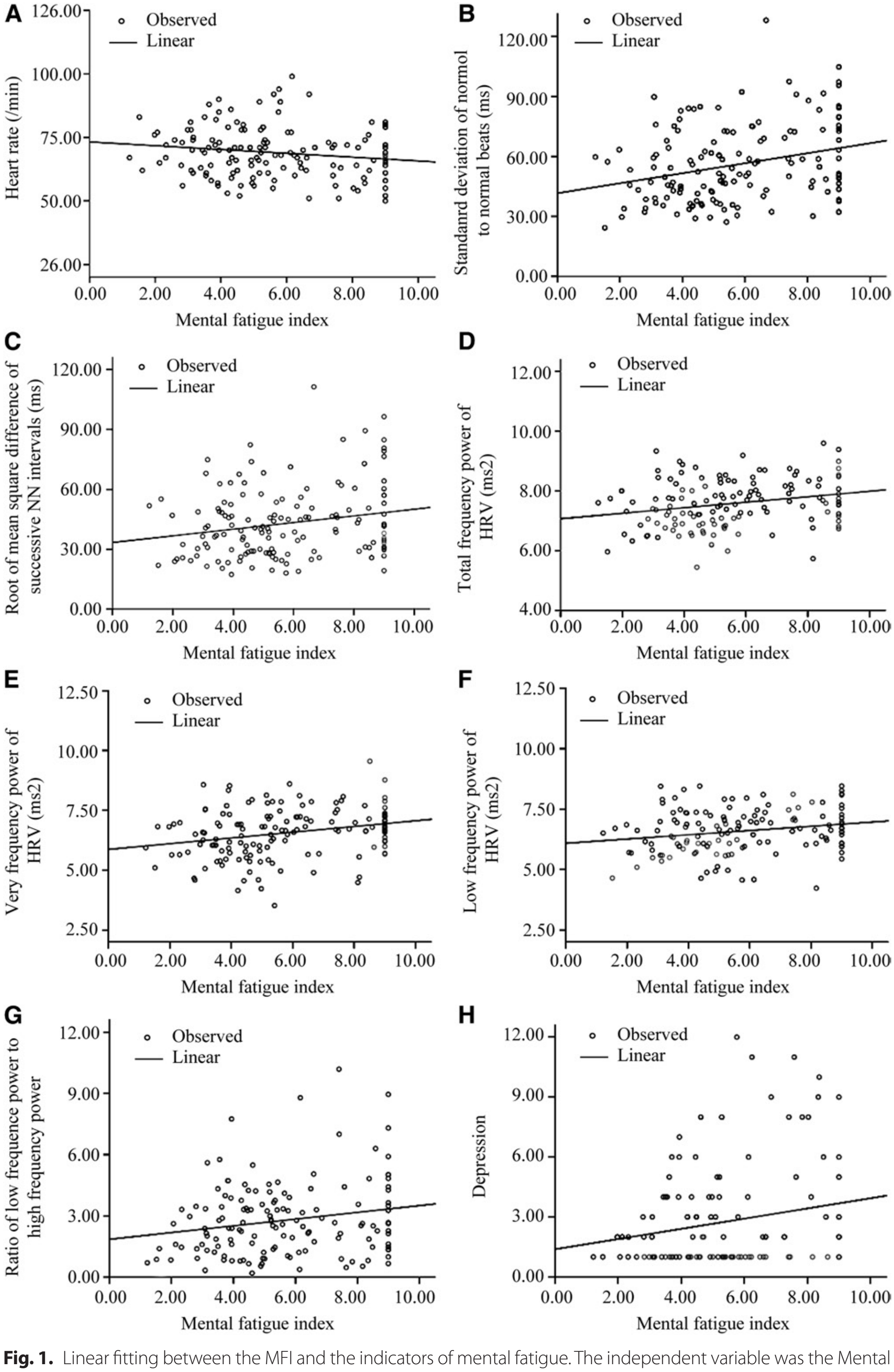

Fig. 1. Linear fitting between the MFI and the indicators of mental fatigue. The independent variable was the Mental Fatigue Index.

(**Fig. 1**). Those results suggest that MFI could linearly reflect the change in physiological signals related to mental fatigue.

After the pedaling tasks, subjective feelings of fatigue in the pedaling group were higher than those in the control group [$t(57) = 2.809$, $P = 0.007$]. Though their DBP and MBP did not statistically change, their SBP significantly increased [$t(56) = 3.879$, $P < 0.001$]. Moreover, other physiological signals related to physical load also obviously increased in the pedaling group, such as HR [$t(56) = 7.494$, $P < 0.001$], pulse rate (PR) [$t(56) = 3.995$, $P < 0.001$], and BR [$t(56) = 6.266$, $P < 0.001$]. It showed that the WRFFQ, SBP, HR, PR, and BR scores could be considered as indicators of physical fatigue. Correlations analysis showed that the PFI positively correlated with SBP [r = 0.300, $F(1,56) = 5.508$, $P = 0.022$], HR [r = 0.349, $F(1,56) = 7.758$, $P = 0.007$], and PR [r = 0.383, $F(1,56) = 9.635$, $P = 0.003$] and BR [r = 0.266, $F(1,56) = 4.282$, $P = 0.043$] (**Fig. 2**). A statistical relationship between PFI and the WRFFQ score was not observed, but their significant correlations with physiological parameters suggested that increased PFI could predict the aggravation of physical fatigue.

DISCUSSION

In this study, our findings showed that the MFI, derived from static posturographic data, is linearly correlated with HRV among cadet pilots, and the PFI, based on dynamic posturographic balance, is also linearly correlated with the HR, BR, and BP of cadet pilots. Based on the relationships between these physiological indices and fatigue status, our results present the validity of posturographic balance in mental and physical fatigue assessment, which could provide an objective method to rapidly measure fatigue using the fatigue index among pilots in the future.

Our study proved the hypothesis that correlations between posturographic balance and physiological parameters related to mental fatigue also exist among cadet pilots, which provided the validity of posturographic balance in mental fatigue assessment among cadet pilots. It is suggested that the change of postural control could reflect mental fatigue as a result of the correlations between postural control and physiological and psychological parameters. Moreover, the results of experiment 1 showed that the

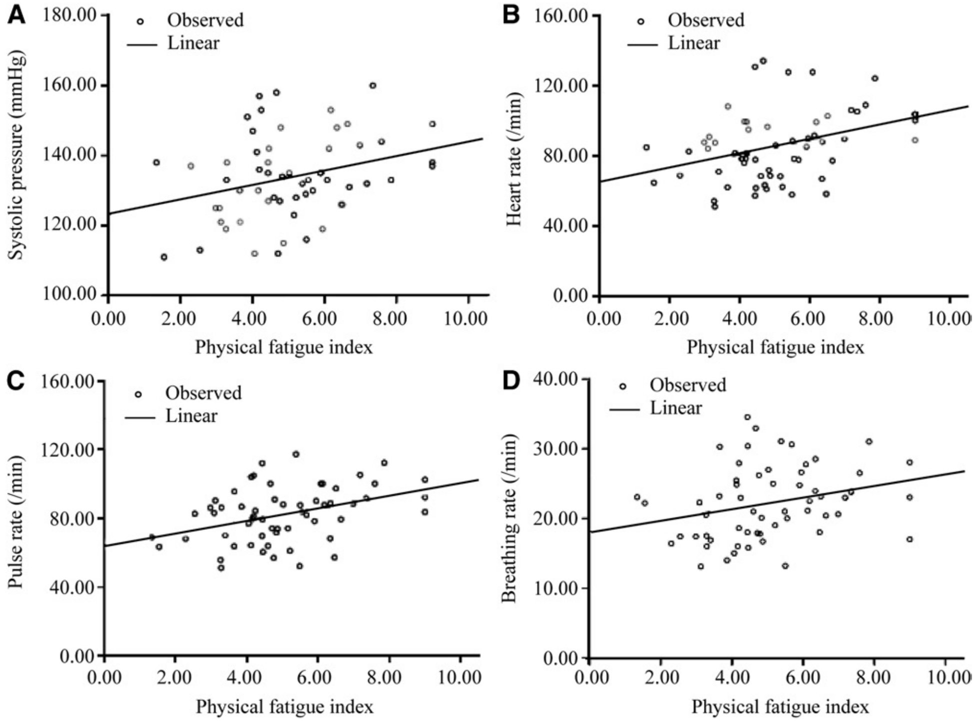

Fig. 2. Linear fitting between the PFI and the indicators of physical fatigue. The independent variable was the Physical Fatigue Index.

correlation between posturographic balance and subjective negative feelings was consistent with the findings of previous studies that the effective posturographic index correlated with the score of the Stanford sleepiness scale or other sleepiness scales when subjects suffered from sleep deprivation.[11]

Previous studies have reported that HRV is mainly modulated by sympathetic and parasympathetic nerves and is one of the important predictors of mental fatigue.[4] Specifically, the time-domain analysis of HRV proved that it was sensitive to mental fatigue, which could distinguish mental fatigue from normal functional status.[24] Additionally, the power of HRV on the high frequency band (0.15–0.4 Hz) decreased and would transfer to a higher frequency band. In other words, the frequency power of HRV under mental fatigue was different from that in a normal status.[28] Furthermore, changes in the frequency power of HRV at 0.02–0.08 Hz were consistent with the increased error rate of psychomotor vigilance task performance that has been proved to correlate with the changes in an electroencephalogram under total sleep deprivation.[5] Moreover, this study also found that HRV is significantly correlated with percentage of time that the eyes were closed, revealing a close relationship between HRV and mental fatigue. In addition, this study also showed that mental fatigue had an adverse effect on emotional status. In experiment 1, MFI, which is based on static postural control, is significantly correlated with HRV and negative emotional status, which suggests that static postural control could reflect mental fatigue to some extent.

The correlations between dynamic posturographic balance and physiological signals in experiment 2 were also consistent with the results in a previous study that dynamic balance significantly correlated with subjective fatigue scores.[6] However, our study mainly focused on the correlations between fatigue index based on posturography and the objective instruments, such as HRV and BP. Previous articles discussed in the introduction section revealed that subjective methods had inherent shortcomings[11] which compromised the accuracy of fatigue measurement. Therefore, validity analysis of posturographic balance based on objective methods in fatigue assessment will improve its application value.

Correlations between the PFI and physiological parameters provided related validity of postural control in physical fatigue assessment. Muscular exercise has been reported to consume much more energy than usual, which would accelerate the flow of body fluids, increase the input of oxygen, and intensify the beating of the heart.[19] As a result, some physiological signals such as BR and HR would increase under physical fatigue in order to meet the increased physical load. This shows that respiratory rate, HR, and BP were closely related to physical fatigue. In experiment 2, the PFI, based on dynamic postural control, significantly correlated with those physiological parameters, which suggested that dynamic postural control could be the predictor of physical fatigue to some extent. Consequently, the findings derived from cadet pilots in our study provide the possibility that the posturographic balance test will be developed and included in the methods to assess mental and physical fatigue of highly experienced pilots in the future.

Our findings have certain limitations when applied to the aviation industry. First, the study samples were cadet pilots who were merely in training from an aviation college, which may result in the limited participation of highly experienced pilots. Although they may have similarities, highly experienced pilots might exhibit different responses to sleep deprivation and physical load in similar procedures. Therefore, further studies among experienced pilots are needed to confirm our findings. On the other hand, the relatively small sample size of our study would abate correlation coefficients to some extent, which would impair the validity of postural control in fatigue assessment. Therefore, further analysis among highly experienced pilots should be conducted to confirm our findings, although correlations between fatigue index based on postural control and physiological and psychological functions related to fatigue were statistically significant.

In summary, the mental and fatigue indices based on effective parameters of posturography linearly correlated with other physiological indices related to fatigue states among cadet pilots, which suggest that the validity of posturographic balance in mental and physical fatigue assessment was good. Therefore, our study provided additional evidence that posturographic balance could positively reflect the changes in physiological and psychological functions among cadet pilots. In the future, the posturographic balance test may be used in forecasting fatigue levels of highly experienced pilots before flight tasks to prevent human errors.

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