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Investigating the effect of mindfulness training for stress management in military training: the relationship between the autonomic nervous system and emotional regulation

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Abstract

Background Military personnel face an increased risk of developing mental disorders owing to the stressful environments they encounter. Effective stress management strategies are crucial to mitigate this risk. Mindfulness training (MT) is promising as a stress management approach in such demanding settings. This study uses a quantitative approach to investigate the impact of MT on the relationship between the autonomic nervous system (ANS) and emotional regulation.

Methods The study evaluated the effectiveness of MT in reducing stress among 86 military personnel. Participants were divided into two groups: MT ($n = 42$) and non-MT ($n = 38$). The study compared the two groups using measures of heart rate variability (HRV), a reliable indicator of ANS activity.

Results The MT group exhibited a significant increase in HRV (14.4%, $p = 0.001$) and alpha asymmetry (AA) in the frontal lobe (45.7%, $p < 0.001$) compared to the non-MT group. Notably, the MT group achieved significantly higher scores on the parachute landing fall (PLF) training performance ($p < 0.001$). These improvements in HRV, AA, and PLF performance were strongly correlated. Furthermore, AA fully mediated the relationship between HRV and PLF training performance.

Conclusions The findings suggest that MT has a positive impact on stress resilience, potentially by mitigating anxiety and attention deficits induced by extreme stressors. These positive effects are facilitated by concurrent modulation of the frontal cortex and autonomic nervous system. Our findings provide insight into the neural mechanisms behind MT-induced stress reduction from the perspective of neuromodulation.

Keywords Mindfulness training, Stress management, Autonomic nervous system, Emotional regulation, Military training

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Background

Military personnel are consistently exposed to a range of stressful situations [1, 2]. Acute stress, a significant risk factor, can contribute to the onset, persistence, and worsening of mental disorders [3]. Furthermore, chronic stress is directly linked to the development of long-term health problems and severe psychiatric conditions [4]. This increased exposure to stress translates to a higher prevalence of psychological disorders among military personnel compared to civilians. Studies have shown that military personnel are more likely to experience depression, anxiety, and alcohol abuse [5]. While the prevalence of stress-related disorders is particularly high among veterans who have experienced extreme situations during deployment [6], even those who have not directly engaged in combat are exposed to significant stress during military training (MilT). MilT, designed to prepare individuals for combat, often involves low controllability and high uncertainty, creating an environment conducive to stress-related disorders [7]. Therefore, implementing effective stress management strategies among all military personnel, including those in training, is crucial to mitigate their vulnerability to mental health issues.

Mental stress significantly influences the autonomic nervous system (ANS), which governs the body's ability to react to external and internal stimuli through the interplay of its sympathetic and parasympathetic branches [8]. Heart rate variability (HRV), defined as the variation in the time intervals between consecutive peaks in related pulse of the heart, serves as a reliable, non-invasive biomarker to assess the activity of ANS and its response to stress. Under normal conditions, HRV reflects the dynamic adaptability of the heart, with a healthy degree of variability indicating effective physiological regulation [9]. However, stress disrupts the equilibrium of the ANS, often manifesting as heightened sympathetic activation and diminished parasympathetic influence, leading to a reduction in HRV [10]. This decrease signals impaired regulatory and homeostatic functions, which reduce the body's resilience to stressors. Studies increasingly recognize HRV as a robust indicator of stress, given its ability to capture real-time physiological responses. While biochemical markers like cortisol and amylase offer insights into stress responses, HRV provides unique advantages in assessing acute stress due to its capacity to measure continuous and dynamic changes in ANS balance. Its application in clinical and high-stress environments, such as military training, underscores its value in evaluating the physiological impact of stress and the effectiveness of interventions aimed at restoring ANS balance.

Furthermore, prolonged stress induces neurological changes, particularly in the structural and functional asymmetry of the brain [8]. While the brain in a healthy demonstrates lateralization toward the dominant hemisphere depending on the structure and function of the brain [11], several stress-related mental disorders are linked to pronounced asymmetric activation in the frontal lobe [8, 12, 13]. For example, patients with post-traumatic stress disorder show hyperactivation in the right frontal area in response to trauma cues, while patients with major depressive disorder show decreased activity in the left frontal area [14, 15]. An increase in alpha power in the right frontal region is associated with a decrease in negative affect and an increase in emotional flexibility [16]. In contrast, an increase in alpha power in the left frontal lobe is positively correlated with anxiety [17]. Given the frontal lobe's role in emotional regulation, FAA serves as a useful measure of how MT may modulate emotional responses under stress.

The Neurovisceral Integration Model provides a theoretical framework linking HRV to brain-based regulatory mechanisms, emphasizing the role of the medial prefrontal cortex (mPFC), amygdala, and brainstem in modulating stress responses [18]. Specifically, the ventromedial prefrontal cortex (vmPFC) regulates the amygdala, which is critical for appraising threats and ensuring appropriate autonomic adjustments under stress, with higher HRV indicating better emotional regulation and adaptive control [19, 20]. Therefore, HRV and frontal alpha asymmetry (FAA) interact as complementary markers of stress and emotional regulation. FAA reflects lateralized activity in the frontal cortex, with left-dominant activity associated with positive affect and right-dominant activity linked to anxiety [8, 11]. For example, patients with post-traumatic stress disorder show hyperactivation in the right frontal area in response to trauma cues, while patients with major depressive disorder show decreased activity in the left frontal area [14]. An increase in alpha power in the right frontal region is associated with a decrease in negative affect and an increase in emotional flexibility [16]. In contrast, an increase in alpha power in the left frontal lobe is positively correlated with anxiety [17]. Stress-induced disruptions in HRV may influence FAA by impairing the vmPFC's regulatory role over the amygdala and its neural connections.Further, stress also affects sympathetic and parasympathetic nervous system (SNS and PNS, respectively) activities, which can manifest as abnormal heart rate variability (HRV) findings [21].

Mindfulness training (MT) has emerged as an effective method to improve emotional resilience and promote mental well-being in high stress settings [22–24]. MT has been shown to be effective in the treatment of mental disorders and can strengthen the ability to regulate emotions and increase mental resilience [25, 26]. Subsequently, the individuals who undergo MT may be better able to cope with high-stress situations, and show a reduced risk of mental illness and an improved quality of life [26, 27]. In this context, the potential benefits of MT could be particularly valuable in alleviating severe psychological distress caused by time constraints, high workload, and demanding tasks.

The benefits of MT in regulating stress and emotions have been demonstrated; however, research on its long-term effects remains limited. The existing research provides only limited quantitative evidence on how MT influences the relationship between FAA and the ANS over extended periods, particularly in its impact on stress responses and emotional regulation. Therefore, this study aims to quantitatively evaluate the effectiveness of a 5-week MT program in reducing stress and enhancing mental health through physiological indicators. Parachute landing fall (PLF) training, with its intense demands on both physical precision and psychological resilience, is a key performance indicator, providing an ideal testing ground for assessing MT's effectiveness in high-stress scenarios. In this study, we investigate the effects of stress reduction with MT, specifically examining its impact on performance during PLF training. Specifically, this study investigated the effects of a 5-week MT program on military personnel (MT group = 42 and non-MT group = 38) undergoing high-stress military training (MilT). The research explored the relationship between the autonomic nervous system (ANS) of the cardiac response and the emotional regulation reflected in brain asymmetry. Participants who underwent PLF training completed a perceived stress scale (PSS), electrocardiography (ECG), and electroencephalography (EEG). This study hypothesized that MT would positively impact ANS balance and emotional regulation, leading to improved performance in MilT and, consequently, a reduction in stress levels.

Methods and materials

Participants

To ensure sufficient statistical power for detecting meaningful effects in our analysis, a minimum of 30 participants was determined through power analysis. Consequently, a total of 116 candidates were initially recruited from the Special Warfare Command of the Republic of Korea Army non-commissioned officer training course. During the recruitment process, the individuals were carefully selected to ensure that they had no diagnosed physical or psychiatric disorders. After the initial recruitment, 12 participants were discharged based on aptitude test results, and 4 were subsequently discharged owing to training-related injuries. To maintain the integrity of the data set, an additional 20 cases were excluded from the analysis. This exclusion was due to contamination by artifacts or mismatched EEG and ECG data sets during the data analysis process. The remaining candidates were then randomly assigned to two groups: MT (n = 42) and non-MT (n = 38). The the experimental protocol approved the ethical guidelines of the Declaration of Helsinki and was approved by the Institutional Review Board of the Korea University (KUIRB-2023-0058-01).

Military training (MilT)

All participants completed a 5-week program encompassing both MilT and MT. The MilT course consisted of five weeks of basic MilT followed by three weeks of advanced PLF training. Basic training included firearm training and long-distance marching, which induced considerable physical and mental stress. The subsequent advanced training course presented a more challenging environment compared to basic training. To minimize potential injuries and other issues associated with the rigorous nature of the training, more stringent control and supervision were implemented in the advanced training phase. In the sixth week, all individuals participated in PLF training using a mock-tower, and their training performance was evaluated and scored. To reduce the potential for experimental bias, the instructors who performed the MilT were unaware of whether the trainees had received MT training. The PLF training scores were based on an evaluation of focus and posture during three critical phases: on the mock tower, during the descent, and after landing. A maximum score of 56 points was assigned according to predefined criteria.

Mindfulness training (MT)

The MT program was performed for seven weeks, drawing inspiration from the Jon Kabat-Zinn program [28]. MT comprised two distinct components: a 60-min session led by an expert certified in the international mindfulness-based stress reduction program at the Mindfulness Center in Brown (121 South Main Street, Providence, Rhode Island 02903, USA) and a 20-min session designed for daily individual practice. The weekly 60-min sessions were structured in three segments. The first segment provided a 5-min overview of the MT process. The subsequent 30-min segment incorporated meditation techniques focusing on mindfulness, attention, and abdominal breathing. During the MT sessions, participants were instructed to sit comfortably in a quiet, noise-free environment. The sessions concluded with a 25-min guided interview led by the experts, focusing on techniques for managing negative emotions. For daily individual MT practice, participants engaged in a 20-min session each evening before sleep, using the same approach used in the second part of the weekly sessions.

This individual practice was self-paced by the MT-trained participants. To minimize experimental bias, the MT and non-MT groups were separated before the start of MT training. Additionally, strict controls were applied to ensure that the groups were unaware of the purpose of the MT training. As a result, during training, the MT and non-MT groups were kept physically separate.

Data acquisition

Experimental setup and measurement conditions

On the same day of weeks 1, 3, and 5, all participants underwent a series of physiological and psychological measurements, including PSS, ECG, and EEG (Fig. 1). PSS was administered first, followed by ECG and EEG recordings. These recordings were performed in a quiet, dimly lit room while participants were seated in a relaxed, resting state to ensure data consistency. However, owing to environmental constraints, physiological measurements were not feasible during the outdoor PLF training sessions; only performance scores were recorded. This approach allowed for standardized conditions for physiological measurements while accommodating the logistical demands of the MilT environment.

Perceived stress scale 10 (PSS-10)

The PSS-10, which is widely used in social psychological research, was used to assess the degree of self-perceived stress in participants [29]. The PSS-10 is a 10-item scale used to assess the degree to which stress is perceived in the environment. The items provide information on how unpredictable, uncontrollable, or overloaded respondents' lives were in the past month. The PSS-10 has a range of 0–40 points, with higher scores generally considered indicative of high levels of perceived stress. The scale has a high internal consistency and retest reliability.

Electrocardiography (ECG) acquisition

ECG (Polar H10, Polar Electro, Kempele, Finland) was recorded simultaneously with EEG for 12 minutes to investigate the quantitative effect of MT on cardiac response. The apparatus was fixed to the celiac plexus using a chest strap.

Electroencephalography (EEG) acquisition

Resting-state EEG was acquired in a dark, quiet room, with the participants sitting in a comfortable position with their eyes closed. Brain activity was recorded for 12 min. The recordings were made using the MINDD SCAN (YBRAIN, Gyeonggi-do, Republic of Korea) device, which uses 17 semi-dry channels (F3, F4, F7, F8, C3, C4, T7, T8, P3, P4, P7, P8, O1, O2, Fz, Cz, and Pz; reference: left ear lobe) based on the 10–20 international system, with a sampling rate of 500 Hz.

Data processing and analysis

Preprocessing of physiologic signal

Data processing and analysis were performed using MATLAB 2023a (MathWorks, Natick, MA, USA) with the EEGLAB toolbox. Both EEG and ECG signals were preprocessed using finite impulse response (FIR) filters, with a 1–40 Hz band-pass filter applied to remove low- and high-frequency noise. EEG data were then converted to the frequency domain using a fast Fourier transform to calculate the power spectral density (PSD). The analysis focused on power within the alpha band (8–12 Hz), which is commonly associated with emotional regulation. ECG data were examined by extracting RR intervals as the primary measure for HRV. Artifacts such as ectopic beats, which were not removed during initial filtering, were manually identified and excluded to maintain data quality. To further ensure reliability, multiple researchers independently reviewed the ECG recordings to verify data accuracy.

Heart rate variability (HRV)

The temporal-domain analysis is derived from the NN interval, representing the time between consecutive R-peaks in a continuous ECG signal. In this study, we used several key metrics: the average R-R interval, the standard deviation of the NN interval (SDNN), the root

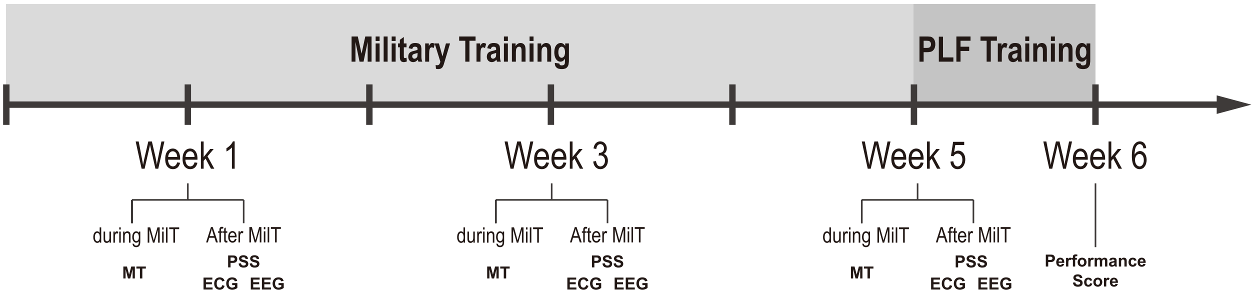

Fig. 1 Illustration of the study design depicting the schedule of Military training and Mindfulness Training

mean square of successive differences in R-R intervals (RMSSD), and the percentage of normal R-R intervals differing by more than 20 ms (pNN20). Frequency-domain HRV parameters were estimated from the PSD of the NN interval series. The analysis focused on three main frequency components: low frequency (LF) from 0.04 to 0.15 Hz and high frequency (HF) from 0.15 to 0.4 Hz.

Alpha asymmetry on frontal cortex

To perform an EEG analysis, a common average reference was applied in order to remove the influence of neural activity that may occur in the reference on the left ear. To calculate alpha asymmetry (AA) in the frontal cortex, the power spectral density (PSD) was estimated using a fast Fourier transform with Hamming window and the alpha-band PSD was calculated using an average PSD of 8–12 Hz. To calculate the laterality of the frontal lobe, the electrode pair was matched with the F7 and F8 electrodes in the frontolateral area, and the F3 and F4 electrodes in the frontomedial area. The equation for alpha asymmetry on frontal cortex is as follows:

$$AA = \ln\left(Right\ channel\right) - \ln\left(Left\ channel\right) \qquad (1)$$

A positive AA indicates that the power of the right hemisphere is greater than that of the left hemisphere, whereas a negative alpha asymmetry on frontal cortex indicates that the alpha activation of the left hemisphere is higher.

Statistical analysis

Repeated measures analysis of variance (ANOVA) was used to compare the means of the PSS, AA in the frontal lobe (including frontolateral and frontomedial areas), and HRV across the different weeks. Tukey's post-hoc test was then applied to perform pairwise comparisons, identifying weeks that differed significantly from each other. The significance value was adjusted using the stricter Bonferroni correction ($\alpha = 0.017$). An independent t-test was performed to examine differences between the MT and non-MT groups. Prior to statistical analysis, the Kolmogorov-Smirnov test was used to assess the normality of the data. To evaluate the association between PLF training performance and the presence of MT training, PLF training scores were analyzed. Owing to the lack of a clear gold standard for dividing PLF training scores into "good" and "bad" performers, we used an exploratory univariate logistic regression model. This model categorized performers based on the median score, resulting in a binary outcome variable representing performance level. The independent variables included a binary variable indicating the presence of MT training and continuous variables representing HRV parameters (indicating ANS balance) and frontal lobe asymmetry (representing emotional regulation). To examine the mediating effect of ANS balance and emotional regulation on the relationship between MT and performance, we performed mediation analysis following Baron and Kenny's approach [30], with a Sobel test to confirm the significance of the mediating effect. Indicators from week 5 and PLF training results were used in the analysis. Bootstrapping with 1,000 resamples was applied to estimate population parameters through replacement random resampling. All statistical analyses were performed using SPSS version 25.

Results

Demographics

The mean age of the MT group was 19.86 ± 1.30 years, while that of the non-MT group was 20.38 ± 1.23 years, with no significant age difference between the groups ($p = 0.062$). Each group included one female participant.

Basic military train (MilT)

Results of perceived stress scale

A gradual increase in PSS scores was observed in both the MT and non-MT groups (Fig. 2). However, these changes were not statistically significant in the MT group ($F(2,84) = 2.608$, $p = 0.080$). In contrast, the non-MT group exhibited a significant increase in PSS score at Week 5 compared to the score measured at Week 1 ($F(2,76) = 5.143$, $p < 0.01$). While the PSS score was slightly higher in the MT group compared to the non-MT group, there were no significant differences in PSS scores between the two groups at Week 1 ($p = 0.061$).

Results of heart rate variability

HRV parameters derived from ECG signals were assessed in both the MT and non-MT groups after 5 weeks (Table 1). The MT group demonstrated an increase in the mean NN interval ($F(2,84) = 4.049$, $p<0.001$), indicating increased PNS activity. Post-hoc analysis revealed a statistically significant increase across all weeks in the MT group. However, the mean NN interval did not change significantly in the non-MT group ($F(2,76) = 1.565$, $p = 0.213$). Post-hoc analysis revealed a change from Week 1 to Week 3, but no further changes were observed. As the mean NN interval increased in the MT group, there were significant differences in the mean NN interval parameters between the MT and non-MT groups at Week 5 ($p = 0.024$).

Results of alpha asymmetry on frontal cortex

AA patterns in the frontal cortex of the MT and non-MT groups were monitored over five weeks (Fig. 3). In the MT group, frontal cortex AA showed a continuous increase from F8-F7, reaching its highest level by

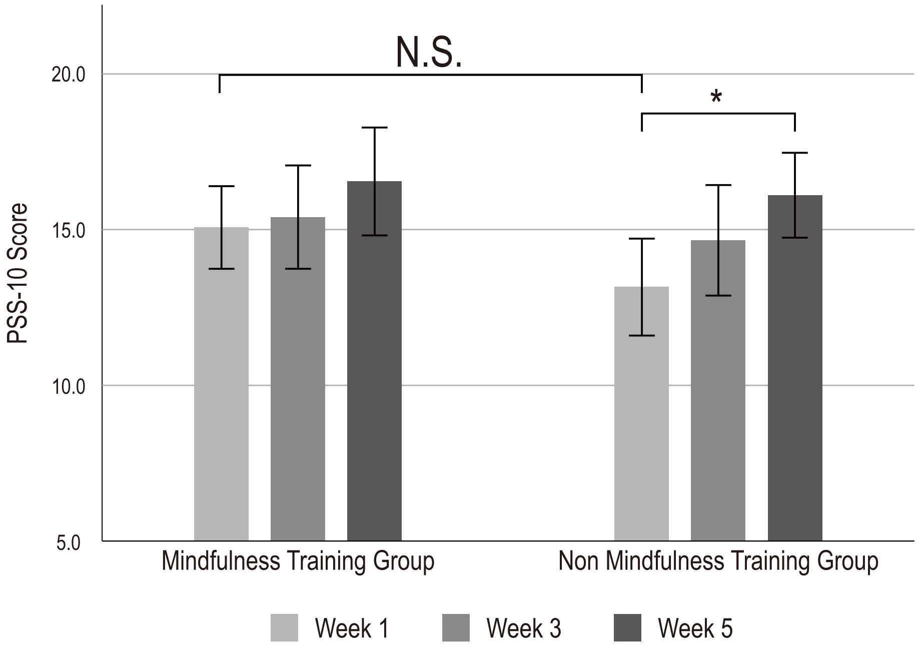

Fig. 2 The change in the score of the 4-item Perceived Stress Scale (PSS-10) between the mindful and non-mindful training groups. The error bars indicate the standard deviation. The asterisk (*) indicates $p < 0.05$. N.S. indicates Not Significant

Table 1 Heart rate variability (HRV) parameters for the mindfulness training (MT) group and non-mindfulness training (non-MT) group across different time points

	Week 1	Week 3	Week 5	F	*p* value
Mindfulness Training Group					
Mean NN interval	549.825±75.051	584.867±90.156	629.206±100.142	4.049	<0.001
SDNN	39.791±21.516	42.652±22.854	44.056±20.837	0.596	0.554
RMSSD	35.326±23.174	36.388±21.915	39.794±19.451	0.7	0.5
pNN20	2.254±4.467	3.075±6.671	3.070±6.171	0.333	0.718
LF	39.308±19.795	37.903±17.193	42.214±20.772	0.518	0.597
HF	55.052±22.413	54.133±22.255	49.347±25.627	0.681	0.508
Non-Mindfulness Training Group					
Mean NN interval	559.325±93.824	594.799±94.572	593.820±74.566	1.565	0.213
SDNN	38.562±27.752	45.874±44.824	53.847±50.335	1.78	0.176
RMSSD	35.161±31.417	45.321±50.792	51.769±55.095	1.906	0.157
pNN20	2.084±6.983	3.476±9.542	3.634±10.695	0.345	0.71
LF	42.658±19.330	38.599±21.331	41.557±8.063	0.593	0.554
HF	50.792±22.476	55.555±24.874	47.638±17.829	1.322	0.271

Abbreviations: *NN* normal beat-to-beat, *RMSSD* root mean square of the successive differences, *SDNN* standard deviation of NN interval, *pNN20* portion of successive RR interval differences over 20 ms, *LF* Low Frequency, *HF* High Frequency

Week 5 (F(2,84) = 17.722, $p < 0.001$). In the non-MT group, AA at F8-F7 did not change over time. However, starting from Week 3 onward, the AA patterns of F4-F3 decreased in the non-MT group (F(2,76) = 8.099, p = 0.001). A significant difference in frontal cortex AA was observed between the MT and non-MT groups. However, no statistically significant differences were found between the groups in the initial stage of MT (Week 1). By Week 3, a significant difference in frontal cortex AA emerged between the MT and non-MT groups, and this difference persisted through Week 5.

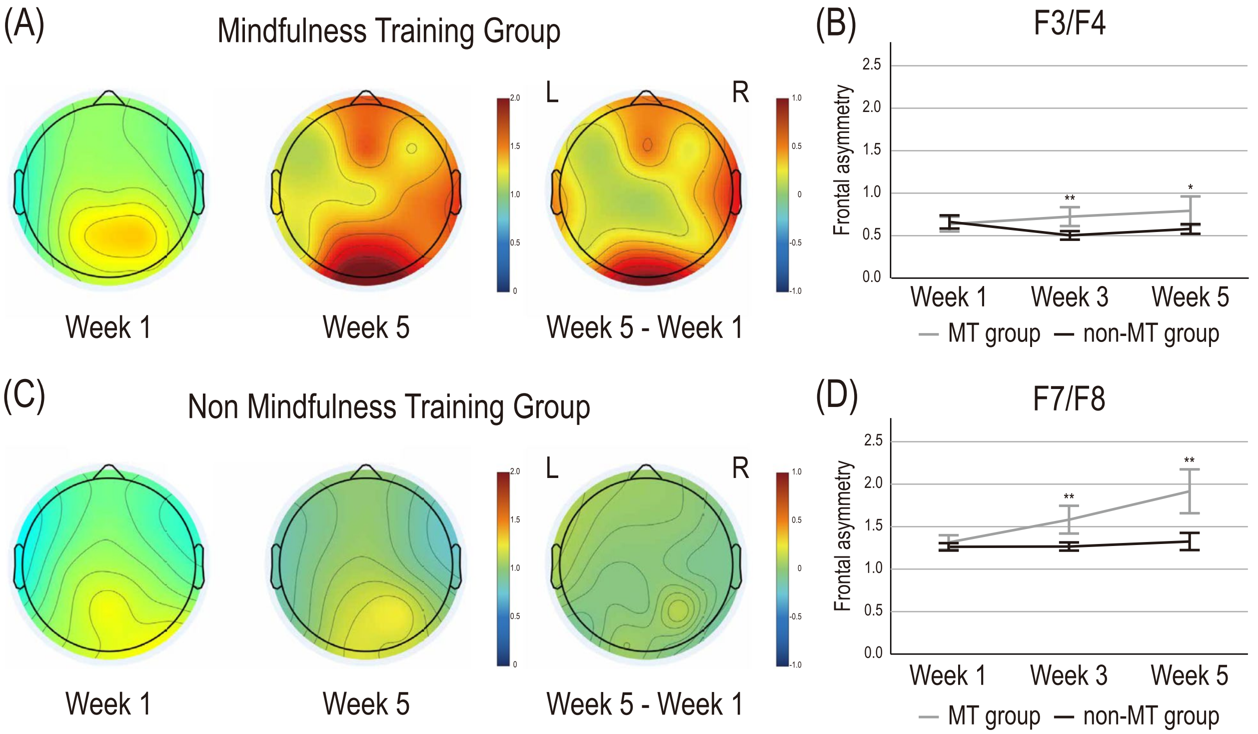

Fig. 3 Results of the frontal alpha asymmetry: **A** Topography of power spectral density of the Mindfulness Training Group. **B** Frontal alpha asymmetry between F3 and F4. **C** Topography of power spectral density of Non-Mindfulness Training Group. **D** Frontal alpha asymmetry between F7 and F8. The gray line indicates the frontal alpha asymmetry among the mindfulness training group and the black line indicates the frontal alpha asymmetry among the non-mindfulness training group. The error bars indicate the standard deviation. The asterisk (*) indicates $p < 0.05$, and the double asterisk (**) indicates $p < 0.01$

Parachute landing fall (PLF) training

During the PLF training, all participants were assigned scores based on their performance, as evaluated by a supervisor (Table 2). The MT group achieved a significantly higher average score of 53.286 ± 2.290 compared to the non-MT group, which scored 47.871 ± 3.361 ($p < 0.001$). The results of the logistic regression analysis, using a median score of 50.5 as the threshold, were as follows. The MT group demonstrated higher performance in PLF (OR = 0.015, 95 % CI 0.002–0.013). The increased mean NN interval in the MT group had a significant effect on PLF performance (OR = 1.007, 95 % CI 1.001–1.014). Additionally, the difference in alpha band power between the left and right frontal lobes significantly affected PLF training (F7/F8: OR = 4.173, 95 % CI 1.55–11.236; F3/F4: OR = 15.114, 95 % CI 1.759–129.866).

The mediation analysis revealed that the relationship between ANS balance, as measured by the mean NN interval, and PLF training performance was fully mediated by emotional regulation, specifically the asymmetric pattern observed between F7 and F8 electrodes. Importantly, no mediation effect was observed for the

Table 2 Logistic regression analysis examining predictors of parachute landing fall training performance, including mindfulness training

Predictor	**Coef**	**SE Coef**	***p***	**Odds ratio**	**95% CI**	
					Lower	**Higher**
Mindful training	−4.168	1.087	<0.00	0.015	0.002	0.013
Mean NN interval	0.007	0.003	0.035	1.007	1.001	1.014
F7/F8	1.429	0.505	0.005	4.173	1.55	11.236
F3/F4	2.716	1.097	0.013	15.114	1.759	129.866

converse relationship-emotional regulation effects on performance through ANS balance Fig. 4).

Discussion

This study examined the effects of MT on military personnel exposed to extreme stress, using EEG and ECG data from two participant groups: MT and non-MT. The results demonstrated that MT led to significant improvements in MilT performance. The MT group exhibited increased HRV, reflecting enhanced ANS balance. Furthermore, the MT group demonstrated improved emotional regulation, which was evident in increased frontal cortex (FC) asymmetry during MilT training (Fig. 3). This enhanced emotional regulation and FC asymmetry were directly related to the duration of MT training, as shown in Table 2. Mediation analysis further revealed that the change in emotional regulation, related to asymmetric patterns in the FC, fully mediated the relationship between the mean NN interval-induced ANS balance and MilT performance after the intervention (Fig. 4).

Several studies have attempted to verify the effects of MT on performance enhancement [31, 32]; nonetheless, the exact mechanism of MT in terms of emotional regulation and ANS balance remains elusive, let alone the effects of long-term MT in a high-stress environment. This study quantified the effects of MT on cardiac and brain responses, which are thought to affect the autonomic nervous system and emotional regulation. A correlation analysis of ANS balance, emotional regulation, and PLF training performance was conducted. PLF training can be highly stressful because of excessive noise, time constraints, high workloads, and restricted conditions. To achieve better performance, it is crucial to cope with and adapt to these stressors effectively. Concentration decreases significantly in noisy environments, leading to cognitive decline and difficulty when making decisions [33]. This can lead to a decrease in task performance [34]. MT may positively affect performance in stressful environments that require considerable attention, which could improve the efficiency of work performance [35]. The results demonstrated that the MT group achieved a lower rate of increase in PSS, an increased mean NN interval, and higher performance in PLF training than the non-MT group.

The findings of our study indicate that MT may be an effective approach for stress management [22–24]. The PSS is a psychometric instrument designed to assess individuals' perceptions of stress in various situations. At the outset of the training program, the group that had not undergone training exhibited lower PSS scores, although this difference was not statistically significant compared to the MT group. However, as the training continued and the difficulty of the training increased, the non-MT group demonstrated greater susceptibility to sustained stress and exhibited a trend of increasing PSS. In contrast, the MT group did not exhibit a statistically significant increase in PSS compared to the non-MT group. These results suggest that the MT group may be relatively more resilient to the stress of training than the non-MT group.

In this study, A brief 10-minute resting-state ECG was used to reduce external influences, but its lower sensitivity to sympathetic activation compared to the gold standard may have limited the detection of differences in HRV parameters. Nevertheless, the significant increase in the NN interval in the MT group suggests that mindfulness training may still be associated with higher PNS activity or lower SNS activation. Therefore, MT could affect PNS activation, as evidenced by an increase in the average NN interval [36]. Heart rate is regulated by the central autonomic network (CAN), a large brain network that includes the brainstem, insular cortex, and anterior cingulate cortex [37]; it plays a pivotal role in controlling autonomic function. Reports have indicated that heart rate can be influenced by the laterality of the CAN components [21, 38]. In addition, elevated right insular cortex activity promotes SNS activation, whereas a similar elevation in the left insular cortex activity enhances PNS activation [39]. To explain brain activation by alpha power of the cortex, the power of the alpha band has

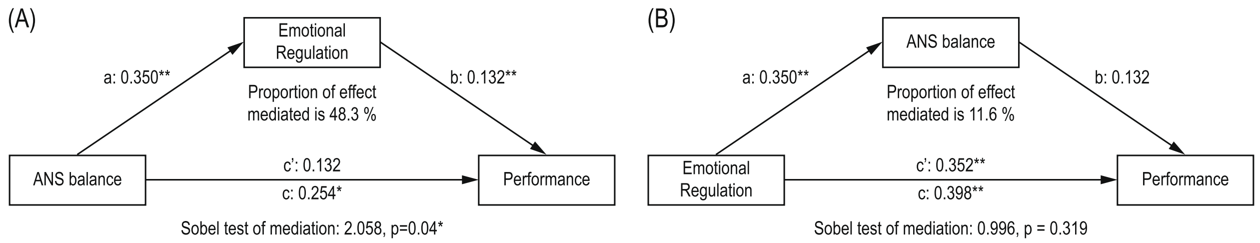

Fig. 4 Results of mediation analysis. **A** The mediation effect between ANS balance and performance by emotional regulation. **B** The mediation effect between emotional regulation and performance by ANS balance. The asterisk (*) indicates $p < 0.05$ and the double asterisk (**) indicates $p < 0.01$

been proposed to suppress brain function [40]. Thus, a higher alpha power indicates lower activation in that brain region. As shown in the Table 1, in terms of the role of cortical suppression in the alpha band, the function of the right insular cortex was suppressed by the high alpha power of the right temporal lobe, which contains the right insular cortex. Therefore, it can be interpreted that the decrease in right insular cortex function increased the dominance of the left insular cortex, resulting in increased activation of the PNS. These results also suggest that the increase in PNS activity is highly influenced by the lateralization of the insular cortex.

Asymmetry in the PFC represents brain lateralization of emotional processing in response to stress. This frontal lobe asymmetry is associated with emotional affective processing [12]. In our study, the index of alpha asymmetry on frontal cortex increased as the MT progressed. The alpha asymmetry on frontal cortex index did not significantly differ between the two groups at the beginning of MT (Week 1); however, the difference increased over time. This suggests that emotional flexibility increased with MT. This phenomenon can be explained as follows: Animal and human studies have shown that the right hemisphere plays a significant role in neuroendocrine and behavioral stress responses [13, 41]. For example, the right ventromedial PFC has been suggested to be dominant in the activation of the hypothalamic-pituitary-adrenal axis (HPA), while the medial PFC plays a role in the integration of stressful experiences [42]. In addition, the right PFC is more active in response to the higher stress [43]. Although the right frontal area is more active in response to the stress [44], the activation of the left hemisphere is associated with a decrease in HPA-axis activation through interhemispheric inhibition [45]. Thus, an increase in the left frontal activity affects emotional control in situations of acute stress. The activity of the left frontal cortex is associated with the re-evaluation of negative emotional situations [46]. Our findings support the existing literature that suggests that PFC laterality can influence the stress response by increasing the alpha power in the right PFC and increasing the dominance in the left PFC (Fig. 3). This, in turn, improves the ability to regulate emotions. Therefore, it is possible that long-term MT-induced neuroplasticity results in better emotional and stress regulation, which manifests as increased alpha power in the right PFC.

The interplay between ANS balance, emotional regulation through MT, and their combined effects on task performance remains a complex and understudied area. Our findings suggest that MT had a positive influence on performance in PLF training, a highly stressful activity demanding effective anxiety management and sustained focus in challenging conditions. While the specific evaluation criteria for PLF training are classified as military secrets, the assessment is designed to evaluate anxiety and focus. Assessment of anxiety management and alertness is essential for successful PLF training because maintaining correct posture and defensive posture is crucial for performance. Mediation analysis revealed that the increase in the mean NN interval owing to MT influenced the asymmetry of the frontal lobe, which in turn mediated its impact on task performance. This observed mediation effect suggests that MT may have improved PLF performance by enhancing PNS activity and modulating SNS activity, thereby facilitating improved focus and anxiety regulation (Fig. 4). While this study did not directly measure subjective stress reduction, it implies that MT can enhance emotional regulation and autonomic function, ultimately leading to improved performance in high-stress training environments [47, 48]. Thus, MT can modulate the balance of the ANS and enhance emotional regulation, leading to improved task performance by increasing stress resilience [49]. In conclusion, the enhancement of positive emotions, influenced by MT-induced ANS balance, may help individuals overcome psychological pressure in highly stressful environments.

Limitations and future work

Our study has several limitations in explaining the relationship between stress reduction and resilience through MT. The MilT curriculum was designed to progressively increase stressor intensity as training progressed, exposing participants to physically and mentally demanding conditions later in the training. However, our study assessed stress indicators using only the PSS, which may limit the comprehensiveness of the evaluation. Stress-related problems, such as depression and anxiety, cannot be adequately assessed using the PSS. Therefore, further research should be performed using a broader range of psychological scales, such as Beck's depression inventory and the generalized anxiety disorder assessment. Furthermore, the influence of handedness on emotional regulation was not considered in this study, given the ongoing debate regarding its impact on brain lateralization in relation to emotional processes. Future research should more strictly control for the potential impact of handedness on emotional regulation because it may be an important factor [50]. Thus, future studies should perform a more comprehensive analysis to investigate the long-term effects of MT. Additionally, we were unable to measure EEG and ECG data during PLF training, making it difficult to directly verify the effects of MT on PLF training performance. However, we indirectly assessed the relationship between ANS balance and emotional regulation by demonstrating a strong correlation between

PLF training performance and parameters derived from EEG and ECG. Future research should use a more precise experimental design that allows for direct measurement of the effect of MT in stressful situations. To enhance the generalizability of these MT effects for stress management, future studies should include a larger sample size.

Conclusion

This study investigated the positive effects of MT during MilT, a training program that exposes participants to extreme stressors. The findings suggest that the increased mean NN interval, indicating a regulation of autonomic functioning through modulation of SNS and PNS dominance following MT, may influence the asymmetric activation of the FC for emotional regulation. These findings suggest that MT generates a positive effect that help overcome anxiety and attention decrements derived from extreme stressors. These positive effects are mediated by the simultaneous modulation of the PFC and ANS. These findings provide insights into the neural mechanisms underlying stress mitigation through MT, offering a neuromodulatory perspective.

Abbreviations

ANOVA	Analysis of variance
ANS	Autonomic nervous system
ECG	Electrocardiography
EEG	Electroencephalography
FAA	Frontal alpha asymmetry
FC	Frontal cortex
HPA	Hypothalamic-pituitary-adrenal
HRV	Heart rate variability
MilT	Military Training
MT	Mindfulness training
PFC	Prefrontal cortex
PLF	Parachute landing fall
PNS	Parasympathetic nervous system
PSD	Power spectral density
PSS	Perceived stress scale
RMSSD	Root mean square of successive R-R interval differences
SDNN	Standard deviation of the NN interval
SNS	Sympathetic nervous system
pNN20	Percentage of normal R-R intervals that differed by 20 ms

Authors' contributions

All authors contributed to the study design. S.L., S.H.L., K.S.K., J.B.K, D-J.K developed the study concept. The empirical experimental methodology for military personnel was conducted by S.L., J.H.K., S.H.K., S.S.P., C.W.H., K.T.K., S.H.L., and K.S.K. Testing and data collection were performed by S.L., S.H.K., S.S.P., C.W.H., K.T.K., H.C. and S.L., J.H.K., H.C., performed the data analysis and interpretation under the supervision of D-J.K. S.L. drafted the paper, and other authors. provided critical revisions. All authors approved the final version of the paper for submission.

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Data availability

The datasets generated and/or analyzed during the current study are not publicly available as they have not been published but can be obtained from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate

The Institutional Review Board of the Korea University (KUIRB-2023-0058-01) approved the experimental protocol. Informed consent was obtained from all participants, and the right to withdraw from the experiment without any negative consequences was instructed. Informed consent was obtained from all the participants involved in the study.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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