A Study of Stress Monitoring and Management for High School Students Using Wearable ECG Sensors

Sophie Fu[1], Stephanie Fu[1], Annie Yang[1], Amy Yang[1] & Janet Roveda[2]

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Wearable smart heart monitors have gained popularity in healthcare due to their small size, lightweight design, and high accuracy. In this study, we utilized these devices to collect real-time ECG (electrocardiogram) data from high school students during academic weeks. Data were transmitted to a smartphone application via Bluetooth, then downloaded and processed to generate the HRV (Heart Rate Variability) parameter Root Mean Square of Successive Differences (RMSSD), which was used to analyze the subjects' stress levels. A significant negative correlation between RMSSD and self-estimated stress was observed across all subjects (Spearman's $r_s < -0.4$, $p < 0.05$). Subsequently, we investigated the potential benefits of yoga breathing interventions on stress management. Specifically, the study examined the influence of this practice on sleep quality, daytime stress relief, and academic performance during exams.

Keywords: Heart Rate Variability, RMSSD, Stress Management, ECG Monitoring, High School Students, Mental Health, Adolescents, Yoga Breathing.

Introduction

High school students face significant and chronic stress from various sources, including academic pressure, social demands, family expectations, and uncertainty about the future. Driven by the need to outperform peers in increasingly competitive environments, students often experience sustained stress levels that may precipitate serious psychological and mental health issues [1,2]. Therefore, implementing accurate stress monitoring systems and finding effective methods to cope with stress are essential to fostering both students' academic success and long-term psychological resilience.

Quantifying stress is inherently challenging due to its subjective nature. While traditional assessments rely on self-reported questionnaires or physical symptoms like anxiety and fatigue, Heart Rate Variability (HRV)—specifically the time-domain parameter RMSSD—offers an objective, physiological alternative to monitoring stress levels for people of all ages [3–13], including adolescents [14–23]. Despite the established validity of RMSSD as a stress metric, its specific association with the academic achievement of high school students remains under-researched.

The purpose of this study is to assess high school students' stress levels by measuring RMSSD across various academic weeks and to evaluate yoga breathing exercises as a stress-relief method for improving sleep quality and academic performance.

Methods

Research Design

This research was a small-scale, longitudinal observational study conducted over a period of four weeks. Participants were recruited voluntarily from a local high school based on their availability during the study period. The sample consisted of four female high school students aged 14–16, all from an Asian demographic background. To protect privacy, all data were anonymized, and informed consent was obtained from both the students and their parents.

Raw ECG data were collected continuously via wearable heart monitors across one final exam week and three regular school weeks at a sampling rate of 256 Hz. The device's non-invasive nature permitted 24-hour monitoring throughout the subjects' daily routines. Data were subsequently processed to extract Heart Rate Variability (HRV) metrics, specifically RMSSD, during the collection period. Each subject's RMSSD baseline was established using 14 days of sleep data recorded during regular school weeks. Concurrently, participants documented daily activities and rated perceived stress on a 9-point scale defined as follows: 1–3 (Low stress/Relaxed), 4–5 (Normal), 6–7 (Moderate stress), and 8–9 (High stress). These self-estimated stress levels were used to assess correlations with

[1] *Reedy High School, Frisco, TX 75034*
[2] *Department of Electrical and Computer Engineering, Department of Biomedical Engineering, University of Arizona, Tucson, AZ 85721*

the physiological marker RMSSD.

In this study, yoga breathing interventions were introduced in two specific contexts: (1) a targeted 10-minute pre-sleep session for one week to evaluate its influence on sleep quality and subsequent daytime stress; (2) a 5-minute pre-test session to evaluate its effect on academic performance.

Statistical analyses, including paired *t*-tests, Spearman's rank correlation, and Cohen's Kappa, were performed in the corresponding case studies to evaluate the significance and reliability of the results.

System Architecture

The complete ECG monitoring system is illustrated in Figure 1. The Heart Smart ECG Monitor from SMW MED Inc. was selected for data acquisition. It integrates an ECG sensor, detection circuit, flash memory, wireless link, and accelerometer into one compact package. The lightweight and comfortable design allowed students to wear it on a daily basis without inconvenience.

The monitor is attached to a single-use patch containing three adhesive electrodes that collect electrical signals from the heart. As shown in Figure 1, the subject wears the patch on the chest near the heart. A dedicated application, installed on an Android smartphone, connects to the sensor via Bluetooth. Once connected, subjects can initiate the data collection process and monitor their real-time ECG signals through the application. The monitor features ultra-low power consumption, enabling continuous data collection for over 24 hours on a single charge. After data collection begins, subjects can resume their daily routines as usual. The monitor dynamically records ECG data and stores it in its internal flash memory. Once a collection period is complete, the application generates a data record that can be exported for further processing. The measurement data are also securely stored in the cloud for later use.

This low-power, non-invasive ECG monitoring system allows students to wear it throughout school, extracurricular activities, and sleep. Their stress information can be evaluated by analyzing the collected raw ECG data.

ECG Stress Analyzer Tool

The ECG monitor records the electrical activity of the heart. A typical ECG waveform, as shown in Figure 2, consists of the P wave, QRS complex, and T wave, each representing a specific electrical event in the cardiac cycle.

Heart Rate Variability (HRV) quantifies the subtle, millisecond-level variations in the time intervals between successive R-peaks. In this study, stress levels were analyzed using the Root Mean Square of Successive Differences (RMSSD), a time-domain HRV metric calculated as:

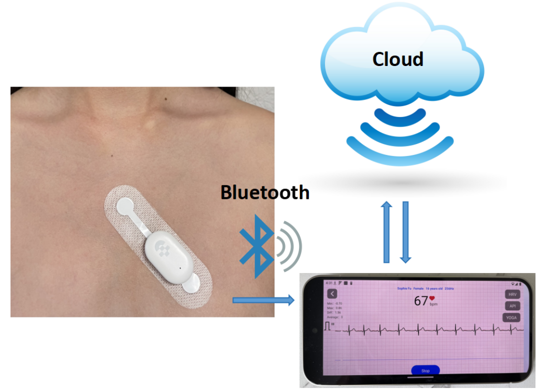

Fig. 1 Architecture of Stress Monitoring System

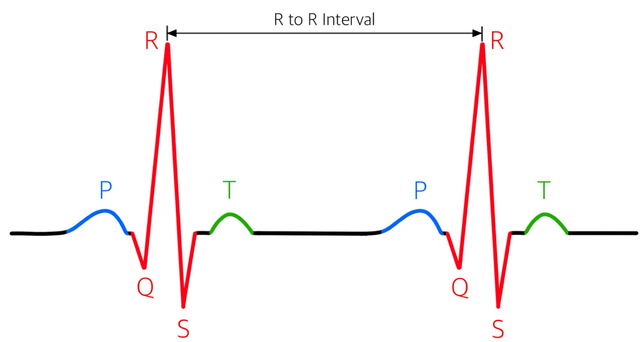

Fig. 2 ECG Signal: QRS Complex and R-R Interval

$$\text{RMSSD} = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N-1}(RR_{i+1} - RR_i)^2} \quad (1)$$

where N is the number of R–R intervals within the selected measurement window.

RMSSD is a reliable and widely used biomarker that reflects the activity and adaptability of the autonomic nervous system (ANS). A healthy cardiovascular system dynamically adapts to internal and external stimuli. A high RMSSD indicates a flexible and responsive ANS, corresponding to a relaxed, low-stress physiological state. In contrast, a low RMSSD suggests reduced autonomic adaptability and is commonly associated with elevated stress, fatigue, or inadequate recovery[4].

In this study, raw ECG data were processed using a Python-based stress analysis tool developed by SMW MED Inc. Signal conditioning began with band-pass filtering to remove baseline wander caused by respiration and electrode drift (low-frequency noise), as well as muscle artifacts and power-line interference (high-frequency noise). A finite impulse response (FIR) filter was applied to ensure accurate R-peak detection. Subsequently, R–R intervals were extracted and used to compute HRV metrics. Average RMSSD values were calculated over user-defined time windows (e.g., 1 minute or 15 minutes), enabling precise and systematic evaluation of subjects' stress states.

Results

Using the monitoring system described in Methods section, we obtained continuous ECG recordings from four students over three regular academic weeks and one exam week. This section presents a series of case studies, together with the corresponding experimental results and principal findings.

Correlation Between RMSSD and Stress Level

As a biomarker for stress, RMSSD varies significantly between individuals due to factors such as age, genetics, fitness level, and health conditions. Therefore, assessment requires comparison against an individualized baseline. In this study, each subject's baseline was established by averaging 14 regular school days of sleep RMSSD data (00:00–06:00, calculated every 15 minutes) to smooth out day-to-day variations. Following the commonly applied HRV methodology[24–29], which suggests that small day-to-day fluctuations in RMSSD typically fall within ±5–10%, while significant stressors precipitate larger reductions, we defined stress categories based on percentage deviation from the baseline. Thresholds were categorized as follows: Low Stress ($> +10\%$), indicating high parasympathetic activity and recovery; Normal ($\pm 10\%$), representing typical daily fluctuations; Moderate Stress (-10% to -30%); and High Stress ($< -30\%$), signaling suppressed parasympathetic activity and escalating autonomic strain.

Figure 3 illustrates one subject's raw RMSSD values (00:00–18:00, calculated every 15 minutes) on a final exam day, which is considered one of the most stressful days for high school students. The subject's established baseline and defined stress thresholds are superimposed on the graph. A fundamental expectation in stress research is that lower RMSSD (indicating higher physiological stress) should be associated with higher self-reported stress[4–12]. Therefore, we plotted the inverted self-reported stress levels (calculated as 10 minus the reported stress score) on the same graph to visually evaluate the alignment of the physiological and subjective trends.

The plot captures the temporal correlation between physiological data and daily stressors. Poor sleep quality and morning anxiety were clearly marked by suppressed RMSSD. A distinct pattern emerged during both exams: extreme pre-test suppression followed by a gradual rise in RMSSD during the testing period, suggesting a transition from anticipatory stress to focused concentration. This recovery was notably reversed only when the subject identified an error in her exam, triggering an immediate drop into the high-stress zone at the end of exam #2. Furthermore, the lowest recorded RMSSD values corresponded precisely with an intense orchestra rehearsal later that evening. The strong trend alignment between these physiological dips and the subject's self-reported intensity shows RMSSD's reliability as a dynamic stress indicator.

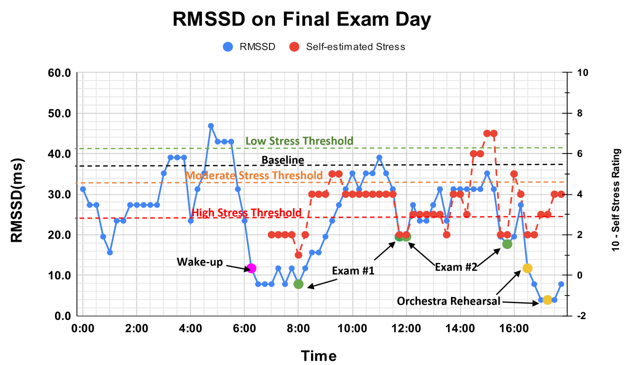

Fig. 3 RMSSDs on Final Exam Day

To investigate the physiological impact of final exam stress, continuous ECG data were collected from three subjects across both a final exam week and a regular school week. Subjects followed their standard daily routines without external intervention. Table 1 presents the weekly mean raw RMSSD and natural logarithm (ln) transformed RMSSD values. Paired t-tests were performed on the ln(RMSSD) data, and calculated p-values are reported. Comparisons were conducted for both the sleep period (00:00–06:00) and the daytime period (09:00–17:00). Additionally, individual baselines and RMSSD stress thresholds are listed for reference.

Table 1 RMSSD Metrics Across Subjects During Sleep and Daytime Conditions

Metric	Subj. 1		Subj. 2		Subj. 3	
	Sleep	Day	Sleep	Day	Sleep	Day
Low-Stress Thr. (ms)	40.4		46.2		35.6	
Baseline (ms)	36.7		42.0		32.4	
Moderate-Stress Thr. (ms)	33.0		38.0		29.2	
High-Stress Thr. (ms)	25.7		29.4		22.7	
$RMSSD_{regular}$ (ms)	39.8	28.3	48.0	13.8	32.1	30.8
$RMSSD_{final}$ (ms)	28.1	20.0	36.2	15.1	32.8	30.5
ΔRMSSD (ms)	11.7	8.3	11.8	−1.3	−0.7	0.3
$\Delta\ln$(RMSSD)	0.38	0.37	0.29	−0.08	−0.02	0.06
t-test p-value	0.018	0.015	0.021	0.722	0.75	0.813

As detailed in Table 1, Subject #1 exhibited significantly higher RMSSD and ln(RMSSD) values during the regular school week compared to the final exam week across both sleep and daytime periods. Both p-values fell below the conventional 0.05 threshold, confirming that the subject experienced higher parasympathetic activity and reduced physiological stress during the regular week. Subject #2 also exhibited a significant decline in nocturnal RMSSD during the final exam week ($p = 0.021$), indicating a possible negative impact of exam stress on sleep quality. However, Subject #2's daytime RMSSD values remained consistently low across both weeks; this persistent suppression aligns with self-reported frequent anxiety, suggesting a state of chronic stress independent of the exam cycle. Conversely, Subject #3 displayed minimal variation in RMSSD between day and night during both weeks. This lack of fluctuation may indicate reduced autonomic adaptability for the individual, a finding consistent with the subject's personal behavioral report of experiencing a reduced sense of urgency and reactivity.

To study the statistical significance of the correlation between RMSSD and subjective perceived stress, we performed Spearman's rank correlation and Cohen's Kappa analysis to evaluate the relationship between daytime RMSSD values (calculated every 15 minutes) and self-estimated stress for all four subjects on a final exam day. The results are shown in Table 2. All subjects exhibited a moderate/strong[30,31] ($r_s < -0.4$) and statistically significant ($p < 0.05$) negative correlation, indicating that as RMSSD decreased, perceived stress increased. This aligns with expected physiological trends across the group under the high pressure of final exams.

To assess specific categorical alignment between RMSSD-based stress state and self-estimated stress levels, Cohen's Kappa parameter was calculated. The results indicate that Subject #3 achieved "Moderate" agreement, suggesting that the physiological thresholds correspond well with their subjective experiences. Subject #4 achieved "Fair" agreement, indicating a recognizable but inconsistent connection between the two measurements. This suggests the subject may only detect their stress when it is extreme and miss subtle intermediate shifts. The "Slight" agreement observed in Subject #1 reflects a limited ability to accurately sense internal bodily signals. For Subject #2, Cohen's Kappa was 0.00 due to a pronounced saturation effect. The subject's RMSSD values (Range: 7.8–15.6 ms) remained consistently below the High Stress threshold (29.54 ms), resulting in a uniform classification of 'High Stress' by the physiological RMSSD measure that could not align with the variability in the subject's self-reports. This individual variation and the mismatch between RMSSD and self-reported stress highlight the complexity of the human stress response[30–35].

The data presented in Table 1 and Table 2 show that HRV RMSSD values are highly individual. Although the test subjects were of the same gender and similar age, each exhibited a distinct baseline and their cardiac responses to similar stressors varied considerably. Nevertheless, a statistically significant negative correlation between RMSSD and stress was observed across all subjects. The absence of perfect agreement between objective physiology (RMSSD) and subjective perception (self-reported stress) is expected and consistent with previous research[30–35].

Table 2 Spearman's Rank Correlation and Cohen's Kappa Test Results

Metric	Subj. 1	Subj. 2	Subj. 3	Subj. 4
Spearman's Correlation (r_s)	−0.51	−0.563	−0.41	−0.53
p-value	<0.001	<0.001	0.015	<0.001
Cohen's Kappa (κ)	0.19	0.00	0.41	0.33
Agreement Level	Slight	No agreement	Moderate	Fair

Effect of Yoga Breathing on Sleep Quality and Daytime Stress

Research and data indicate that high school students frequently suffer from chronic stress. Consequently, monitoring their stress states and identifying effective stress management methods are critical not only for their health but also for improving their performance during this key stage of their lives. One widely recognized intervention is yoga breathing, which utilizes controlled patterns of inhalation, retention, and exhalation to induce relaxation[36–39]. This research aims to quantitatively evaluate the influence of yoga breathing exercises on stress reduction.

In our stress monitoring system, the application on the mobile phone included a guided breathing module, instructing subjects to perform a specific rhythmic cycle (4∼ s inhale, 2∼ s hold, 4∼ s exhale, 2∼ s hold) during measurement. To evaluate the influence of yoga breathing on stress, we first conducted an initial experiment introducing a yoga intervention immediately upon waking. Figure 4 illustrates one subject's RMSSD response (calculated every minute) to a 10-minute yoga breathing session performed immediately upon waking. Initially, the subject exhibited typical morning stress, evidenced by a sharp decline in RMSSD after rising. However, during the breathing exercise, RMSSD values increased significantly, indicating rapid parasympathetic activation and acute stress relief. Notably, the data reveal this effect was temporary; RMSSD values receded once the exercise ceased. Given this acute response, we further investigated the potential long-term benefits of yoga breathing, specifically regarding sleep quality—a critical factor for high school students. In this context, a stable, elevated RMSSD profile during sleep serves as a key indicator of restorative rest[40,41].

To investigate the long-term effects of pre-sleep yoga breathing, we conducted a controlled intervention involving two subjects. For one school week, subjects performed a 10-minute yoga breathing exercise immediately prior to sleep (11:30 PM–12:00 AM) each night. Nocturnal RMSSD values (00:00–06:00) were recorded and compared against data

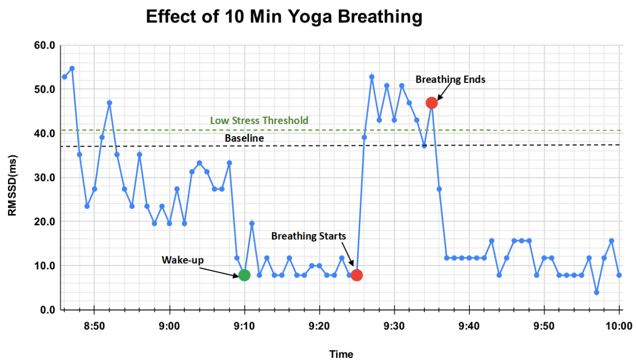

Fig. 4 Effect of Ten Minutes of Yoga Breathing on RMSSD

from a regular school week, during which no exercises were performed. Additionally, daytime RMSSD values were monitored to assess potential carry-over effects on daytime stress levels. Table 3 reports the mean raw RMSSD and ln(RMSSD) values for both weeks, along with the corresponding paired *t*-test *p*-values.

As shown in Table 3, both subjects exhibited an increase in average RMSSD during sleep following the pre-sleep yoga breathing intervention compared to the regular week. The resulting *p*-values (< 0.05) confirm that these improvements are statistically significant. This finding suggests that pre-sleep yoga breathing might be an effective method for mitigating stress and enhancing sleep quality. However, the data regarding daytime stress relief revealed divergent outcomes. Subject #4 exhibited a positive carry-over effect, with daytime RMSSD increasing by 5.6 ms. Conversely, Subject #1 experienced a slight decline of 1.3 ms. This discrepancy highlights significant inter-individual variability, suggesting that the sustained daytime benefits of pre-sleep yoga breathing are not universal. Consequently, further investigation with a larger sample size is needed to clarify these effects.

Table 3 RMSSD Comparison in a Regular Week: With vs. Without Yoga Breathing (Subjects #1 and #4)

	Subj. 1		Subj. 4	
Metric	Sleep	Day	Sleep	Day
Low-Stress Thr. (ms)	40.4		40.7	
Baseline (ms)	36.7		37.0	
Moderate-Stress Thr. (ms)	33.0		33.3	
High-Stress Thr. (ms)	25.7		25.9	
$RMSSD_{regular}$ (ms)	39.8	28.3	36.7	22.8
$RMSSD_{yoga}$ (ms)	49.8	27.0	44.8	28.4
ΔRMSSD (yoga−regular) (ms)	10.0	−1.3	8.1	5.6
$\ln(RMSSD_{regular})$	3.68	3.34	3.60	3.11
$\ln(RMSSD_{yoga})$	3.90	3.29	3.80	3.35
$\Delta\ln(RMSSD)$	0.22	−0.05	0.20	0.24
Paired t-test *p*-value	0.01	0.537	0.014	0.058

Effect of Yoga Breathing on Stress During Exams

Research indicates that chronic stress impairs the neural mechanisms required for learning and memory. This can lead to reduced concentration, poor focus, and diminished problem-solving abilities, all of which directly undermine students' academic achievement[1,2,42]. Previous studies suggest that weeks of yoga practice enhance key cognitive functions and correlate with improved academic scores in mathematics and science[43–45]. Based on the physiological effectiveness of yoga breathing observed in the previous section, we extended this investigation to determine whether these stress-mitigating benefits translate into tangible improvements in academic performance. Specifically, we focused on the immediate effect of a yoga intervention on managing test anxiety and assessed its influence on test performance.

In one experiment, the subject performed a five-minute yoga breathing session immediately prior to a math test. RMSSD data during the exam were compared against a control condition where the subject took a similar exam without prior breathing exercises. As illustrated in Figure 5, the intervention produced a distinct increase in pre-test RMSSD (calculated every minute), indicating a shift toward physiological relaxation and reduced acute stress. Furthermore, this elevated RMSSD profile was sustained throughout the duration of the test, remaining consistently higher than in the control condition. Notably, this physiological improvement coincided with a marked increase in the subject's math score.

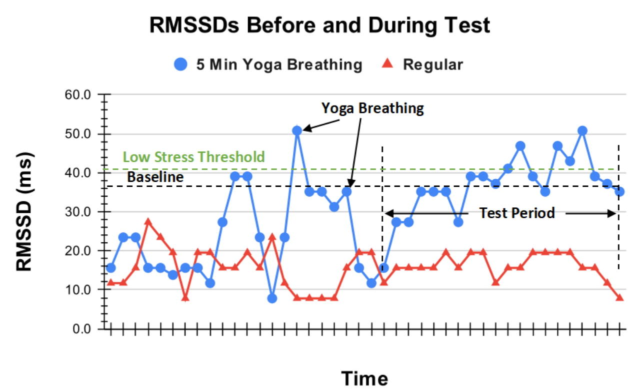

Fig. 5 RMSSDs Before and During Test: Yoga Breathing vs Regular

To further explore these effects, we expanded the data collection to include a broader set of trials. A subject completed a total of twelve 20-minute Texas UIL math tests under two conditions: (1) Regular (no yoga breathing) and (2) Yoga Intervention (5 minutes of pre-test yoga breathing). To minimize confounding variables, six tests per condition were conducted in a randomized order over several weekends, using official

UIL exams of standardized difficulty. Table 4 lists the average test scores, heart rates, raw RMSSD, and ln(RMSSD) values for each trial. A paired t-test was performed on the ln(RMSSD) data, and the resulting p-values are reported. Additionally, the distribution of these results is visualized in a box-and-whisker plot in Figure 6.

As shown in Table 4, the yoga breathing intervention produced distinct physiological benefits compared to the regular condition (no activity). Specifically, five minutes of pre-test breathing increased average RMSSD values by 8.9 ms while simultaneously decreasing heart rate by 6.7%, indicating a significant reduction in physiological stress during the exam. This improvement was statistically confirmed by a p-value of 0.041 (< 0.05). Concurrently, academic performance saw a notable increase of 13.7%. The box-and-whisker plot in Figure 6 visualizes the mean value (marked by $\times$) and distribution of these data, highlighting the clear upward shift in scores following the intervention. These findings suggest that pre-exam yoga breathing is a promising, practical strategy for managing test anxiety and potentially enhancing academic performance, though further research with a larger sample size and more data is necessary to fully validate these results.

Table 4 Effect of 5-Minute Yoga Breathing on RMSSD, Test Scores, and Heart Rate

Metric	Regular	5-min Yoga	Improvement	p-value
RMSSD (ms)	24.3	33.2	8.9	–
ln(RMSSD)	3.156	3.477	0.321	0.041
Test Score (points)	83.3	94.7	13.7%	0.014
Heart Rate (bpm)	79.6	74.3	−6.7%	0.024

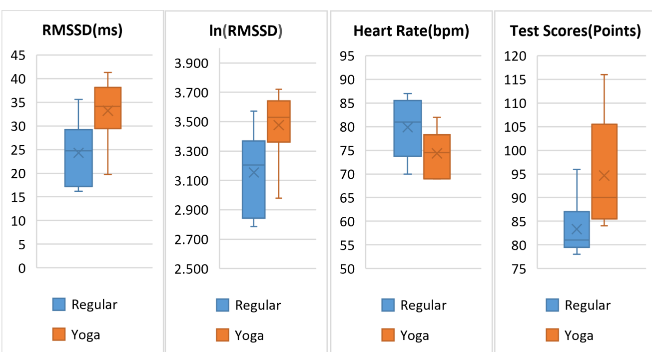

Fig. 6 Yoga Breathing Intervention Before Test

Discussion

Heart Rate Variability (HRV), specifically RMSSD, is a biological marker for stress and anxiety. Every student experiences stress, but its intensity, duration, and psychological response differ greatly between individuals. Even under similar conditions, students vary in how their autonomic nervous systems react. This study investigated these fluctuations in high school students, comparing physiological states across regular school days, final exam week, and during targeted yoga breathing interventions.

Unlike previous research, our study focuses specifically on high school students, applying ECG-based RMSSD analysis to a population that is far less studied than those of young children and adults[2–13,46]. Across all subjects in this research, RMSSD decreased during acute stressors, such as final exams, and increased during periods of relaxation, such as sleep and yoga breathing. However, it is important to acknowledge that HRV is a sensitive metric susceptible to confounding variables, including physical activity, sleep quality, and diet. In this study, dietary factors such as alcohol and caffeine were negligible, as all participants were non-consumers. While we mitigated some of the other factors by focusing on sleep baseline and controlled intervention periods, future studies should aim to rigorously control for daily physical exertion. Additionally, future studies should extend the data collection period to establish more robust individual baselines. Stress cutoff thresholds should also be calibrated for each participant to maximize analysis precision.

Furthermore, our study also examined how a short, accessible breathing exercise can potentially increase RMSSD and test performance, linking changes in HRV, not just perceived stress, with real academic outcomes. These findings support the interpretation that RMSSD is a reliable marker that can be used to continuously monitor psychological stress in adolescents. These data also reveal the clear individual differences in stress responses. All subjects, though similar in age and of the same in gender, exhibited notably different baselines for stress thresholds and changes in RMSSD in response to similar stressors.

Limitations

This study has several limitations that should be noted. First, the small sample size, comprising four participants of the same gender and similar demographic backgrounds, limits the generalizability of our findings. Second, individual environmental variability, including differences in diet, physical activity, and external pressures, may introduce confounding factors influencing RMSSD. Additionally, data collected in naturalistic settings are susceptible to signal noise; while we filtered for artifacts, the wearable hardware lacked the capability for granular sleep staging, which limits our ability to correlate RMSSD with specific sleep cycles. Third, regarding subjective measures, we relied on a simplified daily stress scale rather than validated clinical instruments such as the Perceived Stress Scale (PSS) or Pittsburgh Sleep Quality

Index (PSQI), which may reduce the depth of our psychological data. Fourth, the yoga intervention lacked an active control group (e.g., sham or paced breathing without yoga framing), preventing us from fully separating the physiological effects of the breathing pattern from psychological expectancy.

Finally, the restriction of recruitment to a single site may limit the applicability of results to broader populations. To address these issues, future research should employ larger, more diverse cohorts across multiple demographic and gender groups. Future studies should also incorporate validated surveys (PSS/PSQI), multi-sensor wearables for sleep staging, and active control groups to isolate intervention mechanisms. Additionally, extending the longitudinal data collection period would capture physiological responses to moderate stressors, such as quizzes, rather than just major exams. This would provide a more nuanced understanding of everyday stress dynamics. Expanding the study to include various educational settings—public, charter, and private schools—would also help isolate the influence of the school environment on student stress. Despite these limitations, this study provides valuable preliminary insights into the utility of RMSSD for monitoring and understanding stress patterns in high school students.

Conclusion

This study evaluated RMSSD as a viable physiological marker for objectively monitoring stress in high school students. Our longitudinal data revealed a consistent negative correlation between RMSSD and perceived stress, particularly during high-pressure exam weeks. Furthermore, our limited data showed that the introduction of a yoga breathing intervention resulted in immediate parasympathetic activation, leading to reduced physiological stress during exams and improved test performance. While long-term benefits regarding sleep quality and daytime stress relief exhibited individual variability, these findings underscore the potential of integrating wearable HRV monitoring and breathing exercises into educational and well-being programs as accessible, effective tools for managing student health and positively influencing academic outcomes.

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