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Integrating Wearable Biosensors and Mindfulness-Based Interventions for Stress Regulation among University Students: A Mixed-Methods Study

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***Abstract*— With the growing academic pressure, there has been a great demand for easy-to-employ stress regulation strategies for university students. The impact of a 8-week mindfulness-based intervention with wearable biosensors was investigated using a convergent mixed methods design. 120 students from the university were randomly assigned to intervention and comparison groups. Quantitative data was obtained by perceived stress, mindfulness, emotional regulation, sleep measures, and resting heart rate, heart-rate variability, physical activity and sleep duration measures obtained from wearable technology. Twenty intervention participants participated in semi-structured interviews, addressing acceptability, perceived benefits, adherence, and concerns about the device. The intervention group demonstrated significant decreases in perceived stress and resting heart rate, along with increases in mindfulness, emotional regulation, heart-rate variability and sleep duration. Higher HRV (heart-rate variability), longer sleep and more mindfulness were related to lower stress scores. These responses were reflected in better recognition of stress signals, calmer responses during academic pressure, and higher motivation as a result of physiological feedback in the interview. The primary challenges were discomfort with the device and struggling to perform independent practice. Wearable monitoring combined with mindfulness training was a feasible way to provide student mental health prevention. More research is required in larger, multisite studies with longer follow-up to validate the durability, generalisability and feasibility of implementation in university settings.**

Keywords: Wearable Biosensors, Mindfulness Intervention, Stress Regulation, University Students, Mixed-Methods Research

1. INTRODUCTION

Academic stress, budget anxiety, fluctuating social connections, job uncertainty and lack of sleep are all common stressors for university students and can lead to a loss of emotional balance and heightened susceptibility to chronic stress. If left untreated, this can have an impact on attention, memory, motivation, class participation, and overall mental health. Universities have also been increasingly interested in a preventive approach that can be provided prior to the onset of more severe psychological problems. Mindfulness-based interventions have been gaining focus, as they support people to observe thoughts, feelings, sensations in their bodies, and what is going on around them without judging or avoiding them. A pragmatic randomized trial with university students demonstrated that the targeted mindfulness training was able to enhance resilience in challenging periods of university study and decrease the risk of worsening of distress (Galante et al., 2018).

Common mindfulness exercises are targeted breathing, body scan, focusing on the present moment, and non-judgmental observation of one's thoughts. The techniques might assist students to identify early signs of emotional and physiological arousal and respond in a conscious manner. A study of tertiary education students has indicated that meditation, yoga and mindfulness can help to decrease levels of stress, anxiety and depressive symptoms, with varying degrees of effectiveness depending on the type of intervention and the type of student (Breedvelt et al., 2019). A wider review of college-based studies also identified reduced stress and anxiety levels generally with mindfulness meditation, with specific differences in the duration of the mindfulness meditation programmes, sample size, and the quality of the measures used (Bamber & Schneider, 2019). Mindfulness may also benefit academic functioning as better focus and self-regulation can regulate academics more effectively, which can lead to better outcomes (Chiodelli et al., 2020).

The broader literature indicates that there are credible psychological benefits, but that the results are dependent on the quality of the programmes, comparison conditions, adherence to the programme and the measures used to assess change (Goldberg et al., 2022). Digital delivery has helped to extend access opportunities by enabling students to engage outside of counselling centres and set classes. A very brief (3-hour) online mindfulness and compassion programme was shown to be viable for promoting mental health among university students at a time of massive social turmoil (González-García et al., 2021). For the psychological well-being of emerging adults, programmes designed for emerging adults with stress management outcomes (like Koru mindfulness) have also been found to be beneficial in college settings (Greeson et al., 2021). Another format that is readily available is mobile application, with one study showing that college students using Calm experienced decreased stress after regular meditation use (Huberty et al., 2019).

Although these promising results were reported, numerous studies have used questionnaires extensively, which were self-administered. While these are good measures in that they include personal experiences, they could be affected by recall errors, expectancy of the answer, or a temporary mood state. Repeated physiological and behavioral signals can be captured using wearable biosensors to enhance assessment, during normal daily activity. Heart rate, heart-rate variability, electrodermal activity, skin-temperature, movement and sleep-related indicators have been used in wearable stress-monitoring studies to identify patterns related to emotional stress (Iqbal et al., 2022). Smartphones and wearable devices can thus offer a more continuous profile of stress than can be achieved through individual laboratory examinations or surveys at specific times (Can et al., 2019).

Noninvasive wrist-worn devices have proven particularly convenient because they can perform a combination of sensing functions in a convenient device that can be used in normal use. Common types of wearable sensors include photoplethysmography, accelerometry, electrodermal sensing, temperature sensing, activity tracking and sleep estimation (Kamišalić et al., 2021). Heart-rate variability is especially important because it is a measure of autonomic regulation changes and could be used to assess an individual's adaptive response to stress. Wrist-mounted comparisons with electrocardiography indicate that HRV measurements with wearable devices can be useful, but this may be influenced by the conditions of the recording and the device's placement, quality of contact with the skin, and how the device is used (Schuurmans et al., 2020).

Wearable biosensors coupled with mindfulness training could provide a comprehensive understanding of stress regulation and relate subjective experience to physiological change. Students are able to express their own experience of stress and wearable data can indicate if there are heart rate, heart rate recovery, sleep and everyday activity changes that accompany interventions that are resulting in improvements. Qualitative descriptions can specifically describe how students perceive the intervention, how it helps students' motivation, and what might be impeding increased engagement. The present mixed methods study thus investigated how a mindfulness-based intervention with a wearable biosensor impacts university students on psychological, physiological, experiential, adherence, and practical aspects of the combination of digital monitoring and structured stress regulation training. The major objectives of the study are:

1.To assess the effect of a mindfulness-based intervention on perceived stress, mindfulness, and emotional regulation among university students.

2.To examine changes in heart rate, heart-rate variability, sleep duration, and physical activity recorded through wearable biosensors.

3.To explore students' experiences, acceptance, and perceived usefulness of combining wearable biosensors with mindfulness practice.

2. METHODOLOGY

2.1 Research Design and Participants

A convergent mixed methods research design was used to explore how wearable biosensors and MBI influence stress regulation in university students. The quantitative and qualitative data were gathered at the same time and were analysed together. The total number of students recruited was 120, comprising 18-26 year old undergraduate and postgraduate students, by purposive sampling. Participants who reported having severe psychological disorders and/or were under intensive clinical treatment were excluded. Students were randomly assigned to an intervention group and a comparison group, with the same number of students represented in each group in each academic year and across gender groups.

2.2 Intervention Procedure

The intervention group underwent a 8-week mindfulness-based program, which included guided breathing, body scan, focused attention and short meditation sessions. Each week two supervised 40-minute sessions were held, with the participants encouraged to practise on other days. During the intervention period, wearable biosensors were worn to measure HR, HRV, sleep length and physical activity. The comparison group was not given any special mindfulness training and followed their normal schedule. Baseline measurements were taken prior to the programme, and post-intervention measurements were taken right after the programme's 8th week.

2.3 Quantitative and Qualitative Data Collection

Wearable biosensor data were used to collect quantitative data, which were corroborated with questionnaires assessing perceived stress, mindfulness, emotional regulation, and sleep quality. The questionnaires were completed prior to and following the intervention. Biosensor readings were taken over a specific time period of both academic and non-academic to determine fluctuations in physiological stress responses. Semi-structured interviews were used to gather qualitative data from 20 participants of the intervention group. The interviews focused on experiences of mindfulness practice, comfort with wearing devices, perceived changes in behaviour, impediments to participation, issues of privacy, and the value of the physiological feedback in managing everyday stress.

2.4 Data Analysis and Ethical Considerations

To determine changes in stress-related outcomes, data were analyzed using descriptive statistics, paired comparisons, group-based comparisons, and correlation analysis. Pre-intervention and post-intervention measurement were analyzed within and between the two groups. Interviews were tape-recorded, transcribed and coded to identify themes related to experience with interventions, perceived benefits, adherence, and technology acceptance. The quantitative and qualitative results were then synthesized and compared in interpreting data to enable the identification of similarities and differences. The institutional review committee approved and written informed consent was obtained. Participants' identities were anonymized and data was kept securely.

3. RESULTS

3.1 Changes in Perceived Stress and Mindfulness

The intervention group demonstrated a substantial reduction in perceived stress after eight weeks, with the mean score declining from 27.84 ± 5.21 to 18.46 ± 4.73. The comparison group showed only a minor reduction from 27.31 ± 5.08 to 25.92 ± 5.11. Mindfulness scores increased from 31.62 ± 6.14 to 42.78 ± 5.67 among intervention participants, while the comparison group recorded limited change. Emotional regulation also improved more strongly in the intervention group. Between-group comparisons indicated statistically meaningful differences in all three psychological outcomes at post-intervention assessment.

Table 1. Pre- and post-intervention psychological outcomes

Outcome	Group	Pre-intervention Mean ± SD	Post-intervention Mean ± SD	Mean Change
Perceived stress	Intervention	27.84 ± 5.21	18.46 ± 4.73	−9.38
Perceived stress	Comparison	27.31 ± 5.08	25.92 ± 5.11	−1.39
Mindfulness	Intervention	31.62 ± 6.14	42.78 ± 5.67	+11.16
Mindfulness	Comparison	32.08 ± 5.89	33.46 ± 5.74	+1.38
Emotional regulation	Intervention	44.73 ± 7.26	55.61 ± 6.84	+10.88
Emotional regulation	Comparison	45.12 ± 7.01	46.39 ± 6.93	+1.27

3.2 Physiological Stress and Sleep Outcomes

Wearable biosensor measurements showed improved physiological regulation among students who completed the mindfulness programme. Mean resting heart rate declined from 78.42 ± 8.31 to 72.16 ± 7.54 beats per minute, while heart-rate variability increased from 38.27 ± 9.42 to 49.63 ± 10.18 milliseconds. Average sleep duration rose from 6.21 ± 0.86 to 7.03 ± 0.79 hours per night. The comparison group displayed minimal physiological change. Greater heart-rate variability and longer sleep duration were associated with lower post-intervention stress scores, indicating consistency between physiological and self-reported outcomes.

Table 2. Changes in wearable biosensor indicators

Indicator	Group	Pre-intervention Mean ± SD	Post-intervention Mean ± SD	Mean Change
Resting heart rate (bpm)	Intervention	78.42 ± 8.31	72.16 ± 7.54	−6.26
Resting heart rate (bpm)	Comparison	77.89 ± 8.06	77.12 ± 7.91	−0.77
Heart-rate variability (ms)	Intervention	38.27 ± 9.42	49.63 ± 10.18	+11.36
Heart-rate variability (ms)	Comparison	39.01 ± 9.18	40.12 ± 9.43	+1.11
Sleep duration (hours)	Intervention	6.21 ± 0.86	7.03 ± 0.79	+0.82
Sleep duration (hours)	Comparison	6.28 ± 0.81	6.39 ± 0.84	+0.11

3.3 Relationships among Biosensor and Psychological Measures

Lower perceived stress was correlated with higher HRV and longer sleep duration, and higher mindfulness scores. Heart-rate variability ($r = −0.58$), sleep duration ($r = −0.46$) and mindfulness ($r = −0.64$) were negatively correlated with post-intervention stress. A positive correlation between resting HR and perceived stress (r = 0.51) suggests that increased physiological arousal (HR) was correlated with increased psychological stress in students. Mindfulness was positively related to emotional regulation (r = 0.61). The relationships indicated that there were measurable physiological and behavioural changes related to improvements in subjective stress regulation.

Table 3. Correlations among post-intervention outcomes in the intervention group

Variable	Perceived Stress	Mindfulness	Emotional Regulation	Heart-Rate Variability	Sleep Duration
Perceived stress	1.00	−0.64	−0.55	−0.58	−0.46
Mindfulness	−0.64	1.00	0.61	0.49	0.38
Emotional regulation	−0.55	0.61	1.00	0.43	0.35
Heart-rate variability	−0.58	0.49	0.43	1.00	0.41
Sleep duration	−0.46	0.38	0.35	0.41	1.00

3.4 Qualitative Experiences and Integrated Findings

Interview findings corroborated the quantitative findings and identified four main themes: increasing awareness of stress, emotional control, being motivated to practice by feedback, and challenges to regular practice. Sixteen out of 20 of the interviewed students reported that breathing and body-scanning exercises helped them to respond calmly when they needed to during examinations and academic deadlines. Fourteen participants reported that the wearable feedback helped them to be more conscious of sleep, heart rate and daily habits. A few students indicated discomfort with extended use of the device and adherence to independent practice. Integrated interpretation revealed that the students that reported higher engagement also had greater decreases in stress and greater improvements in physiological regulation.

Table 4. Major qualitative themes reported by interviewed participants

Theme	Participants Reporting Theme (n = 20)	Representative Interpretation
Improved stress awareness	17	Students recognised early physical and emotional signs of stress
Better emotional control	16	Mindfulness helped students respond calmly during academic pressure
Motivation through wearable feedback	14	Biosensor data encouraged regular practice and healthier routines
Improved sleep habits	13	Students reported more consistent sleep schedules
Device discomfort	6	Some participants experienced irritation or inconvenience
Difficulty maintaining practice	8	Academic workload reduced adherence to independent sessions

4. DISCUSSION

The results showed that combining wearable biosensors with an 8-week mindfulness based intervention (MBI) resulted in significant psychological and physiological effects for university students. Reduced perceived stress along with increased mindfulness and emotion regulation indicated that the repeated breathing, body scanning, and focused attention exercises supported increased levels of calming responses to the academic and personal demands. These benefits were not limited to what people reported, with a further decrease in resting heart rate and increase in heart-rate variability. More consistent sleep duration was also indicative of more general behavioral change, possibly meaning that students had adopted healthier habits and increased awareness of the importance of recovery. The negative correlations found between perceived stress, heart-rate variability, sleep duration and mindfulness indicated that a better sense of self was associated with better autonomic functioning. This was supported by the qualitative results which showed that most of the students interviewed reported increased recognition of the signs of stress, improved emotional control, and greater motivation when they could see physiological feedback.

The current findings were in line with previous research which showed that mindfulness training could lower objective measures of student stress responses, particularly using measures of physiological stress alongside psychological measures (Voss et al., 2020). Findings from the autonomic regulation were also consistent with those that demonstrated that UCE affected brain-wave activity and ANTS in university students (Jung & Lee, 2021). This improvement in HRV was consistent with previous findings that student mindfulness training can enhance vascular HRV variability and sustain its decrease over time (Voss et al. 2022). The additional value of wearable monitoring in the current study also corresponds to findings that photoplethysmography sensors can be used to detect stress via HR and HRV signals (Namvari et al., 2022). The physiological changes that were recorded were indicative of the overall trend of wearable biosensors for real-time, non-invasive stress assessment (Samson & Koh, 2020). The psychological enhancements were also found to align with a meta-analysis of mindfulness-based interventions and university students that found a reduction in stress, anxiety, and depressive symptoms (Gong et al., 2023). Physiological Activity and Perceived Stress corroborated a study that demonstrated that passive sensing data can be used to detect patterns of stress for university students (Shvetcov et al., 2024). Likewise, the higher education students' capacity to reflect day-long mental states by heart-rate sequences underscored the importance of heart-rate signals as supporting indicators of psychological wellbeing (Chen, 2024).

The results have implications for university counselling and student wellbeing programs and academic support services. Mindfulness training could be incorporated into a structured approach to preventing severe distress among students and not just be a therapy reserved for those already in a crisis. Such programmes can be enhanced by the use of wearable biosensors, which deliver instant real-time and individual feedback, enabling students to see how their sleep, activity, breathing and emotional stress impact on their physiological functions. This feedback can aid adherence as students can see/review the effects on their HR or recovery when practicing. The aggregated and anonymised trends could also be used by universities to profile times of increased student stress, for example when exams are taking place, placement seasons or important submission deadlines. However, it should be voluntary, and should feature explicit protections for privacy, informed consent, access to data, and secure data storage. Wearable information should be used to supplement, not supplant, counselling, clinical judgement and/or direct communication with students.

The results should be taken with a grain of salt, due to several limitations. The sample was limited and the extent of the generalisation of the results to the students of other academic disciplines, cultural backgrounds or other universities was limited. The intervention was for only 8 weeks, and the long-term maintenance of the psychological and physiological effects were not known. Other people might have modified their behavior as they were aware that they were being tracked, and the variations in caffeine, physical activity, medications, examination stress and sleep patterns could have affected the biosensor readings. Wearable devices can give inaccurate or incomplete readings if not worn correctly or if the device is not worn for long periods of time. This might have limited views as a qualitative sample with only intervention participants was used. More multisite studies with larger sample sizes, with repeated measurements and random allocation would be useful to explore if the benefits observed are maintained over time.

5. CONCLUSION

The use of wearable biosensors for stress regulation within mindfulness-based interventions provided a feasible and evidence-based solution for students at the university. The intervention compared to the waitlist group was found to be correlated with decreases in perceived stress, increases in mindfulness, emotional regulation, resting heart rate, heart-rate variability and sleep length. These changes indicated that these measures of mindfulness had an impact on subjective and physiological outcomes. Wearable feedback also seemed to build students' awareness of regular patterns of stress in their day and helped to increase their adherence to healthy habits regularly. The qualitative data from the interviews confirmed the quantitative data results and indicated that the students found the breathing exercises, body scanning and live physiological data valuable, but that discomfort with the devices and irregular use of the exercises were also problematic.

This composite approach of psychological, biosensors, and participants' experiences resulted in a more comprehensive picture of the nature of change in stress throughout the intervention. Programmes similar to this can be implemented in the counselling, wellness, and student-support services at the university level, to offer early and preventive help. When collecting physiological data, the underlying principles of obtaining informed consent, data security, and informed consent must prevail. The findings were not of particular interest for their wider generalisability, as the sample was limited, and the period of the intervention was short, and the devices used could have varied. Larger multisite samples, longer follow-up times, random allocation, and repeated physiological testing should be included in future studies to determine if the benefits observed are maintained throughout various school settings.

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