

**COMPREHENSIVE EVALUATION OF MENTAL
STRESS USING NOSTRIL BREATHING AND BRAIN
ACTIVITY ANALYSIS**

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by

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Submitted

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CERTIFICATE

This is to certify that the thesis titled “**COMPREHENSIVE EVALUATION OF MENTAL STRESS USING NOSTRIL BREATHING AND BRAIN ACTIVITY ANALYSIS**” submitted by **Mr. Amit Kumar**, to the Indian Institute of Technology, Delhi, for the award of the degree of **Doctor of Philosophy in Biomedical Engineering**, is a bonafide record of the research work done by her under my supervision and guidance. The thesis work, in my opinion, has reached the requisite standard. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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DECLARATION OF PUBLISHED CHAPTERS

I, Amit Kumar, hereby declare that the contents of the following chapters in this thesis have been published in the following respective journals. The published content has been included in the thesis according to the chronology given below.

Published Chapters

1. Chapter 2: Design and Development of a Wearable System for Real-Time Nasal Breathing Monitoring

- **Published as: Kumar, A., Bajpai, R. and Joshi, D., (2022).** “Temperature profile of nasal breathing for respiration monitoring in ambulatory settings”, *IEEE Sensors Journal*, 22(23), pp.23328-23340. DOI: 10.1109/JSEN.2022.3212920.
- **Published as: Kumar, A., & Joshi, D., (2023).** “Effect of Ambient Temperature and Respiration rate on Nasal Dominance: Preliminary Findings from a Nostril-Specific Wearable”, *Journal of Breath Research*, 17(4), p.046011. DOI: 10.1088/1752-7163/acf339.

2. Chapter 3: Investigating EEG-based Deep Learning Models for Multilevel Mental Stress Detection

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- **Published as: Kumar, A., & Joshi, D. (2025).** “Effects of mini-meditation-based breathing exercise as intervention on induced mental stress: An EEG power spectrum evidence-based study”, *Asian Journal of Psychiatry*, 103, p.104341. DOI: 10.1016/j.ajp.2024.104341.
- **Under review: Amit Kumar, Shivani Ranjan, Saurabh Kumar, Lalan Kumar, and Deepak Joshi.** Graph Theory-based EEG Functional Connectivity Analysis for Breathing Intervention on Induced Mental Stress. *Journal of Affective Disorders. (Under review).*

3. Chapter 4: Nasal Dominance and Nasal Breathing Rate Variability During Multi-Level Mental Stress

- **A. Kumar and D. Joshi (2026), "Nasal Dominance and Nostril Breathing Variability: Potential Biomarkers of Acute Stress" in IEEE Transactions on Affective Computing (Impact Factor = 9.8), vol., no. 01, pp. 1-18, PrePrints 5555, doi: 10.1109/TAFFC.2026.3673829.**

4. Chapter 5: Summary and Conclusion

- Contains information derived in parts from the published works referenced in Chapters 2, 3, and 4.

5. Chapter 6: Limitations and Future Scope

- Contains information derived in parts from the published works referenced in Chapters 2, 3, and 4.

I certify that the above declaration is accurate and that I have adhered to applicable institutional and copyright policies in the preparation of this thesis.

Date:

Amit Kumar

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Date:

Amit Kumar

ABSTRACT

The growing prevalence of mental stress and its far-reaching physiological and psychological consequences underscore the urgent need for reliable and non-invasive solutions for mental stress assessment. Mental stress has been described as the “Health Epidemic of the 21st Century” by the World Health Organization due to its staggering impact on global health, contributing to cardiovascular diseases, hypertension, diabetes, cognitive decline, and elevated mortality. Despite this growing global burden, current assessment methods rely primarily on subjective self-report measures such as interviews and questionnaires, including tools like the Perceived Stress Scale or the Stress Response Inventory, which, though widely used, are insufficient due to their susceptibility to recall bias, social desirability, variability across cultural contexts, and the inability to objectively capture the changes in stress physiological parameters in real time.

To overcome these research gap, this thesis integrates novel methodologies across engineering, neuroscience, and psychophysiology to propose a comprehensive framework for stress monitoring, structured through three major contributions: the design and development of a real-time wearable nasal breathing monitoring device, development of deep learning models for multilevel stress classification using EEG, and the combined integration of nasal breathing signals and neural activity to investigate multimodal biomarkers of mental stress. Together, these approaches provide an innovative and technically rigorous strategy to establish nasal breathing parameters and EEG signatures as non-invasive, real-time biomarkers for detecting and managing stress. At the core of this thesis lies the conceptualization and implementation of a novel wearable nasal temperature sensing (NTS) device specifically designed to measure the nasal breathing signal.

While traditional tools like respiration belts provide valuable insights, they remain impractical for daily use due to cost, invasiveness, and motion artifacts. Their restriction to laboratory settings limits suitability for real-world contexts that capture everyday stress. In contrast, the developed wearable NTS device is low-cost, lightweight, non-invasive, and capable of continuously monitoring nasal breathing with robustness against motion interference. Crucially, this device monitors the nasal breathing signal and introduces novel features critical to understanding autonomic regulation. The nasal dominance index (NDI) measures the nasal breathing contribution of one nostril compared to the other. In contrast, the nasal laterality ratio (NLR) measures the asymmetry to account for individual differences. The inter-nostril correlation coefficient (iNCC) reflects synchronicity between nostrils, and

nostril-specific breathing rate variability (nBRV) captures fine fluctuations in nasal breathing intervals linked to autonomic regulation. Therefore, the developed wearable NTS device establishes an entirely new breathing signal acquisition modality for the unobtrusive study of nasal breathing as a biomarker of mental stress and health. Having established a reliable physiological signal acquisition platform, the thesis next investigates the cortical dynamics of mental stress through EEG, focusing on developing advanced computational methods for objective, real-time, and scalable multilevel mental stress classification.

While EEG has long been recognized as a non-invasive window into brain activity, existing literature on stress detection has been limited by manual feature extraction and insufficient exploration of continuous stress gradations. To address this gap, this thesis introduces StreXNet, a deep learning model uniquely designed for EEG-based stress analysis. StreXNet integrates three state-of-the-art components: a squeeze-and-excitation enhanced convolutional neural network (CNN-SE) for spatial-temporal feature extraction and emphasis on informative features, a long short-term memory (LSTM) network with self-attention to model temporal dependencies and contextualized sequence information, and finally an XGBoost classifier for robust categorical decision-making for classification. Collectively, this architecture enables multi-level classification of stress beyond binary detection. The results established significant improvements in classification accuracy compared to previous models, thereby validating EEG as a scalable diagnostic biomarker of mental stress. In addition to mental stress classification, this chapter explores stress management through a short-duration mini-meditation-based breathing exercise (MMBE) intervention, applied following induced stress across multiple levels. Furthermore, this study also analyzes the significant changes in brain functional connectivity from MMBE using EEG across different brain waves. This Analysis revealed variation in graph theoretical parameters, including average degree, average strength, clustering coefficient, and characteristic path length, indicating that MMBE modulates cortical network parameters.

Building upon these complementary approaches, the major component of this thesis integrates both nasal breathing signals obtained via the NTS device and EEG recordings for simultaneous analysis of stress-induced changes in nasal breathing and neural activity signals. This multimodal framework addresses a gap in mental stress research: while stress has been studied extensively through cardiovascular indices or respiration signals using a respiration belt, the nasal breathing signal remains unexplored, despite evidence of links with mood, cognition, and neurological conditions such as Parkinson's disease and schizophrenia.

This thesis examines how experimentally induced multi-level stress alters NDI, NLR,

iNCC, and nBRV in conjunction with changes in frontal log alpha power (FLAP), an established biomarker of mental stress. Results reveal that increased mental stress significantly disrupts nasal breathing patterns consistent with a dysregulated autonomic state. This thesis also investigates the correlation between NDI and FLAP. By examining this relation, this work may offer a valuable foundation for how peripheral respiratory patterns may correlate with neural processes, offering a new perspective for exploring stress-related physiological and neurological interactions. Establishing this connection constitutes an original contribution to psychophysiological research, proposing that nasal breathing indices can complement EEG markers as a non-invasive biomarker of stress assessment.

The broader significance of this work lies in its establishment of a multimodal, integrative paradigm for mental stress assessment. Collectively, the contributions of this thesis can be summarized as follows: the design and development of a novel nasal wearable for nasal breathing monitoring, the development of StreXNet as a state-of-the-art EEG-based deep learning model for multi-level classification of mental stress, and the evidence that short-duration breathing interventions for stress management, and the demonstration of multimodal linkages between stress-induced changes in nasal breathing signal and cortical activity, presenting a powerful conceptual integration of autonomic and cortical biomarkers.

Beyond scientific contributions, the translational implications of this thesis are substantial: by providing a novel wearable nasal breathing device and an integrative framework with EEG for mental stress assessment. It lays the foundation for real-world systems capable of mental stress monitoring in occupational, educational, clinical, and domestic settings. The combined use of NTS wearable devices and EEG-based neural activity measurements could form the basis for healthcare solutions, including stress tracking, biofeedback-driven interventions, and future clinical decision-support systems integrating respiratory and neural biomarkers. Moreover, this research introduces the novel possibility of using nasal breathing fingerprints as accessible and individualized indicators of mood, cognition, and neurological health, positioning nasal breathing not merely as a biomarker of mental stress but as a central and underutilized biomarker that could inform the detection of stress-linked disorders ranging from depression and anxiety to neurodegenerative disease.

In conclusion, this thesis presents a technically sound and conceptually integrative body of work advancing mental stress research through engineering innovations in wearable sensors, computational advances in EEG-based deep learning, and multimodal exploration of autonomic-cortical coupling under mental stress. Together, these contributions pave the scientific and technological foundation for next-generation, non-invasive, real-time, and

personalized systems for mental stress detection and regulation, addressing one of the most pressing health challenges of the twenty-first century.

सारांश

मानसिक तनाव की बढ़ती व्यापकता तथा उसके दूरगामी शारीरिक और मनोवैज्ञानिक परिणाम विश्व स्तर पर एक गंभीर स्वास्थ्य चुनौती बन चुके हैं। विश्व स्वास्थ्य संगठन ने मानसिक तनाव को 21वीं सदी की 'स्वास्थ्य महामारी' कहा है, क्योंकि यह हृदय-वाहिका रोगों, उच्च रक्तचाप, मधुमेह, संज्ञानात्मक क्षीणता तथा मृत्यु-दर में वृद्धि से जुड़ा हुआ है। इसके बावजूद, वर्तमान मूल्यांकन विधियाँ मुख्यतः व्यक्तिपरक self-report उपायों, जैसे साक्षात्कार और प्रश्नावलियों, पर निर्भर करती हैं। Perceived Stress Scale और Stress Response Inventory जैसे उपकरण व्यापक रूप से प्रयुक्त होते हैं, परंतु recall bias, social desirability, सांस्कृतिक संदर्भों के अनुसार भिन्नता, और वास्तविक समय में तनाव-संबंधी शारीरिक परिवर्तनों को वस्तुनिष्ठ रूप से पकड़ पाने में असमर्थता के कारण उनकी सीमाएँ स्पष्ट हैं।

इन शोध-अंतरालों को दूर करने के लिए, यह शोधप्रबंध अभियांत्रिकी, तंत्रिका-विज्ञान और मनो-शारीरिकी को एकीकृत करते हुए मानसिक तनाव निगरानी के लिए एक समग्र रूपरेखा प्रस्तुत करता है। यह कार्य तीन प्रमुख योगदानों के माध्यम से संरचित है: (1) वास्तविक समय में कार्य करने वाले पहनने योग्य nasal breathing monitoring device का डिजाइन और विकास, (2) EEG आधारित बहु-स्तरीय तनाव वर्गीकरण के लिए deep learning models का विकास, और (3) मानसिक तनाव के multimodal biomarkers की जाँच हेतु nasal breathing signals और neural activity का संयुक्त एकीकरण। सामूहिक रूप से, ये दृष्टिकोण nasal breathing parameters और EEG signatures को तनाव की पहचान और प्रबंधन के लिए non-invasive, real-time biomarkers के रूप में स्थापित करने की दिशा में एक नवीन तथा तकनीकी रूप से सुदृढ़ रणनीति प्रदान करते हैं। इस शोधप्रबंध का केंद्रीय आधार एक नवीन wearable nasal temperature sensing (NTS) device की परिकल्पना और कार्यान्वयन है, जिसे विशेष रूप से nasal breathing signal को मापने के लिए विकसित किया गया है।

यद्यपि respiration belts उपयोगी जानकारी प्रदान करते हैं, वे दैनिक उपयोग के लिए महंगे, अपेक्षाकृत invasive और motion artifacts से प्रभावित होने के कारण कम व्यावहारिक हैं। इनकी प्रयोगशाला-निर्भरता वास्तविक जीवन की उन परिस्थितियों में उपयोग को सीमित करती है, जहाँ दैनिक तनाव को समझना महत्वपूर्ण है। इसके विपरीत, विकसित wearable NTS device कम लागत वाला, हल्का, non-invasive और निरंतर nasal breathing monitoring करने में सक्षम है, साथ ही motion interference के प्रति अधिक robust है। यह device केवल nasal breathing signal को दर्ज नहीं करता, बल्कि autonomic regulation को समझने के लिए महत्वपूर्ण कई नवीन features भी प्रस्तुत करता है। Nasal Dominance Index (NDI) एक nostril की breathing contribution को दूसरे nostril की तुलना में मापता है। Nasal Laterality Ratio (NLR) व्यक्तिगत भिन्नताओं को ध्यान में रखते हुए asymmetry को मापता है। Inter-nostril Correlation Coefficient (iNCC) दोनों nostrils के बीच synchronicity को दर्शाता है, और nostril-specific Breathing Rate Variability (nBRV) nasal breathing intervals में सूक्ष्म उतार-चढ़ाव को पकड़ता है, जो autonomic regulation से जुड़ा होता है। इस प्रकार, विकसित wearable

NTS device unobtrusive अध्ययन के लिए breathing signal acquisition की एक नई modality स्थापित करता है और मानसिक तनाव तथा स्वास्थ्य के biomarker के रूप में nasal breathing के अध्ययन के लिए नई दिशा प्रदान करता है।

एक विश्वसनीय physiological signal acquisition platform स्थापित करने के बाद, यह शोधप्रबंध EEG के माध्यम से मानसिक तनाव की cortical dynamics की जाँच करता है, विशेष रूप से objective, real-time और scalable multilevel mental stress classification के लिए उन्नत computational methods के विकास पर ध्यान केंद्रित करते हुए। EEG को लंबे समय से brain activity की non-invasive window माना जाता रहा है, परंतु stress detection पर उपलब्ध साहित्य प्रायः manual feature extraction और stress gradations की सीमित जाँच तक ही सीमित रहा है। इस अंतराल को संबोधित करने के लिए, यह शोधप्रबंध StreXNet नामक एक deep learning model प्रस्तुत करता है, जिसे विशेष रूप से EEG आधारित stress analysis के लिए डिजाइन किया गया है। StreXNet तीन state-of-the-art घटकों को एकीकृत करता है: informative features पर बल देने और spatial-temporal feature extraction के लिए squeeze-and-excitation enhanced convolutional neural network (CNN-SE), temporal dependencies और contextualized sequence information को मॉडल करने के लिए self-attention युक्त long short-term memory (LSTM) network, तथा अंततः robust categorical decision-making के लिए XGBoost classifier। यह संरचना binary detection से आगे बढ़ते हुए stress के multi-level classification को संभव बनाती है। परिणामों ने पूर्ववर्ती मॉडलों की तुलना में classification accuracy में महत्वपूर्ण सुधार प्रदर्शित किया, जिससे EEG को मानसिक तनाव के scalable diagnostic biomarker के रूप में मान्यता मिलती है।

मानसिक तनाव वर्गीकरण के अतिरिक्त, यह शोधप्रबंध तनाव-प्रबंधन के संदर्भ में short-duration mini-meditation-based breathing exercise (MMBE) intervention की भी जाँच करता है, जिसे विभिन्न स्तरों पर induced stress के बाद लागू किया गया। आगे, यह अध्ययन EEG के माध्यम से विभिन्न brain waves में MMBE के कारण brain functional connectivity में होने वाले महत्वपूर्ण परिवर्तनों का भी विश्लेषण करता है। इस विश्लेषण में average degree, average strength, clustering coefficient और characteristic path length जैसे graph theoretical parameters में परिवर्तन पाए गए, जो संकेत देते हैं कि MMBE cortical network parameters को modulate करता है।

इन परस्पर पूरक दृष्टिकोणों पर आधारित होकर, इस शोधप्रबंध का प्रमुख भाग NTS device से प्राप्त nasal breathing signals और EEG recordings को एकीकृत करता है, ताकि stress-induced परिवर्तनों का simultaneous analysis किया जा सके। यह multimodal framework mental stress research में एक महत्वपूर्ण अंतराल को संबोधित करता है: यद्यपि stress का अध्ययन cardiovascular

indices या respiration belt आधारित respiration signals के माध्यम से व्यापक रूप से किया गया है, nasal breathing signal अभी भी लगभग अन्वेषित नहीं है, जबकि इसके mood, cognition और Parkinson's disease तथा schizophrenia जैसी neurological conditions से संबंध के प्रमाण उपलब्ध हैं। यह शोधप्रबंध जाँच करता है कि experimentally induced multi-level stress किस प्रकार NDI, NLR, iNCC और nBRV को प्रभावित करता है, और यह परिवर्तन frontal log alpha power (FLAP) जैसे स्थापित mental stress biomarker के साथ किस प्रकार संबंधित हैं। परिणाम दर्शाते हैं कि बढ़ता मानसिक तनाव nasal breathing patterns को महत्वपूर्ण रूप से बाधित करता है, जो dysregulated autonomic state के अनुरूप है।

यह शोधप्रबंध NDI और FLAP के बीच संबंध की भी जाँच करता है। इस संबंध का परीक्षण यह समझने के लिए एक महत्वपूर्ण आधार प्रदान कर सकता है कि peripheral respiratory patterns किस प्रकार neural processes से सहसंबद्ध हो सकते हैं। यह दृष्टिकोण stress-संबंधी physiological और neurological interactions के अध्ययन के लिए एक नया परिप्रेक्ष्य प्रदान करता है। इस प्रकार का संबंध स्थापित करना psychophysiological research में एक मौलिक योगदान है, जो यह प्रस्तावित करता है कि nasal breathing indices, EEG markers के पूरक के रूप में, stress assessment के लिए non-invasive biomarkers की भूमिका निभा सकते हैं।

इस कार्य का व्यापक महत्व मानसिक तनाव मूल्यांकन के लिए एक multimodal और integrative paradigm की स्थापना में निहित है। इस शोधप्रबंध के प्रमुख योगदानों को संक्षेप में इस प्रकार प्रस्तुत किया जा सकता है: nasal breathing monitoring के लिए एक नवीन wearable device का डिजाइन और विकास; multilevel mental stress classification के लिए StreXNet नामक state-of-the-art EEG-based deep learning model का विकास; short-duration breathing interventions के माध्यम से stress management की उपयोगिता का प्रदर्शन; तथा stress-induced nasal breathing signal changes और cortical activity के बीच multimodal linkages का प्रमाण, जो autonomic और cortical biomarkers के एक शक्तिशाली वैचारिक एकीकरण को प्रस्तुत करता है।

वैज्ञानिक योगदानों से परे, इस शोधप्रबंध के translational implications भी अत्यंत महत्वपूर्ण हैं। एक नवीन wearable nasal breathing device तथा EEG के साथ एकीकृत framework प्रदान करके यह occupational, educational, clinical और घरेलू settings में real-world mental stress monitoring systems की नींव रखता है। NTS wearable devices और EEG-based neural activity measurements का संयुक्त उपयोग stress tracking, biofeedback-driven interventions और भविष्य के clinical decision-support systems के लिए आधार बन सकता है, जिनमें respiratory तथा neural biomarkers का समावेश संभव है। इसके अतिरिक्त, यह शोध

accessible और individualized nasal breathing fingerprints को mood, cognition और neurological health के संकेतकों के रूप में उपयोग करने की नवीन संभावना प्रस्तुत करता है। इस प्रकार nasal breathing को केवल mental stress biomarker ही नहीं, बल्कि एक केंद्रीय और अब तक कम उपयोग किए गए biomarker के रूप में स्थापित किया गया है, जो depression, anxiety से लेकर neurodegenerative disease तक तनाव-संबंधी विकारों की पहचान में सहायक हो सकता है।

अंततः, यह शोधप्रबंध wearable sensors में engineering innovations, EEG-based deep learning में computational advances, तथा mental stress के अंतर्गत autonomic-cortical coupling की multimodal exploration के माध्यम से mental stress research को आगे बढ़ाने वाला एक तकनीकी रूप से सुदृढ़ और वैचारिक रूप से एकीकृत कार्य प्रस्तुत करता है। सामूहिक रूप से, ये योगदान अगली पीढ़ी की non-invasive, real-time और personalized mental stress detection तथा regulation systems के लिए वैज्ञानिक और तकनीकी आधार तैयार करते हैं, और 21वीं सदी की सबसे महत्वपूर्ण स्वास्थ्य चुनौतियों में से एक को संबोधित करते हैं।

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ABBREVIATIONS

EEG	Electroencephalography
NTS	Nasal Temperature Sensing
NMHS	National Mental Health Survey
MAT	Mental Arithmetic Task
nBRV	Nasal Breathing Rate Variability
NDI	Nasal Dominance Index
NLR	Nasal Laterality Ratio
iNCC	Inter-Nostril Correlation Coefficient
CNN	Convolutional Neural Network
LSTM	Long Short-Term Memory
XGBoost	Extreme Gradient Boosting
bpm	Breathe per Minute
T _{PP}	Peak-to-Peak Temperature
MMBE	Mini-meditation-based Breathing Exercises
FC	Functional Connectivity
PLV	Phase Lock Value
MIST	Montreal imaging stress task
MSL	Mental Stress Level
NB	Normal Breathing
ASR	Artifact subspace reconstruction
BN	batch normalization
wMNE	weighted minimal norm estimate
Av.D	average degree
Av.S	average strength
Ch.PL	Characteristic path length
CLC	clustering coefficient
ICA	Independent Component Analysis
ANOVA	Analysis of Variance
RF	Random Forest
AdaBoost	Adaptive Boosting
SVM	Support Vector Machine

ROC	Receiver Operating Characteristic
PR	Precision-Recall
MCC	Matthew's correlation coefficient
JI	Jaccard Index
LUCN	Left cuneus
RST	Right superior temporal
RFUS	Right fusiform
RENT	Right entorhinal
RFP	Right frontal pole
RCAC	Right caudal anterior cingulate
RPREC	Right precuneus
RIT	Right inferior temporal
RTP	Right temporal pole
RPRC	Right precentral
RPOC	Right postcentral
RLO	Right lateral occipital
RMT	Right middle temporal
RPARAC	Right inferior parietal
RTRANS	Right transverse temporal
RHIP	Right parahippocampal
LST	Left superior temporal
LENT	Left entorhinal
LLO	Left lateral occipital
LMT	Left middle temporal
LMOF	Left medial orbitofrontal
LFP	Left frontal pole
LSUPRA	Left supramarginal
LPREC	Left precuneus
LSF	Left superior frontal
LPT	Left parstriangularis
LPOC	Left postcentral
LPARA	Left paracentral
LPERI	Left pericalcarine

LCUN	Left cuneus
LRMF	Left rostralmiddlefrontal
LFUS	Left fusiform
BB	Breath-to-Breath
FLAP	Frontal Log Alpha Power
MMSE	Mini-Mental State Examination
PSD	Power Spectrum Density
mBR	Mean Breathing Rate