



Article

A Comprehensive Analysis of Trapezius Muscle EMG Activity in Relation to Stress and Meditation

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Abstract: Introduction: This study analyzes the efficacy of trapezius muscle electromyography (EMG) in discerning mental states, namely stress and meditation. Methods: Fifteen healthy participants were monitored to assess their physiological responses to mental stressors and meditation. Sensors were affixed to both the right and left trapezius muscles to capture EMG signals, while simultaneous electroencephalography (EEG) was conducted to validate cognitive states. Results: Our analysis of various EMG features, considering frequency ranges and sensor positioning, revealed significant changes in trapezius muscle activity during stress and meditation. Notably, low-frequency EMG features facilitated enhanced stress detection. For accurate stress identification, sensor configurations can be limited to the right trapezius muscle. Furthermore, the introduction of a novel method for determining asymmetry in EMG features suggests that applying sensors on bilateral trapezius muscles can improve the detection of mental states. Conclusion: This research presents a promising avenue for efficient cognitive state monitoring through compact and convenient sensing.

Keywords: stress monitoring; meditation; trapezius muscle; EMG; signal processing; physiological sensors



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1. Introduction

With the evolution of the fast-paced modern workplace, occupational-related stress has notably increased [1], particularly in careers involving persistent pressure and high-stake decision making. Stress can be separated into three different categories: acute stress, episodic stress, and chronic stress [2]. Acute stress results from short-term challenges, episodic stress is a more frequent form of acute stress that is still highly variable, and chronic stress is a constant severe stress resulting from constant demands [3]. The chronic stress experienced by many professionals in high-pressure environments can lead to an increased rate of coronary heart disease [4], an increase in depression and anxiety [5], and decreased work productivity [6]. The escalation and dangers of workplace stress highlight the need for innovative approaches to monitor and manage the severity of stress.

The inverted-U model of arousal [?] provides a framework for understanding how stress influences performance. According to this model, stress induces an increase in arousal levels. Initially, this heightened state of arousal can be beneficial, as it primes individuals to respond effectively to the demands of the stressor. However, if stress levels remain elevated for an extended period or become excessively intense, it can lead to over-excitation. This over-excitation can have detrimental effects on task performance. When arousal levels surpass the optimal point on the arousal–performance curve, individuals may experience difficulty focusing, coordinating movements, or making decisions effectively [8]. Consequently, the quality of performance deteriorates despite the initial surge in arousal. Convenient real-time monitoring systems offer a practical solution to mitigate the negative

impact of stress on performance. By providing continuous quantitative feedback on arousal levels, individuals can gauge their current state of arousal and take proactive measures to regulate it. This feedback loop enables individuals to stay within their optimal range of arousal, striking a balance between being sufficiently alert and avoiding the pitfalls of over-excitation.

Stress is typically considered a subjective mental state. Previously, the reliance on a survey to identify stress levels among professionals has been a common approach [9]. However, this method is time-inefficient and lacks the continuity of biometric monitoring techniques. In response to these limitations, prior studies have explored the use of physiological measures including electroencephalography (EEG) [2], electrocardiography (ECG)-derived heart rate variability (HRV) [10], galvanic skin response (GSR) [11], and electromyography (EMG) [12] to monitor experimentally induced stress. Among these measures, EMG shows promise as an integrative measure to perpetually monitor stress with ease.

EMG is a diagnostic tool that utilizes the intrinsic electrical activity within muscles to monitor skeletal muscle activity and health [13]. EMG hinges on the detection of local electrical charges caused by the neuromuscular junction. These charges trigger a wave of excitation that travels along the muscle fibers, leading to muscle contractions [14]. Specifically, EMG records the action potentials generated when muscle fiber voltage rapidly exceeds a threshold, resulting in the development of a nerve signal. These myoelectric signals, produced by variations in muscle fiber membranes, allow for the analysis of motor unit recruitment and firing characteristics within the measured muscle [15].

Motor planning is the decision to move a muscle or imagine performing a task, and it originates in higher brain regions. Signals are then transmitted from planning areas in the brain to the primary motor cortex (M1). M1 decodes the intended action and activates the appropriate junctions through the corticospinal tract [16]. EEG studies have analyzed how muscle activity correlates with changes in the sensorimotor cortex [17–23]; however, fewer studies have focused on analyzing EMG changes during various cognitive states [12,24].

Trapezius muscle EMG has been demonstrated to exhibit a strong association with stress [25]. Previous literature depicts increased trapezius muscle activation during cognitive tasks [26] and reports that blood flow to the trapezius muscles has the potential as an indicator of stress [27]. Prior studies have also analyzed right and left trapezius muscles and erector spinae muscles for stress recognition [28]. Asymmetries in left and right muscle activity have previously been recorded with stress [25]. Determining the optimum sensor positioning and improving stress identification with enhanced features can bring us closer to more convenient, real-time stress detection. In this study, right trapezius muscle EMG features are compared with left trapezius muscle EMG features to assess the usefulness of obtaining bilateral EMG data and determine whether obtaining an asymmetry metric can improve cognitive state detection over unilateral analysis.

Although current literature mostly considers EMG features above 20 Hz [29–31], analyzing low-frequency (LF) EMG may hold potential in enhanced stress detection. Differing EMG frequencies corresponding to various oscillatory drives have been explored [32], and LF EMG features can provide insight into various parts of the brain. Low-frequency oscillations in trapezius muscle EMG have been suggested as a tool to study neural mechanisms including slow-wave cortical oscillations represented in the descending corticospinal pathways and monoaminergic pathways originating in brain stem reticular formation [33]. Consequently, the 0.5–4 Hz range has revealed neurophysiological regularities in patients with Parkinson's disease [34] suggesting the possibility for improved diagnostic capabilities of cognitive functioning. Additionally, the 6–12 Hz frequency range has been associated with differing parts of the brain, including the cerebellar [35], subcortical [36], sensorimotor cortex [37], and primary motor cortex [38]. Given these interconnections between LF EMG and cognitive activity, our study seeks to investigate the relationship between LF EMG and cognitive states, particularly stress and meditation.

This study seeks to explore the viability of trapezius muscle EMG in providing insight into cognitive function. It employed prevalent cognitive tasks to induce a stress response and a mindfulness meditation approach to induce a meditative state. The subsequent sections elaborate on the protocol, signal processing, and feature analysis. The experiment's validity in eliciting the desired cognitive effects is portrayed through EEG analysis, followed by an examination of trapezius muscle EMG patterns during these states. Features are categorized into different groups, including positioning and frequency ranges. EMG features above 20 Hz, referred to as high-frequency (HF) EMG, are compared with LF EMG features. Additionally, a comparative analysis is conducted between the left and right trapezius muscles along with an evaluation of asymmetry for cognitive state detection.

2. Materials and Methods

2.1. Experimental Protocol and Data Acquisition

After Institutional Review Board (IRB) approval, 15 healthy participants, 7 males and 8 females, between the ages of 18 and 30 with no history of neurological diseases were recruited. All participants had no prior experience with meditation and were trained on how to meditate before starting the experiment.

The protocol involved a 5 min resting data collection, followed by a questionnaire, and a 10 min guided meditation, followed by a 5 min mental stress segment; Figure 1. The participants answered a stress survey between each segment. The questionnaire (QS) had participants input age, amount of sleep, waking time, gender, dominant hand, nationality, current profession, stress level at work, and caffeine and food intake. The stress surveys had the participants rank their current stress level on a visual scale from 1 to 10. At all gaps and intervals, the participants were instructed to relax and avoid any physical activity or conversation.

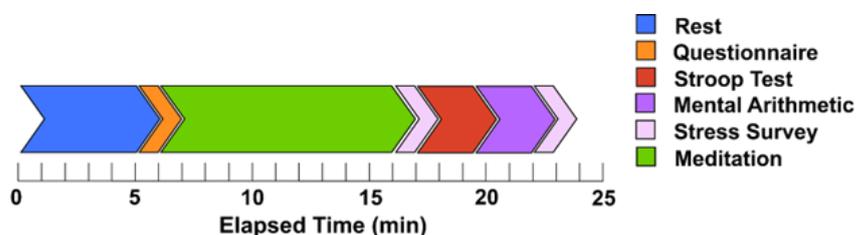


Figure 1. Experimental Protocol.

The 5 min stressor involved a Stroop color–word test (SCWT) for the first 2.5 min and a mental arithmetic (MA) task for the last 2.5 min. For the mental arithmetic, news was played in the background while subjects were asked to count backward from 2043 in integers of 17 [24].

The meditation training involved a 10 min guided meditation practice where the participants were instructed to focus on their breathing and follow a visual breathing bubble that expanded with inhalation and deflated with exhalation. The visual was accompanied by a calming tone that matched the inhalation and exhalation patterns. This guided practice was repeated during data collection. There was a 20 min gap time following the meditation training and the start of the experiment.

Electroencephalography (EEG) data were collected as control to ensure that the expected cognitive results were achieved and used as a comparison for EMG findings. A DSI-24 system was used for data collection, and mid-trapezius muscle EMG was collected at 300 samples/second. The electrode setup is shown in Figure 2. The experiment was conducted in a naturally lit and noiseless environment to minimize signal interference and other artifacts. To reduce muscle artifacts in the trapezius muscle sensors, the participants were instructed to sit in a natural position while keeping their elbows on the armrests and to maintain a neutral head position throughout the study.

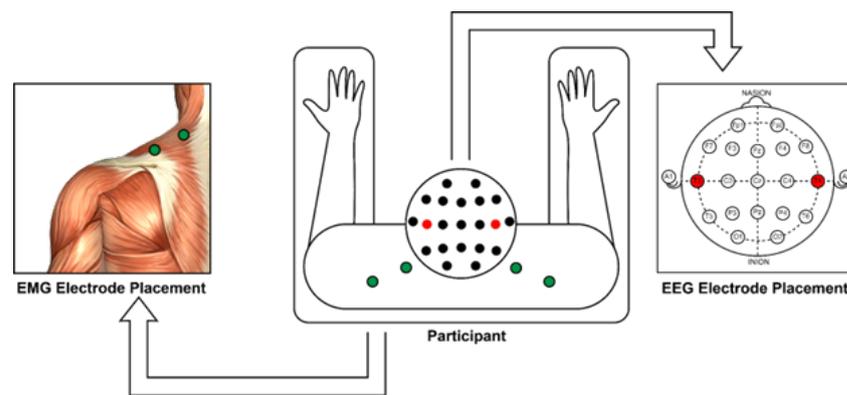


Figure 2. Electrode Setup: All EEG electrodes shown were used to obtain scalp topology plots. Red electrodes indicate temporal electrodes used for frequency analysis. Green electrodes portray the bilateral trapezius muscle EMG collection.

2.2. Signal Processing

Stressful tasks have been linked to the development of pain and fatigue in the trapezius muscles [39]. To investigate the relation between cognitive states and trapezius muscle EMG, a high-pass fourth-order butterworth filter at 20 Hz was applied to obtain HF EMG features, and a bandpass fourth-order butterworth filter from 0.5 Hz to 20 Hz was applied to obtain LF EMG features. Min–max normalization was performed for each segment. EEG signals were preprocessed using EEGLab [40]. EEG data were re-referenced using an average reference approach. Subsequently, a basic Finite Impulse Response (FIR) high-pass filter at 1 Hz and a basic FIR low-pass filter at 45 Hz were applied to the data. Segmentation of the EEG signal was conducted using trigger data as reference points. Independent Component Analysis (ICA) was then employed on these segments, with components visually scrutinized for potential removal. Finally, a Short-Time Fourier Transform was utilized to extract signals within various frequency bands [41]. Surface topology maps were created from the EEG electrodes in the DSI-24 system to assess the effect of stress and meditation. Arousal index, a ratio of beta power to alpha power [41], was calculated from averaged temporal electrodes T3 and T4 due to enhanced stress-related beta wave activity seen in these electrodes [42], as shown in Figure 2.

2.3. Feature Evaluation

Five EMG features were analyzed, namely median frequency (MDF), mean power spectral density (PSD), variance (VAR), Simple square integral (SSI), and asymmetry. Mean PSD can be highly informative [12,43] and has shown better performance when specifically assessing muscle fatigue [44] and motor unit recruitment [45]. Mean frequency (MNF) and MDF are understood as the ideal frequency domain features, frequently used to assess muscle fatigue [46]. Although MNF and MDF are similar, MDF is less affected by signal noise and more sensitive to muscle fatigue [47]. Muscle fatigue increases EMG signal amplitude; therefore, time-domain features based on energy information can also track this behavior. MNF and MDF, typically around 8 Hz, have previously been shown to decrease significantly during stress than during rest [48]. Stress also tends to increase muscle tension and increase muscle contraction variations. SSI expresses the energy of the EMG signal; an increase in this energy indicates heightened muscle activity. Variance in EMG signals helps capture the variability in muscle activity.

The data were split into the 3 segments—rest, stress, and meditation—to determine whether a significant difference could be observed between these segments in either frequency range for any of the 4 features. Furthermore, an analysis of whether this observation was improved on one side more than the other was also performed. Asymmetry in either frequency range was assessed to determine whether a certain segment could be better differentiated using bilateral sensors to determine this metric. As each subject contributed measurements during rest, stress, and meditation states, a paired *t*-test was performed

for statistical significance between segments due to its effectiveness in detecting changes between paired observations [49]. The significance level was set at $p < 0.05$, implying that results with a p -value below this threshold were considered statistically significant.

3. Results

Band power data from EEG were used as a control for the protocol to observe cognitive changes throughout the experiment. Figure 3 depicts transient changes in the arousal index throughout the experiment for one subject. A decrease in this metric can be observed with meditation, followed by a significant increase during the stressor. Similar results were observed for other subjects.

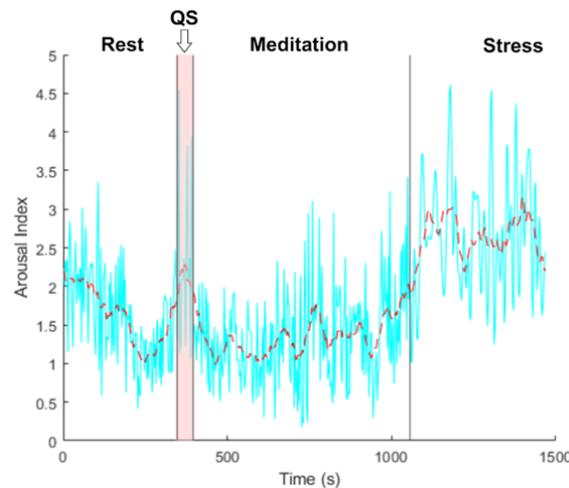


Figure 3. Transient Changes in EEG Arousal Index. The Dashed Red Line Indicates the Average Envelope of the Arousal Index for Enhanced Visual Observations of the Data.

The surface topology maps shown in Figure 4 further demonstrate the effects of stress and meditation and the overall reproducibility of the protocol in providing the desired results. With meditation, a slowing of brain activity is observed with decreased hemispheric asymmetry. Prior research has found that effective meditation led to slowed down synchronous alpha activity with an overall shift towards the parasympathetic system [50]. The stress segment in this study increased both the beta and alpha band powers as expected, with an increase in hemispheric asymmetry. This parallels prior literature that has observed increased frontal asymmetry favoring the left during stress [51].

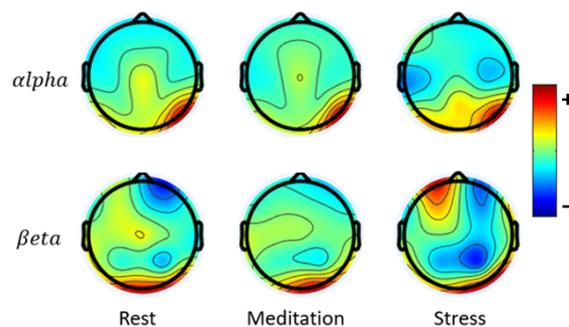


Figure 4. EEG surface Topology Maps for Alpha and Beta Band Frequencies during Each Segment.

Table 1 indicates paired t -test p -values for the aforementioned parameters. A time-frequency distribution analysis using continuous wavelet transform throughout the study is shown for one subject in Figure 5. Other subjects demonstrated similar results. Interestingly, the LF activity during the MA portion demonstrates fluctuations similar to the LF activity during the QS. The cognitive task of responding to questions in the QS and the task of mental arithmetic elicited similar variations, implicating that there may be

a significant relationship between cognitive functioning and LF EMG. Less variation is observed during the SCWT compared to the MA segment, likely due to task difficulty. Resting and meditation appeared similar in this frequency range, whereas a stark difference can be observed during the stressor.

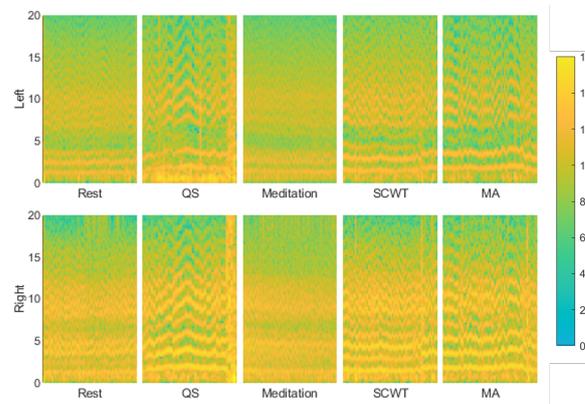


Figure 5. Time-Frequency Distribution of LF EMG PSD from 0 to 20 Hz During the Protocol. Color Represents Amplitude in dB.

Table 1. Statistical significance of EMG Features between cognitive states.

Feature			Rest vs. Stress	Stress vs. Med	Med vs. Rest
Left	PSD	LF	0.5374	0.6092	0.2199
		HF	0.3201	0.3279	0.4499
	VAR	LF	0.0023 *	0.0355 *	0.8765
		HF	0.0910	0.7800	0.0386 *
	SSI	LF	2.3828e-04 *	6.4430e-12 *	6.2021e-09 *
		HF	0.1781	2.6360e-13 *	4.0569e-04 *
	MDF	LF	5.7280e-04 *	6.0001e-07 *	3.8382e-04 *
		HF	0.0123 *	4.9363e-07 *	0.0075 *
Right	PSD	LF	0.1662	0.8771	0.1926
		HF	0.5023	0.4079	0.8108
	VAR	LF	0.0831	0.3113	0.0284 *
		HF	0.1246	0.8013	0.0183 *
	SSI	LF	4.0402e-06 *	1.2465e-12 *	7.5624e-09 *
		HF	0.0157 *	0.0010 *	0.0317 *
	MDF	LF	2.7704e-04 *	3.4723e-07 *	1.0251e-04 *
		HF	3.2553e-04 *	4.3678e-07 *	1.2133e-04 *
Asymmetry	LF	0.8077	0.0029 *	0.0013 *	
	HF	0.0172 *	0.2995	0.0946	

* Features with $p < 0.05$ are considered statistically significant.

In Table 1, both the left and right trapezius muscles appear capable of differentiating between segments on their own. An equal number of features was significant for either side. With the right trapezius muscle, there was an even split between LF and HF features in differentiating each segment. For the left trapezius, the LF features appeared to provide a greater differentiation than HF features between rest and stress and between stress and meditation, whereas HF features provided greater differentiation between meditation and rest. When asymmetry was considered, LF features allowed for differentiation between stress and meditation and between meditation and rest but not between rest and stress. HF features demonstrated an opposite trend, implicating that when meditation was involved, LF features were best at identifying a difference using trapezius muscle asymmetry. Therefore, analyzing asymmetry in the LF range can enable an improved differentiation between rest and meditation. Asymmetry in the HF range was only beneficial in differentiating between rest and stress.

Overall, mean PSD was not useful in identifying varying cognitive states. As seen in Figure 6, the mean value of this parameter did not vary significantly between each segment, regardless of which frequency range was considered. There was no preference for laterality in this feature either.

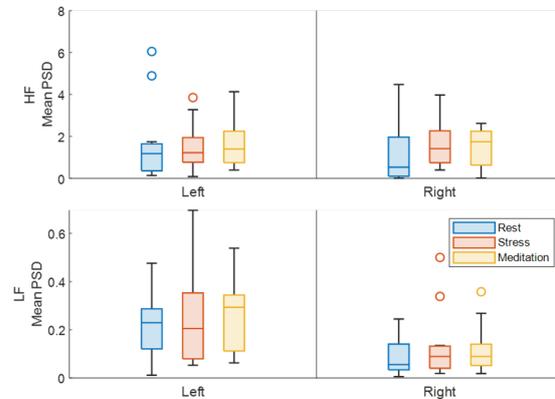


Figure 6. Distribution of Mean PSD.

An analysis of EMG variance in unilateral trapezius muscles, shown in Figure 7, indicates that LF features from the left trapezius were particularly useful in discerning rest from stress and stress from meditation but not in demarcating rest from meditation. Variance in the HF range made up for this deficit, providing significant differences between rest and meditation on the left. The right trapezius muscle allowed for differentiation only between rest and meditation in either frequency range. With this in mind, bilateral trapezius muscle analysis is required to enable accurate identification of the various states.

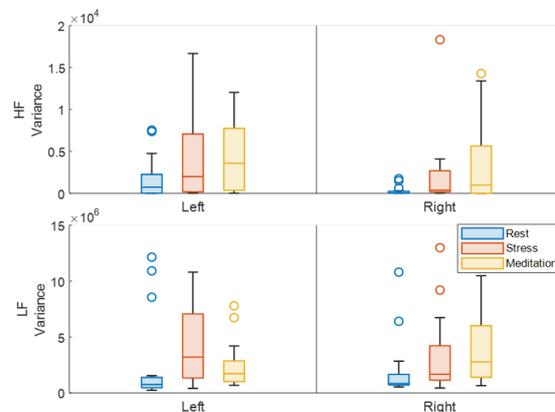


Figure 7. Distribution of Variance.

SSI is an amplitude parameter used to gauge the level of muscle activity. In the LF range, a significantly higher SSI is observed during meditation (Figure 8), which may seem counterintuitive but is secondary to the min–max normalization method applied to each segment. Applying min–max normalization to the whole dataset would have allowed for a different analysis between segments, but this method was chosen to focus more on the feature and its capability to identify the different states rather than highlighting expected trends throughout the experiment. The elevated value indicates that the LF amplitude during the meditation did not vary significantly. In that regard, stress consistently demonstrates the lowest SSI value in either frequency range bilaterally. The LF range did appear to highlight the difference between rest and stress better than the HF range as the *p*-values were much closer to zero. HF analysis of the SSI from the left trapezius muscle, on the other hand, did not allow for differentiation between the rest and stress segments. Overall,

obtaining the SSI from the LF range allowed for the best characterization of the induced neurological states.

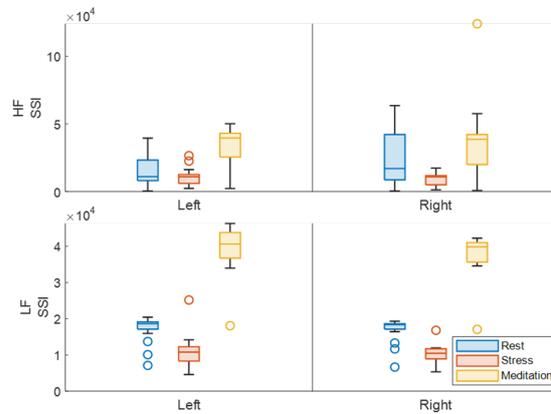


Figure 8. Distribution of SSI.

MDF was another feature that allowed for the identification of stress and meditation. In Figure 9, MDF appears to be elevated during the stressor and reduced during the meditation compared to the baseline resting. Both frequency ranges portrayed this relationship without a preference for laterality. LF asymmetry appeared beneficial in differentiating stress and meditation, and meditation from rest, but not stress from rest; Figure 10. Asymmetry in the HF range provided the opposite result in that only the rest and stress segments were characterized with significant contrast. If asymmetry were to be applied to identify various states, results from both frequency ranges would be required for best results.

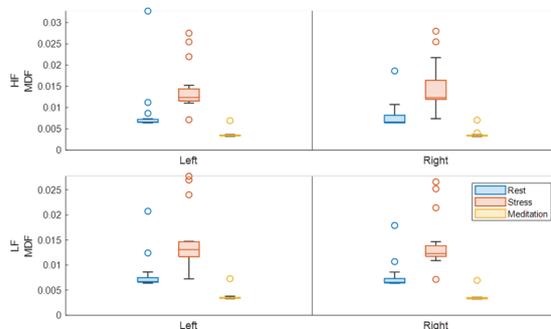


Figure 9. Distribution of MDF.

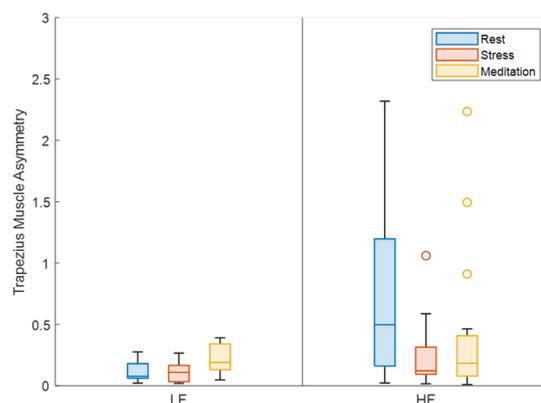


Figure 10. Distribution of Trapezius Muscle Asymmetry.

4. Discussion

In the results, LF EMG shows potential in identifying cognitive functioning and seemingly follows a pattern depending on the task performed. Greater variations in the PSD can be observed during stress, whereas slowing of activity is portrayed during meditation. This parallels the findings from the EEG topology maps, where decreased activity was observed with meditation and greater activity was observed with stress. Meditation has been shown to decrease overall EEG power [52], whereas stress results in significant increases in some spectral EEG indices [53].

Similar to how EEG asymmetry enabled the characterization of rest, meditation and stress, trapezius muscle asymmetry provided accurate identification of these states using both LF and HF EMG analysis. However, given that both trapezius muscles were useful in identifying these states on their own, a bilateral analysis is not needed but can be used to obtain additional information. LF frequency features greatly increased the identification of stress and meditation unilaterally. Analyzing HF features improved the characterization of rest and meditation. Interpreting both frequency ranges in concert can lead to improved state detection when either the left or right trapezius muscle is assessed on its own.

Mean PSD showed the lowest ability in differentiating between segments. When considering EMG variance, the left trapezius muscle appeared best for differentiating between cognitive states. Although both left and right trapezius muscles appeared equally useful in identifying rest, stress, and meditation from the SSI parameter, characterization of these segments was improved with LF analysis. Similarly, the MDF feature did not appear to indicate a preference for laterality, and either muscle was able to effectively differentiate between the different states. All participants in this study were right-hand dominant, which may have influenced these results; however, previous work analyzing nine different EMG features and various electrode positioning determined that the EMG signal of the right trapezius muscle recognized stress better than other muscles [12]. Based on previous findings and results from this study, the right trapezius muscle can be used on its own for accurate stress detection. For better observations of meditational states, a bilateral EMG signal can be beneficial.

As a more direct measure of brain activity, EEG can provide better indications regarding stress and arousal [54]. However, wearing scalp electrodes is not feasible for daily real-time monitoring. Small movements can disrupt the electrode contacts and introduce artifacts into the signal [55], preventing accurate detection. In contrast, trapezius muscle sensors can easily be placed and can provide stress-related information despite physical movements. Studies have shown that when physical stressors are present in addition to mental stressors, there is an increase in trapezius muscle EMG [25], demonstrating the effectiveness of trapezius muscle EMG in detecting stress regardless of daily activities.

5. Limitations

Fifteen subjects were considered in this study, and a paired *t*-test was performed for statistical analysis. Prior studies with similar sample sizes have also employed a paired *t*-test [17,20]. Improved statistical differences can be observed with a larger sample size and improved statistical analysis methods like the Bayesian comparison of means for paired samples [56] can be useful in identifying the differences between cognitive states. In this study, participants were instructed to adopt a comfortable seated posture with their elbows resting on armrests and to maintain a neutral head position throughout the study. This setup was chosen to create an idealized environment for measurements; however, it is important to note that this controlled scenario may not reflect real-life situations where individuals are engaged in various activities. For real-time monitoring, additional signal processing must be performed to account for motion artifacts associated with daily activities. Sensor setups should include an inertial measurement unit (IMU) to enable improved artifact detection.

6. Conclusions

Trapezius muscle EMG emerges as a promising avenue for convenient, non-invasive monitoring of cognitive states. By analyzing various EMG features, such as different frequency ranges and sensor placements, we uncovered significant changes in trapezius muscle activity during periods of stress and meditation. These findings offer valuable insights into the physiological responses associated with cognitive states. In particular, our study found that low-frequency EMG features were particularly effective in detecting stress. This suggests that certain patterns of muscle activity in the trapezius region are indicative of stress levels. Sensor configurations can be minimized to the right trapezius muscle with accurate stress identification. Additionally, the introduction of a novel method for determining asymmetry in EMG features demonstrates that applying sensors on bilateral trapezius muscles improved the detection of stress and meditation. By placing sensors on bilateral trapezius muscles, we were able to capture subtle differences in muscle activity between the left and right sides of the body, highlighting the importance of considering asymmetry in EMG analysis. Overall, our study demonstrates that refined EMG analysis can provide valuable insights into cognitive states, paving the way for more efficient and accurate stress monitoring techniques. These findings hold considerable promise for applications in various fields, including healthcare, psychology, and performance optimization.

Author Contributions: Conceptualization, M.A., M.K. and P.T.G.; methodology, M.A.; validation, A.T., M.K. and P.T.G.; formal analysis, M.A.; investigation, M.A. and M.G.; writing—original draft preparation, M.A. and M.G.; writing—review and editing, M.A., M.G., A.T., M.K. and P.T.G.; visualization, A.T., M.K. and P.T.G.; supervision, M.K. and P.T.G. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: This study was approved by the Institutional Review Board (IRB) at Florida Institute of Technology, IRB number 23-019. The research protocol was reviewed and approved by the IRB Chairperson Jignya Patel. Per federal regulations, 45 CFR 46.110, this study was determined to involve no more than minimal risk for human subjects. Federal regulations define minimal risk to mean that the probability and magnitude of harm are no more than would be expected in the daily life of a normal, healthy person. A written consent form was obtained from all participants. All data, including signed consent form documents, must be retained in a locked file cabinet for a minimum of three years (six if HIPAA applies) past the completion of this research. Any links to the identification of participants should be maintained on a password-protected computer if electronic information is used. Access to data is limited to authorized individuals listed as key study personnel.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author (accurately indicate status).

Conflicts of Interest: The authors declare no conflicts of interest.

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