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The Impact of Indoor and Outdoor Air Temperature Variations on Upper Trapezius Muscle Activity

Mohamed Naeem[1,*], Sahar Ali Fawzi[2], Hamed Anwar[3], and Abdel Salam Malek[1]

1 Textile Department, Faculty of Technology and Education, Suez University, Suez, Egypt
2 School of Information Technology and Computer Science, Nile University, Sheikh Zayed District, 6th of October City, Giza, Egypt
Systems and Biomedical Engineering Department, Faculty of Engineering, Cairo University, Giza, Egypt
3 Electrical Department, Faculty of Technology and Education, Suez University, Suez, Egypt
* Correspondence: mohamed.naeem98@yahoo.com; mohamed.naeem@ind.suezuni.edu.eg

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Abstract: Ambient temperature fluctuations impact human physiology in general, but their direct effects on muscle activity still require further investigation. This research investigates the impact of indoor and outdoor air temperature variations on the upper trapezius muscle activity using a wearable Holter unit. Twenty-three healthy participants were exposed to six different temperature levels ranging from 31 to 40°C, and their muscle activity was recorded using surface electromyography (sEMG) signals. Statistical analysis of the acquired sEMG data, after preprocessing, included the calculation of integrated electromyography (iEMG) and Teager-Kaiser Energy Operator (TKEO) metrics. The results indicate that at 37°C and 40°C, iEMG values showed a decrease of 5.9% and 6.5% respectively, suggesting impaired muscle activation. Analysis of variance (ANOVA) revealed significant differences in both iEMG and TKEO values at 37°C ($p = 0.0093$ and $p = 0.0130$, respectively) and at 40°C ($p = 0.0056$ and $p = 0.0229$, respectively). These findings provide new insights into the detrimental effects of elevated temperatures on crucial musculoskeletal functions. Exposure to temperatures above 37°C specifically weakens trapezius activation.

Keywords: Air temperature variations, Environmental stressors, Upper trapezius muscle, sEMG measurements, Stress management and Occupational health

1. Introduction

Variations in air temperature have long been known to impact human physiology and performance [1]. High temperatures, especially during the summer months, can induce unfavorable physiological changes in the body and affect muscular activity. Understanding how air temperature influences specific muscles, including skeletal muscles, is crucial for comprehending human responses to environmental stressors.

The upper trapezius muscle, located in the upper back and neck region, holds particular significance among the skeletal muscles that may be impacted by environmental conditions. This muscle is involved in various movements and postural adjustments that are closely linked to measuring mental stress levels and assessing cognitive fatigue [2]. However, further investigation is needed to understand the direct impact of air temperature fluctuations on upper trapezius muscle activity. Exploring the impacts of air temperature on the upper trapezius can provide valuable insights into the interplay between environmental conditions and muscular responses [3]. This knowledge is essential for accurately assessing stress and understanding how the body adapts to various environmental stressors. Additionally, it can help in developing strategies to mitigate the adverse effects of the environment on skeletal muscle function [4].

Many studies have explored the effects of various stressors on the upper trapezius muscle, including mental tasks, cognitive challenges, and emotional stressors. These stressors have been shown to stimulate the mind and elicit specific responses in the muscles. However, the direct influence of environmental stressors, particularly variations in air temperature, on upper trapezius muscle activity remains understudied.

Girard et al. [5] examined 12 physically active participants exposed to neutral (24°C, 30% relative humidity (RH)) or hot (35°C, 40% RH) environments during repeated sprint cycling. Findings indicated that hot conditions did not significantly impact neuromuscular fatigue characteristics. Dennis et al. [6] examined 13 male team-sport athletes exposed to cool (20°C), hot (35°C), and very hot (40°C) environments (50% RH in all conditions) during repeated sprint cycling in hypoxia. Muscle oxygenation of the vastus lateralis was measured. Findings indicated that increasing air temperatures to 35°C and 40°C amplified muscle deoxygenation and reoxygenation responses compared to 20°C, without decreasing peak power, mean power, or total work performance. Racinais et al. [7] examined 14 non-heat-acclimated males completing trials in thermoneutral conditions (24°C, 40% RH) and hot conditions (44-50°C, 50% RH) before and after 11 days of heat acclimation. Findings suggest that repeated heat exposure benefits muscle function. Périard et al. [8] studied 12 male cyclists performing incremental exercise in hot (35°C) and cool (18°C) conditions. Voluntary activation of the knee extensors was reduced during cycling in the heat compared to the cool condition. Thomas et al. [9] studied 12 males who underwent leg muscle function tests before and after passive heating to increase core temperature by 1°C. They found that voluntary muscle activation was impaired by increased core temperature but not by local muscle temperature. Todd et al.[10] studied 10 males who performed elbow flexor muscle contractions before and after passive heating to increase core temperature by 1.6°C. They found impaired voluntary muscle activation and contraction force at high core temperatures, indicating a failure of the motor cortex and muscle function. Racinais and Oksa [11] reviewed studies on neuromuscular function during hyperthermia. They concluded that impaired muscle strength and activation at high core temperatures are likely due to central fatigue originating in the brain, specifically in the motor cortex.

Despite the valuable contributions provided by the mentioned studies, some potential limitations should be acknowledged. One such limitation is the small sample sizes used in some studies, which impact the generalizability of the results. While several studies have been conducted under artificially controlled laboratory temperatures, this research investigates the effects of natural ambient temperature variations on certain muscle activities. Additionally, conclusions regarding the effects of heat on muscles were mixed. Some studies reported negative impacts, while others concluded positive effects or no influence. Most studies have focused on lower body muscles, with minimal attention paid to the upper trapezius, despite its importance for practical outcomes. Moreover, wearable devices were rarely utilized, even though facilitating outdoor measurements with such tools could enhance accuracy and provide additional real-life insights. By addressing limitations related to small sample sizes, controlled settings, variable results, muscle selection, and measurement tools, future research can produce more definitive and ecologically valid insights into the effects of heat on musculoskeletal function.

Our study aims to examine the direct effects of indoor and outdoor air temperature variations on upper trapezius muscle activity to provide insights into how environmental temperature impacts muscular function and performance. By focusing on the upper trapezius, we can enhance our understanding of how temperature fluctuations influence muscle activity in various contexts.

The findings can inform the development of effective strategies for stress management and performance optimization in occupational, sports, and rehabilitation settings. In particular, understanding how the upper trapezius muscle responds to temperature variations may help in designing targeted interventions to mitigate the adverse effects of environmental stressors on muscle function for workers in extreme temperature environments. Moreover, our approach utilizes wearable devices and naturalistic measurements, enhancing ecological validity compared to laboratory studies alone. The practical insights gained can help bridge the gap between controlled experiments and complex real-life conditions across various applied settings.

The research is organized into the following main sections:

1. Introduction: provides background information and explains the rationale for the study.
2. Experimental work: describes the participants, eligibility criteria, signal acquisition methods, measurement context and procedures, and statistical analysis approaches used.
3. Results: presents the findings from the TKEO visualization and ANOVA analysis, detailing the variations in muscle activity and energy levels under different temperature exposures.
4. Discussion: interprets the results, compares them to previous research, highlights limitations, and suggests future research directions.

5. Conclusion: Summarizes the main outcomes and implications of the study.

The research also includes tables and figures to visually represent key data and concepts throughout the various sections.

2. Experimental Work

This study employed a comprehensive experimental protocol to investigate the effects of varying ambient temperature levels on upper trapezius muscle activity. The overall workflow, as illustrated in the flowchart (Figure 1), involved a repeated measures design, wherein each participant underwent multiple cycles of temperature exposure and data acquisition. The study commenced with participant selection based on predefined eligibility criteria. For each temperature level, denoted as T1 through T6, the following steps were systematically executed: First, participants were exposed to a controlled, temperate environment to establish baseline muscle activity measurements, and sEMG recordings were obtained from the upper trapezius muscle to capture baseline muscle activity patterns. Subsequently, participants were exposed to different experimental temperature conditions (T1 through T6), representing progressively higher ambient temperatures. During this period, sEMG signals were recorded to evaluate changes in muscle activity in response to the thermal stress.

The acquired sEMG data then underwent preprocessing and statistical analysis, including the calculation of iEMG and TKEO metrics. The statistical significance of the observed differences in muscle activity between the baseline and experimental temperature conditions was evaluated using ANOVA with a predetermined significance level ($p < 0.05$). Based on the statistical analysis results, conclusions were drawn regarding the effect of temperature on upper trapezius muscle activity.

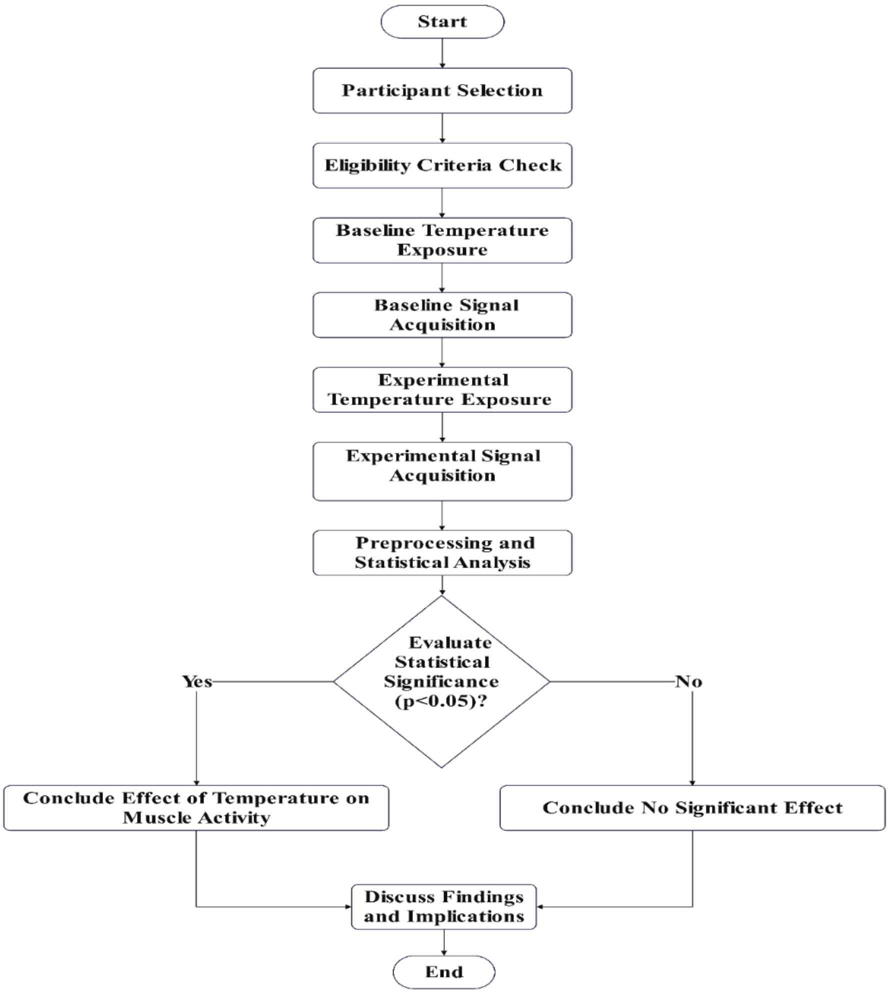

Figure 1 Flow chart of the study.

2.1 *Description of Selected Participants*

Twenty-three healthy, right-handed participants (16 males and 7 females) were selected for the study. All participants provided informed consent and willingly agreed to participate. Table 1 summarizes the key descriptive statistics of the study participants. It displays the mean and standard deviation (SD) values for the age, weight, height, and body mass index (BMI) of the subjects who consented to be included.

Table 1 Descriptive statistics of study participants

	Age (years)	Weight (kg)	Height (cm)	BMI (kg/m2)
Mean	30.91	68.04	169.4	23.62
SD	±10.71	±7.71	±6.63	±1.16

Eligibility Criteria to Participate in The Experiments

Participants needed to be healthy and free of any shoulder muscle issues or conditions sensitive to temperature changes. Individuals with psychological conditions that could interfere with the measurement process were excluded to ensure accurate and reliable data collection.

Participants were instructed to avoid consuming fatty meals one hour before each measurement session to minimize the potential impact of food intake on muscle activity [12]. They were advised to wear lightweight and breathable clothing made of cotton or similar materials suitable for the summer season. This clothing choice aimed to facilitate adaptation to warm weather conditions while ensuring comfort and breathability. Participants were also asked to refrain from engaging in strenuous exercise for 24 hours before each session to manage fatigue.

2.2 *Measuring Muscle Activity*

Surface electromyography (sEMG) signals were recorded from the upper trapezius muscle using the muscle sensor v3 [13 – 15]. Sensor electrodes were placed over the upper trapezius muscle following the surface electromyography for the non-invasive assessment of muscles (SENIAM) guidelines [16]. The sensor was connected to a custom-designed, lightweight data acquisition unit. The unit was equipped with a rechargeable lithium-polymer battery, an LED display for battery level indication, and an ESP32 microcontroller for analog data conditioning and bluetooth transmission [18 ,17]. The sEMG signals were sampled at 1000 Hz by the ESP32 microcontroller before being wirelessly transmitted to a laptop via Bluetooth for further analysis. The raw data underwent preprocessing on the laptop, which involved bandpass filtering between 10-400 Hz using a 2nd-order Butterworth filter to remove motion artifacts and high-frequency noise. Subsequently, the root mean square (RMS) of the filtered sEMG signal was calculated using a moving window approach with a window size of 50 ms. Figure 2 illustrates the block diagram of the signal acquisition system. Figure 3 illustrates a sEMG Holter, showing the placement of sensor electrodes over the upper trapezius muscle, the measured signal before and after preprocessing, and the RMS of the signal.

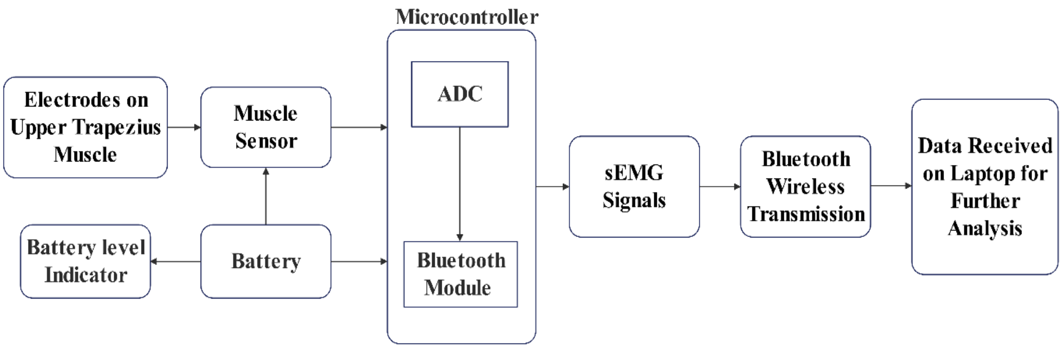

Figure 2 Block diagram of the signal acquisition system.

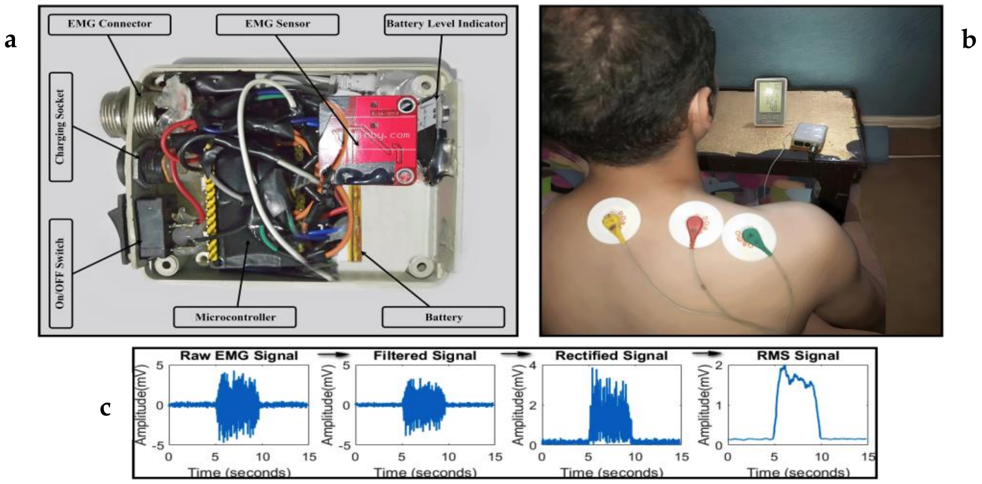

Figure 3 Measuring Muscle Activity
a) sEMG Holter b) Electrodes placement during measurement c) Preprocessed Signal

The measurements were conducted both indoors and outdoors during the summer season in August. The study was conducted in Zagazig, Egypt, where the average summer temperatures reach 42°C during the day [19]. The study included three different periods throughout the day: morning, afternoon, and evening. Air temperature and humidity were measured using a DC-803 digital LCD temperature thermometer [20]. Noise levels were measured using a UT353 digital sound level meter [21]. To effectively detect differences in muscle activity levels, the measurements were divided into two stages.

2.2.1 Baseline Measurements Stage

This stage is referred to as the pre-exposure stage and is conducted before exposure to high ambient temperatures. During this stage, muscle activity signals were considered as the reference signal. The measurements were conducted in an air-conditioned room with a controlled temperature of 25°C. This stage was repeated during the three different periods while maintaining a constant, moderate temperature of 25°C. This repetition accounted for potential variation in muscle activity signals throughout the day due to circadian rhythm effects [22].

2.2.2 Experimental Temperature Exposure Stage

This stage is referred to as the post-exposure stage and is conducted after exposure to high ambient temperatures. This stage involved measurements taken during three different periods, both outdoors and indoors. For outdoor measurements, the noise level was maintained between 30 and 40 decibels by selecting low-traffic areas. Exposure to higher noise levels could potentially influence the stress levels of participants and affect the measurements [23]. Participants' exposure to humidity was consistent throughout each period to avoid any additional influences on the measurements. Similarly, indoor measurements were conducted in a controlled room environment with one electric lamp for illumination, and ventilation was provided through an open window. No fans or air conditioning units were in operation during the indoor measurements. The measurement periods are shown in Table 2.

Table 2 the measurement periods and temperature

Temperature	Average Temperature Value (°C)	Time	Environment	Humidity Range
T1	31	7:00 PM - 9:00 PM	Outdoor	50-60%
T2	33	7:00 PM - 9:00 PM	Indoor	50-60%
T3	34	9:00 AM - 11:00 AM	Outdoor	60-70%
T4	35	9:00 AM - 11:00 AM	Indoor	60-70%
T5	37	2:00 PM - 4:00 PM	Indoor	40-60%
T6	40	2:00 PM - 4:00 PM	Outdoor	40-60%

2.3 Measurement Procedure

Our study utilized a within-subject design with a counterbalanced order of indoor and outdoor environments. Each participant underwent bilateral EMG measurements of their upper trapezius muscles in both environments.

Each measurement session lasted one hour, with 30 minutes spent indoors and 30 minutes outdoors. Maximum voluntary contraction (MVC) of the trapezius muscles was performed before each session under controlled, moderate thermal conditions to obtain reference EMG signals. MVCs were also measured at the end of each session to evaluate the maximum muscle activity after exposure to each environment.

Participants received guidance throughout the sessions to ensure consistent and repeatable measurements. After completing measurements in one environment, participants rested in an air-conditioned room for 30 minutes to recover and acclimate to the new conditions before starting the next set of measurements. This break helped relax their muscles and minimize potential fatigue effects.

The complete measurement procedure was repeated three times for each participant across all periods and environments, enabling within-subject comparisons while controlling for potential confounding from circadian rhythm effects.

2.4 Statistical Analysis

Integrated electromyography (iEMG) values, which represent the mean amplitude over time, were extracted from the raw sEMG signals recorded by the surface electrodes. The iEMG was calculated using Equation (1).

$$\text{iEMG} = \sum \left| x(n) \right| \qquad \text{Eq. (1)}$$

where x(n) represents the EMG signal at the nth sample, and Σ denotes the summation over the entire time window. This provided a measure of the total motor unit activity in the upper trapezius muscle during each temperature period. We also illustrated the differences using Teager-Kaiser Energy Operator (TKEO) visualizations, which depict changes in signal energy over time, revealing variations between periods. The TKEO was calculated using Equation (2).

$$TKEO[x(n)] = x(n)^2 - x(n-1) * x(n+1) \qquad \text{Eq. (2)}$$

Both the iEMG data and TKEO waveforms were analyzed using one-way repeated measures analysis of variance (ANOVA). This statistical test enabled the comparison of metrics between the different temperature periods (T1–T6) for each participant. By having each subject act as their own control, this within-subject design mitigated any effects of individual variability. Baseline values obtained before exposure to heat stress were used as a reference point for comparison with values obtained during the actual exposure periods. A statistically significant effect was defined as $p < 0.05$.

3. Results

3.1 TKEO Visualization

The TKEO is a local oscillatory signal energy tracking measure that can be easily and efficiently implemented [24, 25]. TKEO provides an instantaneous energy measurement that can detect subtle changes in muscle activity.

Analyzing signals using the TKEO revealed noticeable variations between the different temperature exposure periods. Specifically, the TKEO profiles demonstrated distinct trends during the T5 and T6 periods, reflecting changes in the energy of the muscle contractions. This suggests that the muscle signals have varying energy content in response to the temperature changes in T5 and T6. Additionally, smaller differences were observed between the TKEO profiles from T1 to T4.

The TKEO findings indicate that temperature changes influence muscle behavior and contraction energy. Figure 4 shows EMG signals and their TKEO profiles under varying temperature conditions. The TKEO visualizations facilitate the quick identification of signal changes over time.

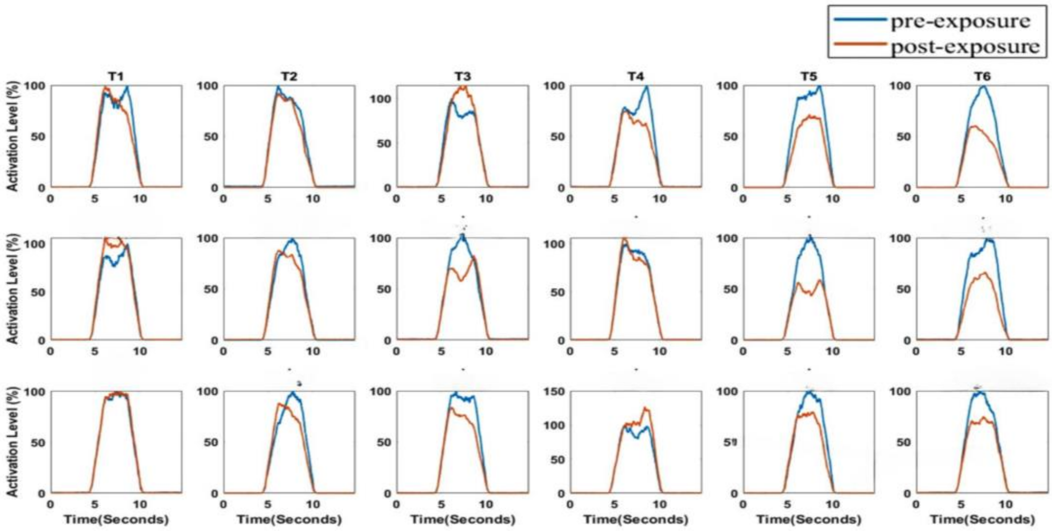

Figure 4 TKEO Visualization

3.2 ANOVA Analysis

Both iEMG and TKEO metrics provide valuable insights into changes in muscle activity under different conditions. While iEMG measures cumulative electrical activity over time, TKEO indicates instantaneous shifts in contraction intensity.

Our analysis utilized both iEMG and TKEO to measure changes in upper trapezius muscle function during the various temperature periods. Understanding these variations is essential for assessing environmental impacts on muscles. The null hypothesis is that there is no difference between EMG signals at different temperatures. The alternative hypothesis is that the mean EMG signals at different temperatures are not equal. The results demonstrated significant decreases in Upper Trapezius activity during T5 and T6, as indicated by the iEMG and TKEO analysis. To evaluate the significance of these observations, ANOVA tests were conducted, as depicted in Table 3, Figure 5, and Figure 6.

Based on the ANOVA results presented in Table 3, the between-groups analysis of iEMG showed a marginally significant effect, indicating that the changes in ambient temperature had a noticeable impact on the overall upper trapezius muscle activation patterns. In contrast, the between-groups analysis of TKEO did not reveal a statistically significant difference, suggesting that the instantaneous muscle contraction energy was not strongly influenced by the temperature variations.

Table 3 ANOVA analysis results

ANOVA results	**iEMG**		**TKEO**	
	Between Groups	**Within Groups**	**Between Groups**	**Within Groups**
Sum of Squares (SS)	1767	8293	3743	25749
Degrees of Freedom (DF)	11	22	11	22
Mean Square (MS)	160.6	377	340.3	1170
F-statistic	2.432	5.709	1.821	6.263
P value	P=0.0681	P<0.0001	P=0.1598	P<0.0001

However, the within-groups analysis for both iEMG and TKEO metrics demonstrated highly significant effects, highlighting substantial individual differences in muscle activity and contraction energy among the participants, regardless of the temperature conditions. These findings underscore the importance of considering individual variability when examining the effects of environmental factors on muscle function.

Furthermore, when examining the p-values for each individual temperature period separately, statistically significant differences in both iEMG and TKEO metrics were observed specifically during the T5 (37°C) and T6 (40°C) conditions, as depicted in Figure 5 and Figure 6. For iEMG, the p-value for T6 was 0.0056 and for T5 was 0.0093, indicating a statistically significant difference. Similarly, the TKEO p-values of 0.0130 at T6 and 0.0229 at T5 also signify noticeable changes in contraction energy between periods.

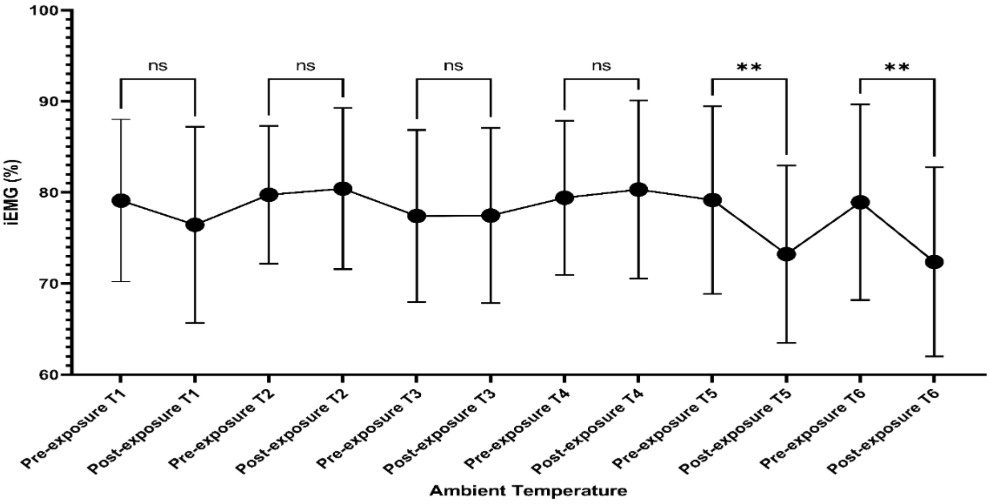

Figure 5 iEMG analysis.

On the other hand, the p-values for the remaining periods were greater than 0.05, suggesting no significant differences in muscle activity during those periods.

The observed decrease in Upper Trapezius muscle activity during the T5 and T6 periods, corresponding to the highest temperature conditions, suggests that high ambient temperatures may lead to muscle weakness or reduced muscle activation. These findings align with previous research indicating that heat exposure can affect muscle performance [8 - 10].

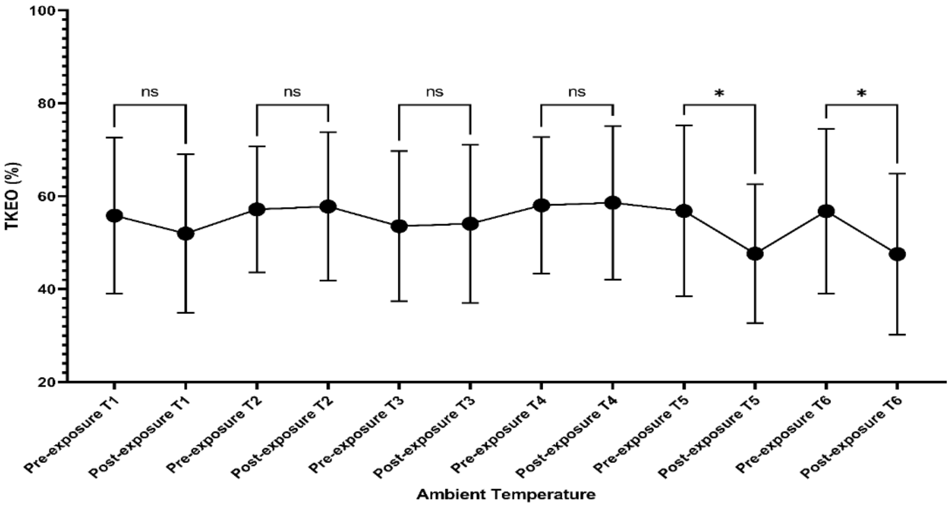

Figure 6 TKEO analysis.

The calculation and analysis of percentage differences in the iEMG values, as shown in Figure 7, provide additional insight into the magnitude of the observed changes in muscle activity. In our study, we observed a decrease of 6.5% at T6 and 5.9% at T5 compared to the pre-test values.

Moreover, the percentage differences can serve as a valuable metric for comparing the effects of various environmental conditions or interventions on muscle activity. They provide a standardized measure that allows for direct comparisons and facilitates the identification of patterns or trends across multiple data sets.

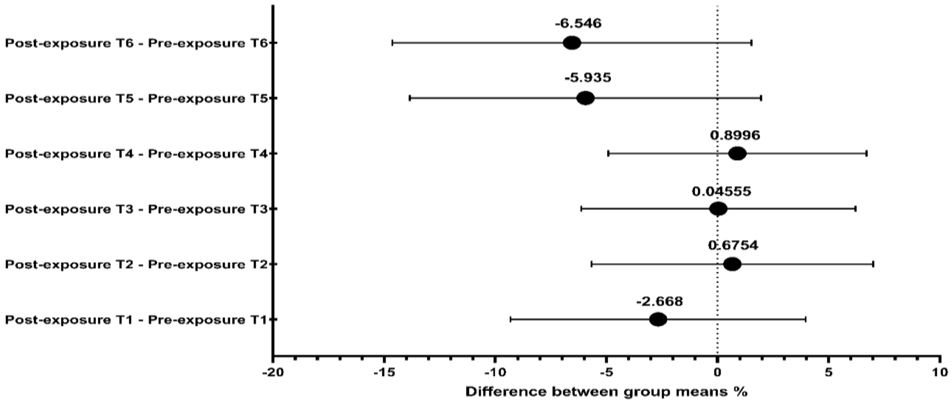

Figure 7 percentage of difference between pre-exposure and post-exposure groups.

To elucidate the sex-based differences in upper trapezius muscle responses to heat stress, the percentage of mean difference values was calculated between male and female muscle activity across a range of temperatures.

Figure 8 illustrates the temperature-dependent percentage of the mean difference in upper trapezius muscle activity between males and females. At T5, males showed a mean difference of 4.2%, while females had a mean difference of 9.8%. Similarly, at T6, males exhibited a 4.3% change, while females displayed an11.4% change.

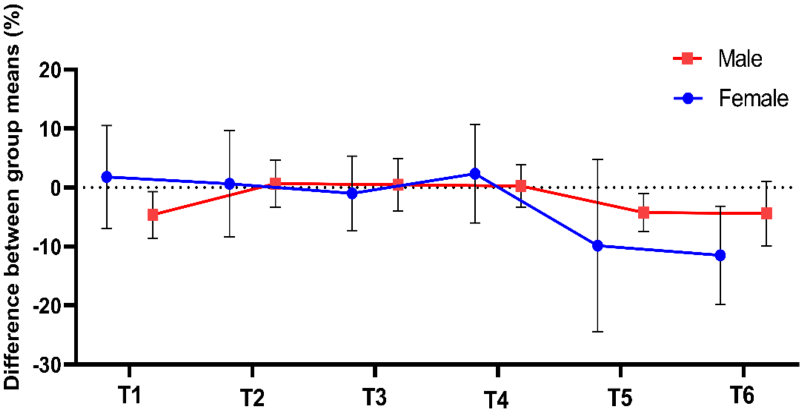

Figure 8 percentage of difference between males and females.

4. Discussion

The key finding is that extreme heat exposure impairs upper trapezius activation, as evidenced by declined iEMG and TKEO metrics during peak temperature periods T5 and T6. TKEO uniquely revealed neuromuscular signal energy reductions, substantiating altered motor unit firing. Quantified iEMG decreases of 6.5% at 40°C and 5.9% at 37°C signify impaired muscle performance resulting from profound heat strain.

The results indicated a significant difference between males and females in the decline of upper trapezius muscle function during heat exposure. The larger negative mean difference values for females compared to males at both T5 and T6 indicate that women's upper trapezius muscles were more significantly affected by the elevated heat exposure. Potential reasons may include females having higher subcutaneous fat levels, lower sweat rates, and hormonal influences that collectively reduce their heat tolerance. While the sample sizes between the male (n = 16) and female (n = 7) groups were uneven, the results still provide preliminary evidence that females experience greater muscular disruptions at high temperatures. However, future investigations with larger and more balanced samples are warranted to definitively conclude whether significant gender-based differences exist in trapezius heat tolerance. Potential influencing factors such as subcutaneous fat, sweat rates, and hormones must also be measured and controlled.

The observed neuromuscular disruptions likely stem from heat-induced changes in motoneuron excitability, conduction velocity, muscle perfusion, and cardiovascular function [26]. Thermal extremes exceed the body's ability to maintain homeostasis, leading to decreases in voluntary force and endurance [27].

However, the absence of significant decreases in both iEMG and TKEO metrics during the lower temperature periods of T1-T4 suggests that muscle activity remains largely unaffected below a certain threshold of thermal strain. Nevertheless, it is likely that subtle reductions in activity still occur during T1-T4 but were simply not captured within the limited periods of heat exposure. Although the iEMG findings were insignificant during these periods, small deviations emerged in the TKEO analysis, suggesting early signs of thermal stress. During the T1 period, with an average temperature of 31°C, the TKEO profiles did not exhibit a significant difference in comparison to the baseline energy levels in the muscle signals. As the temperature increased to 33°C in T2, the TKEO profiles showed a gradual decrease in energy content, suggesting that the muscle contractions were becoming less vigorous in response to the warming environment. In T3, where the average temperature was 34°C and represented outdoor conditions, the decrease in TKEO values was more pronounced compared to T4, despite T4 having a higher average temperature of 35°C in indoor settings. The more significant decrease in TKEO during T3 could be attributed to the additional environmental factors associated with outdoor exposure, such as direct sunlight and wind, contributing to a greater impact on muscle activity and energy levels. This highlights the superior sensitivity of TKEO for detecting subtle activity changes that are missed by conventional analyses.

Future research should involve longer exposure durations to further stress the thermoregulatory systems and reveal diminished neuromuscular function across a broader spectrum of thermal loads.

Additionally, evaluating a broader range of muscles would provide a more comprehensive overview of how heat strain manifests in a region-dependent manner. Nonetheless, the results significantly advance our understanding of how heat stress challenges neuromuscular systems [28].

5. Conclusion

Our study investigated the impact of high ambient temperatures on upper trapezius muscle activity by utilizing a wearable surface EMG Holter system. The results demonstrated a statistically significant decrease in both integrated electromyography (iEMG) and Teager-Kaiser Energy Operator (TKEO) metrics during the highest temperature periods (T5 at 37°C and T6 at 40°C) compared to baseline measurements.

Specifically, the iEMG analysis revealed a 5.9% decrease in muscle activation at T5 ($p=0.0093$) and a 6.5% decrease at T6 ($p=0.0056$), indicating impaired muscle performance under heat strain. Similarly, the TKEO analysis showed significant reductions in contraction energy at T5 ($p = 0.0229$) and T6 ($p = 0.0130$), substantiating altered motor unit firing patterns.

The convergence of these two metrics, along with the TKEO visualizations depicting distinct changes in signal energy, strengthens the finding that high temperatures may lead to transient muscle weakness or reduced muscle activation. Furthermore, our results indicated a significant gender-based difference, with females showing a greater decline in upper trapezius muscle function compared to males during heat exposure, suggesting potential physiological variations in heat tolerance.

During lower temperature periods (T1-T4), the effects were insignificant. However, subtle deviations emerged in the TKEO profiles, indicating early signs of thermal stress even at moderately elevated temperatures. These findings advance our understanding of how heat strain challenges neuromuscular systems and highlight the potential for wearable EMG technology to monitor real-world muscle function under varying environmental conditions.

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