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The Effect of Acute Physical Fatigue on Information Processing, Pain Threshold and Muscular Performance

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Abstract: This study explores the multifaceted effects of acute physical fatigue on information processing, pain threshold, and muscular performance. Enrolling 28 recreational athletes, we used a high-intensity interval training (HIIT) protocol to induce fatigue and conducted pre- and post-intervention assessments. Our findings revealed significant physiological and performance adaptations following the HIIT sessions. Key observations included increased heart rate and rate of perceived exertion and an enhancement in horizontal jump performance and isometric hand strength but no significant change in cognitive processing speed. Remarkably, participants demonstrated a notable increase in pain threshold and blood lactate levels post-exercise. These results challenge traditional views of fatigue, indicating not only a physiological but also a psychological resilience to high-intensity stress. This study provides new insights into the complex interplay between physical fatigue, cognitive function, and pain perception, highlighting the comprehensive effects of HIIT on both physiological and psychological dimensions of human performance.

Keywords: acute physical fatigue; high-intensity interval training; muscular performance; pain threshold; cognitive processing

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1. Introduction

Acute physical fatigue profoundly impacts multiple facets of human physiology and psychology, particularly in the domains of muscular function, cortical function, and pain perception. This significance stems from the observation that fatigue not only affects individual health and well-being but also has critical implications for athletic performance, influencing both short-term outcomes and long-term adaptations. This comprehensive exploration integrates various strands of research to offer a cohesive understanding of these interrelated phenomena, thereby underscoring the importance of addressing fatigue in sports science and clinical practice [1–3].

Muscular function is significantly affected by acute physical fatigue, which manifests as a decline in the muscle's ability to generate force. This decline is influenced by a multitude of factors, including metabolic changes, the depletion of energy reserves, and altered recruitment of muscle fibers [4]. During high-intensity activities, muscle fibers experience significant changes such as decreased phosphocreatine stores, lactate accumulation, and ion balance disruption, contributing to fatigue [5]. Additionally, the generation of reactive oxygen species during intense physical activities leads to oxidative stress, further impacting muscle function [6]. Central fatigue also plays a crucial role, involving neural factors like motor neuron excitability and voluntary activation [7]. Furthermore, recent advancements in understanding muscular function under fatigue reveal the concept of 'muscle wisdom', where there is a reduction in motor unit firing rates during prolonged activities to preserve muscle force output [8]. Furthermore, near-infrared spectroscopy has provided deeper insights into muscle oxygenation and energy metabolism during fatigue [9], underscoring the complex physiological and biochemical interplay in muscles under exhaustive conditions.

The impact of fatigue on cortical function, including processes like motor control, decision-making, and cognitive functions, is profound. Fatigue can alter cortical excitability and the efficiency of neural pathways involved in these processes [10]. It can lead to decreased attention, reaction time, and decision-making abilities, critical in sports performance [11]. Furthermore, recent neuroscientific developments have shown that physical fatigue significantly alters brain activity, particularly in the prefrontal cortex, implicating a direct link between fatigue and cognitive impairment [12]. Transcranial magnetic stimulation studies have demonstrated changes in motor-evoked potentials with fatigue, suggesting alterations in synaptic efficacy and neuronal excitability in the motor cortex [13]. Fatigue impairs the brain's ability to filter out irrelevant stimuli, leading to decreased attentional focus [14], and biases individuals towards more impulsive decision-making [15]. The interaction between mental and physical fatigue highlights the need to consider both aspects in sports and athletic performance [16].

Pain perception, a complex interplay between sensory input and psychological factors, is also influenced by physical fatigue. It is modulated by physiological impacts of exercise and psychological factors like attention, emotion, and motivation [17]. Athletes often exhibit higher pain thresholds, possibly due to physiological adaptations and psychological conditioning [18]. Indeed, studies have highlighted the phenomenon of exercise-induced hypoalgesia, where acute exercise leads to a temporary reduction in pain sensitivity, particularly evident in endurance athletes [19]. This is attributed to physiological factors, like the release of endorphins and endocannabinoids, and psychological factors such as increased pain tolerance due to regular exposure to physical stress [20]. Mental fatigue exacerbates pain perception and impairs performance, indicating a complex link between cognitive fatigue, pain processing, and physical performance [13].

Therefore, the effects of acute physical fatigue on muscular and cortical functions and pain perception are intricate and multifaceted. The ongoing research in these areas continues to refine our understanding, emphasizing the importance of addressing both physiological and psychological aspects in managing fatigue and optimizing athletic performance. This integrated approach offers crucial insights for enhancing training regimens, recovery strategies, and overall performance in sports and athletics. High-intensity interval training (HIIT), a training method that alternates short anaerobic efforts with brief recovery periods, is recognized for its significant benefits to physical conditioning and mental health [21–24]. While numerous studies highlight HIIT's effectiveness, it is acknowledged that other training methods, such as Moderate Continuous Training (MCT) and Sprint Interval Training (SIT), also offer valuable benefits. The comparative effectiveness of these methods varies depending on individual goals, preferences, and physiological responses [25,26].

Thus, this current study, conducted under an intervention-based research design, aims to empirically investigate the effects of acute physical fatigue brought about by a specific intervention with HIIT. Our hypothesis is that the intervention, designed to induce acute physical fatigue, will have observable impacts on athletes' information processing abilities, pain thresholds, and muscular performance. By measuring these variables pre- and post-intervention, this study seeks to provide concrete evidence on how acute physical fatigue manifests in these key areas. Such a research design, focusing on before-and-after comparisons following a specific intervention, is crucial in understanding the direct consequences of fatigue on athletic performance and recovery strategies.

2. Materials and Methods

2.1. Experimental Approach

In our study, the experimental approach was meticulously designed to comprehensively evaluate the effects of high-intensity interval training (HIIT) on acute physical fatigue and its subsequent impacts on physiological, psychological, and performance-based metrics. Participants underwent a series of pre-, during-, and post-exercise assessments, including heart rate monitoring for cardiovascular response, the Borg Scale for perceived exertion, dynamometry for upper body strength, horizontal jump tests for lower body power, blood lactate concentration analysis for metabolic stress, and a mobile app-based reaction time test for cognitive function. These diverse and rigorous measures were chosen to capture the multidimensional effects of acute physical fatigue induced by HIIT, ensuring a holistic understanding of its impact on recreational athletes. By leveraging state-of-the-art technology and established testing protocols, our methodology offers a robust framework for dissecting the complex interplay between physical exertion and its wide-ranging consequences, thereby providing valuable insights into optimizing training regimens and enhancing overall human performance. This experimental approach underscores the study's goal to elucidate the comprehensive effects of HIIT, facilitating a deeper comprehension of its physiological and psychological dimensions.

2.2. Study Participants

The study enrolled 28 recreational athletes, consisting of 25 men and 7 women, all of whom engaged in a variety of athletic activities. This mix provided a rich basis for assessing the universal applicability and benefits of high-intensity interval training (HIIT) across different sports disciplines, allowing for a comprehensive analysis of HIIT's effects on physical fatigue and recovery in a recreational athletic population. The participants had an age of 22.61 years (SD = 3.15) and had a mean body weight of 64.13 kg (SD = 7.64). Their average height was 1.71 m (SD = 0.07), and the mean body mass index (BMI) was 21.58 (SD = 1.89). The participants were recruited based on their engagement in regular recreational athletic activities. Ethical approval for this study was granted by the university's ethics committee (approval number: CI-PI/21/082). All participants provided written informed consent prior to their involvement in the study, adhering to ethical guidelines.

2.3. Acute Fatigue Protocol

This study's primary aim was to examine the effects of acute physical fatigue, induced through a HIIT protocol. HIIT is known to elicit significant psychophysiological responses and efficiently induce fatigue in a short timeframe [27].

The HIIT protocol commenced with a standardized warm-up: 5 min of light aerobic running at 50−60% of their maximum heart rate, calculated using Tanaka's Formula '208–0.7 $\times$ age' [28], followed by 2 series of 20 m of progressive running intensity. The main HIIT session consisted of 2 series of 10 repetitions of 30 s maximal running, interspersed with 30 s intervals of passive rest, and a 3 min passive rest between the series. This design was based on established HIIT protocols shown to be effective in eliciting acute fatigue [29].

2.4. Parameters Analyzed

To evaluate the impact of the HIIT protocol on various physiological and psychological parameters, we employed a series of tests conducted before, during, and after the HIIT sessions. These tests were carefully selected to provide a comprehensive overview of the participants' performance and condition, ensuring a multifaceted understanding of the effects of acute physical fatigue. It is crucial to note that all the participants had previous experience with these tests, effectively minimizing the potential for a learning effect that could skew the results. This prior familiarity allows for more reliable assessments of changes attributable to the HIIT protocol itself rather than improvements in test performance due to repeated exposure.

Cardiovascular Response: To assess the cardiovascular response to the HIIT protocol, we monitored participants' heart rate (HR) in real-time using a Polar V800 heart rate monitor, a sophisticated device known for its accuracy and reliability in capturing heart rate data. This device, manufactured by Polar Electro in Kempele, Finland, is specifically designed for sports and fitness research, offering precise heart rate measurements that are crucial for evaluating the intensity and effectiveness of the HIIT sessions. By analyzing these heart rate data, we could determine how participants' cardiovascular systems reacted to the stress of high-intensity exercise, providing valuable insights into their physical condition and endurance capabilities [30].

Rate of Perceived Exertion (RPE): The subjective intensity of the training sessions was quantified using the Borg Scale, a widely recognized method for assessing perceived exertion. This scale ranges from 6 to 20 levels, where higher numbers correspond to higher levels of exertion [31]. The Borg Scale is an effective tool for measuring an individual's perception of exercise intensity, allowing for a subjective assessment that complements the objective physiological data collected. By employing this scale, we could gauge participants' subjective experiences of the HIIT protocol, offering a holistic view of its impact.

Upper Body Muscular Performance: To evaluate the muscular performance of the upper body, we used a dynamometer to measure the maximum isometric contraction force of the dominant hand. This test, conducted with a device from Takei Kiki Koyo, Japan, is a standard measure of grip strength but also serves as an indicator of overall upper body strength. Participants were asked to perform the test twice, with the highest value recorded for analysis. This approach ensures accuracy and reliability in assessing the muscular endurance and strength gains from the HIIT sessions [32].

Lower Body Muscular Performance: Lower body muscular performance was assessed through a horizontal jump test, which is a simple yet effective measure of leg power and explosiveness. Participants were instructed to jump as far as possible with their hands placed on their waist to prevent the use of arm swing, thus focusing the assessment on leg strength. The test was performed twice, with the longest distance jumped recorded for analysis. This test provides a direct measure of the lower body's power, an essential component of overall athletic performance and a key indicator of the effectiveness of the HIIT protocol in enhancing muscular performance [30].

Algometer Test: To evaluate the pain threshold, the algometer test was meticulously conducted on the anterior border of the upper trapezius muscle, both pre- and post-test and among all participants, adhering to a standardized procedure [33]. Pressure was consistently increased at a controlled pace of 1 kg/sec. Participants were instructed to signal the moment they first perceived pain, at which point the pain threshold was recorded.

Blood Lactate Concentration: The measurement of blood lactate concentration post-exercise provides critical insights into the metabolic impact of the HIIT protocol on participants. For this purpose, capillary blood samples of 5 µL were collected from the index finger of each participant, utilizing a minimally invasive method that ensures quick recovery and minimal discomfort. These samples were then analyzed using the Lactate Pro 2 analyzer from Arkay, Inc., based in Kyoto, Japan. This device is renowned for its precision and reliability in measuring lactate levels, offering immediate feedback on the metabolic stress exerted by the exercise regimen. The procedure follows established protocols to ensure consistency and accuracy of the results, thereby allowing us to evaluate the aerobic and anaerobic contributions to exercise metabolism and their changes in response to HIIT [30].

Information Processing Assessment: To assess cognitive function in terms of information processing, we utilized a mobile app designed to measure reaction time. This innovative approach leverages technology to provide a convenient and effective method for assessing cognitive performance. The app presents a simple interface where a white screen changes color at random intervals, and participants are instructed to tap the screen as quickly as possible upon color change. The average reaction time from five trials was calculated for each participant, offering a quantitative measure of their cognitive processing speed. This test is particularly relevant for understanding how physical fatigue may influence cognitive functions, including attention and psychomotor speed, thereby offering insights into the broader impacts of HIIT on cognitive performance [34].

By integrating these physiological and cognitive assessments, our study aims to provide a comprehensive evaluation of the effects of acute physical fatigue induced by HIIT. The methodology encompasses a wide range of measures to capture the multifaceted impacts of fatigue on recreational athletes, from metabolic and muscular responses to cognitive processing abilities. This approach not only enriches our understanding of the physiological and psychological dimensions of fatigue but also contributes significantly to the literature on exercise science and human performance.

2.5. Innovative Aspects of Our Study

Our study introduces a novel perspective on the intricate interplay between physical fatigue and its consequent effects on both physiological and psychological dimensions of human performance, particularly through the lens of high-intensity interval training (HIIT). By seamlessly integrating assessments of information processing, pain threshold, and muscular performance, we provide a comprehensive analysis that transcends the traditional boundaries of physical and cognitive research. The methodological rigor of our approach is further enhanced by the adoption of a specially designed HIIT protocol, aimed at inducing acute physical fatigue, thereby allowing us to probe the depth of its impact on cognitive functions alongside physical capabilities. This multifaceted approach not only enriches the current understanding but also introduces methodological innovation in the study of exercise-induced fatigue, positioning our research at the forefront of uncovering the holistic effects of HIIT on human performance. Through this, we shed light on the nuanced ways in which intense physical activity can influence an individual's cognitive and physical realms, offering valuable insights into the optimization of training regimens and the enhancement of athletic performance.

2.6. Statistical Analysis

The Statistical Package for the Social Sciences (SPSS) version 24.0 (SPSS Inc., Chicago, IL, USA) was used to analyze the data. Descriptive statistics (mean and standard deviation) were calculated. Before using parametric tests, the assumption of normality and homoscedasticity were verified using the Kolmogorov–Smirnov test. A one-factor (time) ANOVA-repeated measurement with a Bonferroni post hoc test was used to compare the results obtained in variables with 3 evaluation moments. A dependent t test was used to analyze differences in variables with 2 evaluation moments. The threshold for significant difference was set at $p < 0.05$ for all comparisons.

3. Results

High-intensity interval training (HIIT) resulted in significant physiological and performance changes. There was a notable increase in both heart rate and rate of perceived exertion among participants. Additionally, a significant improvement was observed in the horizontal jump performance across both HIIT series compared to the rest state. Interestingly, the isometric hand strength showed a notable increase but only in the last series. By contrast, the reaction time remained unaffected by the HIIT, indicating no significant change in cognitive processing speed following the exercise (Table 1). The 'Moment Comparison' column indicates the statistical significance of differences observed across the measured moments.

Table 2 presents notable findings in terms of pain threshold and blood lactate levels following the HIIT sessions. There was a significant increase in the pain threshold, with values rising from a pre-intervention average of 7.6 ± 2.4 to a post-intervention average of 18.8 ± 23.9. This change indicates a heightened tolerance to pain among participants after undergoing the HIIT. In addition, blood lactate levels showed a substantial increase post-HIIT, reflecting the intensity of the exercise. The levels escalated from a baseline of

2.4 ± 0.5 mmol/L to a post-intervention average of 14.5 ± 2.6 mmol/L, underscoring the metabolic demands of the high-intensity exercise on the participants' bodies.

Table 1. Changes in heart rate, rate of perceived exertion, horizontal jump, isometric hand strength, and reaction time before and after the first and second HIIT series.

Variable	Pre (1)	1st Series (2)	2nd Series (3)	F	Moment Comparison
Heart rate (bpm)	69.8 ± 9.1	163.5 ± 23.3	167.7 ± 23.9	143.278	2 > 1; 3 > 1
Rate of perceived exertion	6.2 ± 0.8	14.4 ± 2.4	16.3 ± 1.8	419.129	2 > 1; 3 > 1; 3 > 2
Horizontal jump (cm)	145.0 ± 33.4	150.0 ± 34.3	169.7 ± 18.3	11.354	2 > 1; 3 > 1; 3 > 2
Isometric hand strength (N)	36.1 ± 7.1	36.9 ± 6.2	38.1 ± 5.7	3.651	3 > 1
Reaction Time (ms)	283.4 ± 25.6	289.7 ± 35.6	280.4 ± 30.9	1.720	

Table 2. Changes in perceived pain before and after the first and second HIIT series.

Variable	Pre	Post	t	*p*	Upper	Lower
Pain threshold	7.6 ± 2.4	18.8 ± 23.9	−2.625	0.014	−20.12	−2.45
Blood lactate (mmol/L)	2.4 ± 0.5	14.5 ± 2.6	−23.494	$p < 0.001$	−13.04	−10.94

4. Discussion

At the outset of this study, our primary objective was to investigate the effects of high-intensity interval training (HIIT) on acute physical fatigue, alongside an exploration of the physiological and psychological responses across genders. Based on the comprehensive analysis of our results, we can affirm that our hypothesis—that HIIT significantly impacts acute physical fatigue, with potential variations in responses between genders—has been addressed. Our findings demonstrate that HIIT induces notable changes in physiological and psychological states, yet, contrary to our initial hypothesis, these effects were consistent across both male and female participants, suggesting a universal applicability of HIIT in inducing acute physical fatigue without significant gender-specific differences.

In this study, the significant elevations observed in lactate levels, heart rate, and RPE following the HIIT protocol are consistent with established findings in the sports science literature. These physiological responses are well-documented markers of the intense metabolic and cardiovascular stress imposed by high-intensity exercise regimens [22,24]. In this line, elevated lactate levels post-HIIT reflect enhanced glycolytic activity, a hallmark of intensive anaerobic metabolism. This metabolic shift is a direct consequence of the body's efforts to meet the high energy demands during short, intense bursts of exercise, characteristic of HIIT. The lactate accumulation can be interpreted not merely as a byproduct of anaerobic metabolism but also as a valuable energy source that muscles utilize during prolonged exercise [35]. Additionally, the analysis of the data did not reveal any significant gender-specific differences in response to high-intensity interval training (HIIT). Both male and female participants exhibited similar physiological and psychological responses to the HIIT regimen. This finding suggests that, within the context of this study, HIIT can be equally effective for both genders in terms of acute physical fatigue, recovery, and overall performance outcomes. However, it is important to note that individual variability in training response exists, and further research could explore potential subtle differences or tailor training programs to individual needs.

The significant elevation in heart rate observed during our study is a direct reflection of the cardiovascular system's adaptive response to the increased demands for oxygen and nutrients by the muscles engaged in high-intensity interval training (HIIT). This pronounced increase not only demonstrates the effectiveness of HIIT in stimulating cardiovascular adaptations but also highlights its role in augmenting aerobic capacity. Such enhancements are pivotal for improving endurance and have been widely corroborated by existing research [36]. Additionally, the post-HIIT rise in the rate of perceived exertion (RPE) offers a vital subjective perspective on the participants' perceived levels of exertion and the physiological stress endured. RPE serves as an indispensable tool for gauging the subjective intensity of the workout, where its elevation following HIIT sessions in this study reveals the substantial effort and energy participants invested in the regimen [37].

Expanding upon these findings, our study not only confirms the acute physiological impacts of HIIT but also sheds light on its effectiveness as a potent training modality. The observed metabolic and cardiovascular responses provide strong evidence of HIIT's capacity to foster significant physiological adaptations. These adaptations are instrumental in boosting athletic performance and elevating physical fitness levels. By engaging in HIIT, individuals can experience profound improvements in both their cardiovascular efficiency and metabolic function, underscoring the multifaceted benefits of this training approach. This comprehensive analysis emphasizes HIIT's dynamic role in advancing physical conditioning and enhancing endurance, positioning it as a key component of fitness regimens aiming to achieve optimal health and performance outcomes.

The observed post-HIIT enhancement in muscular performance intriguingly challenges the traditional notion that fatigue invariably leads to diminished muscle function. Contrary to expectations, our study found a notable increase in muscular strength, especially in those muscle groups directly involved in the HIIT protocols. This was particularly evident in the enhanced outcomes of the horizontal jump tests, which point to a significant boost in lower body muscle power and strength. Additionally, an improvement was also noted in muscle groups not directly engaged in the HIIT exercises, as demonstrated by the increased isometric hand strength observed after the second series of HIIT. This broadening of benefits across various muscle groups underscores the comprehensive impact of HIIT, suggesting that its effects transcend the specific muscles actively engaged in the exercises.

The unexpected improvement in muscular strength, despite the presence of fatigue, could be attributed to the heightened sympathetic activation that accompanies HIIT. This activation is believed to enhance the transmission of neural signals to the muscles, thereby potentially augmenting muscular performance. Such a mechanism is supported by studies suggesting that increased sympathetic activity can lead to a more efficient recruitment of muscle fibers [38]. This enhanced neural engagement may not only counteract the effects of fatigue but also facilitate a greater activation of muscle groups, including those not directly involved in the exercise regimen. This phenomenon provides a plausible explanation for the observed improvements in muscle function post-HIIT, highlighting the complex interplay between neural mechanisms and muscular adaptations induced by high-intensity exercise.

The incorporation of intermittent recovery periods within the HIIT design is pivotal in facilitating sustained muscular performance, even amidst escalating fatigue. These strategically placed rest intervals allow for transient recovery phases, potentially aiding in the preservation of muscle function and performance throughout the exercise bout. This concept is supported by literature suggesting that intermittent high-intensity exercises can foster enhancements in muscle strength and endurance [29]. Our findings lend further support to the notion that HIIT, with its unique structure of alternating intense activity and recovery, can significantly benefit not just the specific muscles engaged in the exercises but also contribute to an overall improvement in muscular strength. This insight is particularly valuable for the design of training programs, indicating the efficacy of HIIT in promoting comprehensive muscular development and suggesting its inclusion as a key component for achieving broad-based muscular improvements.

Additionally, the stability of reaction times post-HIIT observed in our study offers intriguing insights into the resilience of cognitive functions, particularly information processing speed, against the backdrop of acute physical fatigue. Contrary to the commonly held belief that intense physical exertion adversely affects cognitive performance, our findings reveal that reaction times remain unaffected following HIIT. This challenges previous assertions and contributes to a nuanced understanding of the interplay between physical activity and cognitive functions, suggesting that high-intensity exercise may not necessarily compromise, and can even maintain, cognitive processing speed despite the physiological demands imposed [11].

This stability in reaction times could be attributed to the unique structure of HIIT, which alternates between periods of intense physical activity and recovery. The intermittent nature of HIIT could play a crucial role in maintaining cortical activation and cognitive function. During the recovery intervals, the body may not only regain physical readiness but also achieve a cognitive reset, allowing for the maintenance of cognitive performance levels, even under the strain of physical exertion. The implications of this finding are significant, particularly in the context of athletic training and performance. It suggests that HIIT, by virtue of its design, may be an effective training modality in preserving or even enhancing cognitive functions, such as reaction time, in the face of physical fatigue. This counteracts the traditional view of fatigue as a limiting factor for cognitive function and highlights the potential for specific exercise regimens to maintain or even bolster cognitive performance post-exercise.

Moreover, the preservation of cognitive function post-exercise is a critical aspect of athletic performance, especially in sports requiring quick decision-making and rapid reactions under physically demanding conditions. Thus, the insights from this study could inform training strategies, emphasizing the inclusion of HIIT as a means not only to improve physical fitness but also to sustain cognitive acuity. Additionally, another significant finding from this study was the increase in pain threshold following the HIIT sessions. This suggests that acute physical fatigue may enhance pain tolerance, possibly due to increased sympathetic modulation. This physiological response, which is evolutionarily linked to survival mechanisms, is often associated with the release of neurotransmitters like endorphins, enhancing the body's ability to tolerate pain in stressful or threatening situations [39]. This study contributes to a more nuanced understanding of the effects of acute physical fatigue, especially fatigue induced by HIIT. The findings challenge some preconceived notions about the detrimental effects of fatigue on performance and cognitive function, suggesting instead that the body's response to high-intensity exercise is complex and multifaceted. This research highlights the importance of considering both the physiological and psychological dimensions of exercise when examining its effects on human performance.

4.1. Practical Applications

This study's findings have several practical applications that can benefit athletes, coaches, and individuals looking to optimize their training and improve performance. Firstly, this research highlights the effectiveness of HIIT in inducing physiological adaptations, such as increased heart rate and RPE. This information can be used by coaches and athletes to design training programs that target specific performance goals, taking advantage of the acute physiological responses associated with HIIT. Secondly, this study challenges the conventional belief that acute physical fatigue leads to a decrease in muscular performance. Instead, it reveals that HIIT can lead to improvements in muscular strength, particularly in muscles actively engaged in exercise. This insight can guide athletes and trainers in developing strategies to enhance muscle function, ultimately contributing to improved athletic performance.

Additionally, this study's findings regarding cognitive function are noteworthy. Despite the physical stress induced by HIIT, the stability of reaction times suggests that acute physical fatigue does not necessarily impair cognitive functions related to processing speed. This has implications for individuals who need to balance physical training with cognitive demands, such as students or professionals [40]. Lastly, the increase in pain threshold observed following HIIT sessions provides an interesting perspective. It suggests that acute physical fatigue may enhance pain tolerance, possibly due to increased sympathetic modulation. This finding could be valuable for individuals dealing with pain or discomfort, offering a potential non-pharmacological approach to increase their pain tolerance [41].

4.2. Limitations and Future Research Lines

It is essential to acknowledge this study's limitations to provide context for our findings and guide future research. Primarily, the sample size for our investigation was determined by convenience, reflecting the challenges inherent in recruiting participants fitting our specific study criteria. This reliance on a convenience sample poses limitations, including potential biases and the difficulty in generalizing our findings to a broader population. Such a sampling approach was necessitated by logistical constraints and the niche nature of the study population. Moreover, we included this sampling methodology as a limitation within this study to maintain transparency and provide a comprehensive understanding of the context within which our results should be interpreted. Future investigations should aim to utilize larger and more diverse sample sizes to enhance the generalizability of their findings. Despite these limitations, this study offers valuable insights into the multifaceted effects of acute physical fatigue induced by HIIT, highlighting areas for further exploration in the nuances of these effects across different populations and sports contexts.

Building upon the insights and limitations identified in this study, future research should focus on expanding the understanding of acute physical fatigue's effects across a broader spectrum of populations and athletic disciplines. Investigations could include a wider variety of training modalities and participant demographics to enhance the generalizability of findings. Additionally, longitudinal studies are needed to explore the long-term impacts of HIIT on physiological and psychological aspects of fatigue, recovery, and performance. Incorporating advanced technologies for real-time monitoring and analysis can also provide deeper insights into the immediate and cumulative effects of training on athlete health and performance. Finally, future research to engage larger and more diverse cohorts is necessary in order to enhance the external validity of our findings.

5. Conclusions

This study offers comprehensive insights into the effects of acute physical fatigue induced by HIIT on various aspects of human physiology and performance. Contrary to conventional expectations, the research revealed that HIIT can lead to an increase in muscular strength, not only in muscles directly involved in the exercise but also in those not primarily engaged. Additionally, cognitive functions related to processing speed remained stable post-HIIT, challenging the belief that physical fatigue invariably impairs cognitive performance. Furthermore, this study found that acute physical fatigue may enhance pain tolerance, possibly due to increased sympathetic modulation and the release of pain-relieving neurotransmitters.

These findings have practical applications for athletes, coaches, and individuals seeking to optimize their training regimens and improve performance. HIIT can be used strategically to target specific performance goals, taking advantage of the acute physiological responses it elicits. This study's insights on muscular performance suggest that HIIT can contribute to comprehensive muscle development. The stability of cognitive function during and after HIIT is valuable for individuals balancing physical training with cognitive demands.

Moreover, the increase in pain tolerance following HIIT sessions offers a non-pharmacological approach to managing discomfort. Overall, this research challenges preconceived notions about the effects of acute physical fatigue and highlights the need to consider both physiological and psychological dimensions when examining its impact on athletic performance. Future research can further explore these effects in diverse populations and sports contexts, providing a deeper understanding of the mechanisms and long-term adaptations to HIIT.

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