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Article

Effects of photobiomodulation therapy on acute recovery after exhausting cycling exercise

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Abstract: The application of photobiomodulation therapy (PBMT) to delay skeletal muscle fatigue and shield against muscle damage represents a novel frontier in the field of exercise physiology. Further research is warranted to understand the physiological impact of PBMT on post-exercise recovery and muscle functionality. The objective of this research is to assess the impact of PBMT on the quadriceps following strenuous cycling, focusing on blood lactate (BL) levels, heart rate (HR), perceived exertion (RPE), and performance in the Wingate (WG) test. The study involved 12 male participants who were randomly allocated to either an active PBMT group or a control group, with treatments administered to the rectus femoris muscles bilaterally post-exhaustive cycling. The cycling exercise workload was 50 Watts (W); it increased by 50 W every 30 s at 60 rpm until the onset of exhaustion; and 30 s of active recovery was allowed between intervals. The BL, HR, and RPE were measured at several time points: pre-exercise, post-exercise, and at 10 min and 20 min post-exercise, as well as post-WG test. BL was significantly reduced in the PBMT group compared to the placebo group at the 10-min ($p < 0.05$) and 20-min ($p < 0.01$) marks post-exercise, and also post-WG test ($p < 0.01$). Additionally, HR was significantly lower in the PBMT group immediately following the WG test ($p < 0.01$). Both the mean ($p < 0.05$) and peak power outputs ($p < 0.05$) were found to be superior in the PBMT group. The application of PBMT to the quadriceps post-exhaustive exercise resulted in reduced BL and HR, along with improved WG test results, suggesting that PBMT may facilitate faster recovery following physical exertion.

Keywords: skeletal muscle fatigue; acute recovery; performance; photobiomodulation; blood lactate; heart rate

1. Introduction

Intense physical training, rigorous drills, and competitive games, when not complemented by adequate rest periods, can lead to overtraining syndrome in athletes [1,2]. Optimizing recovery from overtraining is essential in the realm of sports, particularly for those that involve a series of high-intensity workouts. A variety of recovery techniques are employed post-exercise to aid in the recuperation of skeletal muscles. Among these, cryotherapy [3], massage [4], flexibility exercises [5], and PBMT [6,7] are frequently utilized.

The application of PBMT to delay the onset of skeletal muscle fatigue and mitigate muscle damage is an emerging area within the field of exercise physiology [8,9]. Evidence suggests that PBMT may contribute to the enhancement of mitochondrial activity in the musculoskeletal system [10], stimulate the production of ATP [11], elevate antioxidant concentrations, and facilitate the reduction of BL levels [12].

Elevated BL levels and accompanying H^+ accumulation have long been associated with impaired musculoskeletal mitochondrial function and exercise tolerance [13,14], which are also directly related to the recovery process of the musculoskeletal system [15]. Tullberg et al. [16] reported that lower BL induced by PBMT could be caused by several factors, such as improved microcirculation and increased in blood flow. Furthermore, the beneficial impact of PBMT on enhancing muscle performance is linked to the cellular capacity to harness light energy, which promotes improved microcirculation and reduces the occurrence of local ischemia following intense physical activity [6,17]. Strong positive evidence suggests that PBMT is a unique, noninvasive, nonpharmacological way to accelerate recovery from muscular fatigue and prevent exercise-induced damage [8,9].

The most effective timing for administering PBMT in relation to exercise—whether prior, concurrent, or subsequent—remains undetermined. Initial research indicated that PBMT targeted at the quadriceps post-strength training notably decreased BL levels at the 10-min and 15-min marks post-exercise within the PBMT group, yet it did not significantly affect the quantity or intensity of repetitions that could be managed 15 min into recovery. In subsequent work, Fritsch et al. [18] observed that PBMT post-plyometric activity lessened the muscle echo intensity response and perceived soreness in the knee extensors, with no notable impact on the strength of the lower limbs at 24 h, 48 h, or 72 h post-exercise. Further investigation is essential to understand how PBMT influences muscle recovery and performance after physical activity. Consequently, the goal of this study was to determine the impact of PBMT on alleviating muscle fatigue, as measured by BL, HR, rated RPE, and outcomes from the WG test.

The ideal moment (i.e., before, during, or after exercise) for administering PBMT remains undetermined. A groundbreaking investigation indicated that PBMT on the quadriceps post-strength training notably decreased BL at the 10-min and 15-min marks following exercise in the PBMT group, as opposed to the placebo group. However, no significant differences were observed in the number of repetitions or the maximum load tolerated at the 15-min mark post-fatigue [12,19]. In a more recent study, Fritsch et al. [18] demonstrated that PBMT post-plyometric exercise significantly reduced knee extensor muscle echo intensity and muscle soreness. Yet, no significant improvements in lower limb strength were noted at 24 h, 48 h, and 72 h post-exercise. Further research is necessary to explore the physiological impacts of post-exercise PBMT on immediate recovery and muscle functionality. Consequently, the goal of this study was to investigate the potential influence of the PBMT on muscle fatigue recuperation by assessing BL, HR, RPE, and performance in the WG test.

2. Methods

2.1. Participants

Twelve male volunteers were enrolled in this research. The participants were all healthy, engaged in regular physical activity, and not involved in competitive sports. Their demographic details included an average age of 21.5 (± 1.21) years; an average body mass of 65.3 (± 4.44) kg; an average height of 174 (± 5.5) cm; and an average BMI of 21.7 (± 1.5) $kg \cdot m^{-2}$. Individuals with conditions such as diabetes,

hypertension, cardiac issues, or those with severe psychological disorders were not included in the study. The research adhered to the ethical guidelines set forth in the most recent version of the Declaration of Helsinki and received approval from the local institutional review board.

2.2. Study design

The subjects reported to the laboratory on three separate occasions 1 week apart and at the same time of day. Familiarization with the cycle ergometer was completed over 1 day to ensure that all participants understood the experimental protocol by the time of their first visit (visit 1). The next two visits comprised the experimental phase. During visit 2 or visit 3, the subjects were randomly divided into three groups; one group reported per day for 3 consecutive days during the protocol and each group consisted of 3 subjects comprising the placebo group and 3 subjects comprising the PBMT group. The groups met at intervals of 1 week. Every consecutive day, the subjects underwent primary baseline assessments of HR, RPE, and BL after warm-up and a short stretching period. Subsequently, the subjects were asked to perform exhausting exercises on the cycle ergometer. Finally, PBMT was performed immediately after exercise. HR, BL, and RPE were determined in the supine position before exercise (baseline), immediately after exercise, 10 min after exercise, 20 min after exercise, and immediately after the WG test; the WG performance test was evaluated 20 min after exhaustion (**Figure 1**).

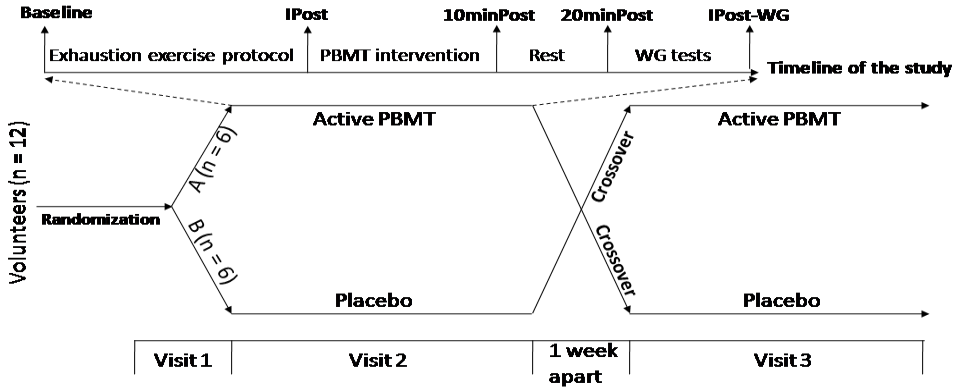

Figure 1. Protocol of the experiment.

2.3. Randomized, double-blind, crossover design

This experiment had a randomized, double-blind, crossover design. Randomization was performed by drawing lots (A or B), which determined whether active PBMT (treatment A) or placebo (treatment B) would be administered at visit 2. Then, the subjects were crossed-over so that at visit 3 they would receive whichever treatment (A or B) they did not receive at visit 2 (if they received treatment A at visit 2, then they received treatment B at visit 3; if they received treatment B at visit 2, then they received treatment A at visit 3). A technician preset the control unit according to whether the subject was to receive PBMT or placebo. To uphold the double-blind protocol, the technician, who was in a separate room from the subjects, was explicitly instructed not to disclose the nature of the treatment to the subjects, therapist, or any

observers. The integrity of the blinding process was enhanced by having the subjects wear opaque goggles during the PBMT sessions. The participants were advised to abstain from any form of exercise for a period of 72 h prior to the testing sessions. Additionally, they were requested to avoid food intake for at least 2 h preceding the experiment.

2.4. Exercise protocol

Upon arrival for each testing session, the participants were asked to sit and rest for a 10-min period. Following the rest, each participant engaged in a 5-min warm-up at an intensity of 100 watts, accompanied by some brief stretching exercises. After the warm-up, a baseline blood sample was taken, and the HR and RPE were documented. The participants subsequently underwent an incremental cycling test on an ergometer (Powermax VII; Combi, Tokyo, Japan), which involved cycling until they reached exhaustion. The test began at a power output of 50 W, with the intensity increasing by 50 W every 30 s until the participant could no longer continue. Each increase in intensity was followed by a 30 s period of active recovery. A cadence of 60 rpm was required throughout the protocol. After exhaustion, a 20-min recovery period was allowed, during which the subjects rested in the supine position.

2.5. Photobiomodulation therapy procedure

Immediately following the exhaustion phase, PBMT was administered. The participants were randomly assigned to receive either an active PBMT session (KX-350-1B helium-neon laser; Guilin Kangxing Medical Instrument Co., Ltd., Guiling, China) or a placebo. To maintain the double-blind setup, the laser device was activated only when the laser probe was in direct contact with the skin over the rectus femoris muscle, ensuring that the subjects were unaware of the treatment conditions. The rectus femoris muscle was targeted for treatment, with the muscle belly being divided into two equal irradiation points along the central ventral line, ensuring that the majority of the muscle belly was treated (as depicted in **Figure 2**). Since irradiation was applied to both the left and right rectus femoris muscles, there were a total of four irradiation points per leg. Each leg was treated for 5 min, with each site receiving laser irradiation for 300 s. This resulted in an energy dose of f 9.5 $J \cdot cm^{-2}$ per diode and 19 $J \cdot cm^{-2}$ per leg [20] (**Table 1**). To ensure that the same position was used during the placebo and experimental trials, the exact position was marked.

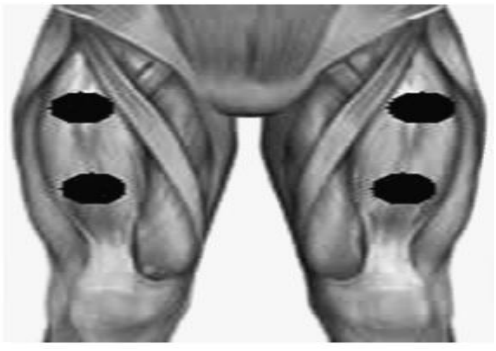

Figure 2. The prototype PBMT device used in this study and sites of PBMT laser irradiation on rectus femoris.

Table 1. Photobiomodulation therapy (PBMT) parameters.

Laser source type	Wavelength (nm)	Output power (mW)	Power density ($W \cdot cm^{-2}$)	Spot size (cm^2)	Energy density ($J \cdot cm^{-2}$)	Irradiation time per point (s)
Helium-neon	632.8	5	0.016	0.313	9.5	300

2.6. Outcome measurements

2.6.1. Heart rate (HR)

HR was consistently monitored throughout both the experimental and placebo sessions via an HR monitor (RS800; Polar Electro, Kempele, Finland). The collected data were subsequently downloaded onto a computer for analysis via the appropriate Polar software, which is designed to be compatible with the monitoring device [21] (Polar Precision Performance SW5.20; Polar Electro, Kempele, Finland).

2.6.2. Blood lactate (BL) level

Blood samples were collected by fingertip puncture using sterile disposable lancets (Sanwa Kagaku Kenkyusho Co., Nagoya Aichi, Japan). The fingertip was cleaned with a 70% alcohol solution prior to blood collection. A 30 μL blood sample was obtained and placed into tubes treated with heparin; subsequently, this blood was moved into another set of tubes that had 60 μL of a 1% sodium fluoride solution, and these tubes were kept in a fridge at a constant temperature of −20 °C. Afterward, once the samples were defrosted, they were tested twice using the Lactate Scout instrument (SensLab GmbH, Leipzig, Germany).

2.6.3. Rated perceived exertion (RPE)

RPE was measured using the RPE scale (range, 6–20), which ranges from 6 to 20, a common tool for gauging the perceived exertion level during physical activity [22]. This scale evaluates the subjective experience of effort, strain, or fatigue that participants feel while exercising.

2.6.4. Wingate (WG) test

The WG test was conducted 20 min post-exhaustion. This test involves 30 s of maximal effort cycling against a resistance that is personalized to the participant's body weight. For the study, the ergometer was set with a resistance of 0.08 $kg \cdot kg^{-1}$ body weight for all participants. The participants were instructed to start pedaling at their fastest possible speed and to sustain this peak rate throughout the 30-s duration. The peak power output was ascertained from the highest 5-s average of the power readings taken each second. The mean power output was derived from the average of all the 5-s power values recorded during the test, which were captured and processed via a computer interface; both peak and mean power outputs were documented.

2.7. Statistical analyses

Data analysis was conducted using GraphPad Prism software (v 5.0; GraphPad Prism Software, La Jolla, CA, USA). Prior to statistical analysis, the normality of the data was assessed using the Kolmogorov–Smirnov test for each data set. HR, BL, and RPE were analyzed using a two-way repeated measures ANOVA, with Bonferroni post hoc tests applied to identify specific differences between the PBMT and placebo conditions. The peak and mean power outputs were compared between the PBMT and

placebo groups using a paired t-test. The level of statistical significance was set at 5% ($p < 0.05$), and the results are expressed as the mean ± standard error of the mean. To quantify the effect sizes for the differences observed between the PBMT and placebo groups across all variables, Cohen's d statistic was utilized. The effect sizes were interpreted according to the following criteria: trivial for $d < 0.19$, small for $0.20 \leq d < 0.39$, moderate for $0.40 \leq d < 0.79$, and large for $d \geq 0.80$ [23].

3. Results

3.1. BL level

A significant two-way interaction between treatment and time, as well as main effects for both time and treatment, were detected for the BL levels, with *p*-values of 0.001, less than 0.0001, and less than 0.0001, respectively (as illustrated in **Figure 3**). In both treatment groups, the subjects presented similar BL levels at baseline (PBMT: 2.35 ± 0.33 mmol·L^{-1}; placebo: 2.31 ± 0.36 mmol·L^{-1}; $d = 0.04$) and immediately after exercise (PBMT: 9.69 ± 1.12 mmol·L^{-1}; placebo: 10.64 ± 0.99 mmol·L^{-1}; $d = 0.26$), with no significant between-group differences ($p > 0.05$, **Figure 3**). However, notable disparities were observed between the two treatment groups in terms of the BL level changes at the 10-min mark post-exercise (PBMT: 8.46 ± 0.69 mmol·L^{-1}; placebo: 11.05 ± 1.1 mmol·L^{-1}; $p < 0.05$, $d = 0.80$), 20 min after exercise (PBMT: 5.46 ± 0.6 mmol·L^{-1}; placebo: 9.25 ± 1.2 mmol·L^{-1}; $p < 0.01$; $d = 1.18$), and immediately after the WG test (PBMT: 13.2 ± 0.68 mmol·L^{-1}; placebo: 17.6 ± 0.96 mmol·L^{-1}; $p < 0.01$; $d = 1.55$; **Figure 3**).

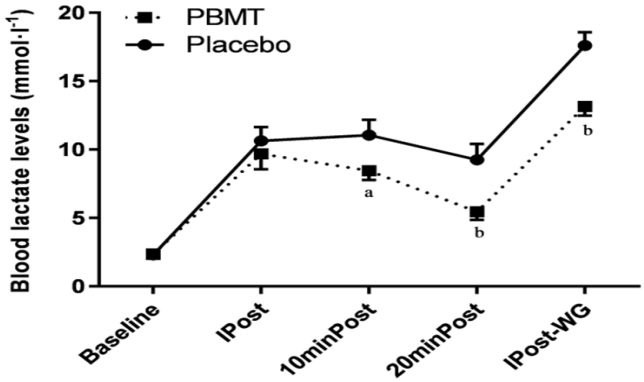

Figure 3. BL level results for PBMT and placebo throughout the study protocol.
Notes: The presented data are expressed as the mean value ± the standard error of the mean. The abbreviations used are as follows: "IPost" for immediately after exercise, "10 min Post" for 10 min after exercise, and "20 min Post" for 20 min after exercise. Additionally, "IPost-WG" refers to the time point immediately after the Wingate test, and "PBMT" stands for photobiomodulation therapy. [a] $p < 0.05$ and [b] $p < 0.01$ indicate that the differences are statistically significant compared to the placebo group.

3.2. HR

Significant two-way interaction (treatment–time interaction; $p = 0.02$), main effect for time ($p < 0.001$), and main effects for treatment ($p = 0.02$) for HR were observed (**Figure 4**). In both treatment groups, HR was similar at baseline (PBMT: 73.6 ± 2.0 bpm; placebo: 72.5 ± 2.3 bpm; $d = 0.14$), immediately after exercise (PBMT: 157.8 ± 5.2 bpm; placebo: 162.6 ± 5.0 bpm; $d = 0.27$), 10 min after exercise (PBMT: 96.7 ± 3.7 bpm; placebo: 105.9 ± 4.0 bpm; $p < 0.01$; $d = 0.69$), and 20 min

after exercise (PBMT: 91.3 ± 2.4 bpm; placebo: 100 ± 2.6 bpm; d = 1.0), with no significant between-group differences (p > 0.05, **Figure 4**). However, notable differences were observed between the two treatment groups in terms of the HR changes immediately following the WG test. (PBMT: 106.4 ± 4.6 bpm; placebo: 122.3 ± 3.5 bpm; p < 0.01; d = 1.13; **Figure 4**).

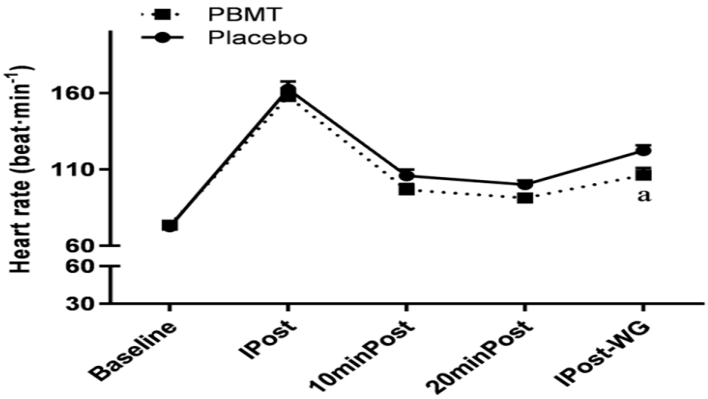

Figure 4. HR results for the PBMT and placebo groups during the study protocol.
Notes: The data are expressed as the mean ± the standard error of the mean. The terms used are as follows: "IPost" for immediately after exercise, "10 min Post" for 10 min post-exercise, "20 min Post" for 20 min post-exercise, and "IPost–WG" for immediately after the Wingate test. "PBMT" refers to photobiomodulation therapy. The notation [a] p < 0.05 signifies that there are statistically significant differences between the treatment groups when compared to the placebo group.

3.3. RPE

A significant treatment–time interaction effect (p = 0.95) and a main effect for treatment (p = 0.09) for RPE were not observed (**Figure 5**); however, a significant main effect for time (p < 0.001) for RPE was found. In both treatment groups, the RPE was similar at baseline (PBMT: 6.5 ± 0.1; placebo: 6.6 ± 0.4; d = 0.13), immediately after exercise (PBMT: 14.7 ± 0.7; placebo: 15.0 ± 0.7; d = 0.12), 10 min after exercise (PBMT: 10.5 ± 0.4; placebo: 11.0 ± 0.3; d = 0.41), 20 min after exercise (PBMT: 9.2 ± 0.5; placebo: 10.0 ± 0.3; d = 0.58), and immediately after the WG test (PBMT: 12.2 ± 0.6; placebo: 12.8 ± 0.9; d = 0.23), with no significant between-group differences (p > 0.05, **Figure 5**).

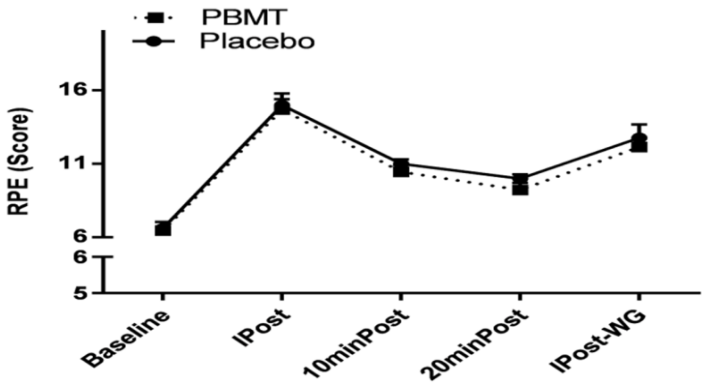

Figure 5. RPE results for PBMT and placebo throughout the study protocol.
Notes: The data are presented as the average value accompanied by the standard error of the mean, which is a measure of the precision of the sample mean. The terms "IPost", "10 min Post," "20 min Post," and "IPost–WG" correspond to different time points relative to the exercise and testing protocol:

immediately after exercise, 10 min after exercise, 20 min after exercise, and immediately after the Wingate test, respectively. "PBMT" stands for photobiomodulation therapy.

3.4. WG performance

Figure 6 shows the effects of PBMT on the two indices of muscle performance 20 min after exercise. Both the mean (372 ± 15 W) (**Figure 6A**) and peak power (627 ± 26 W) (**Figure 6B**) for the PBMT group were significantly higher than those for the placebo group (393 ± 15 W, $p = 0.03$, $d = 0.50$ and 658 ± 24 W, $p = 0.04$, $d = 0.62$, respectively).

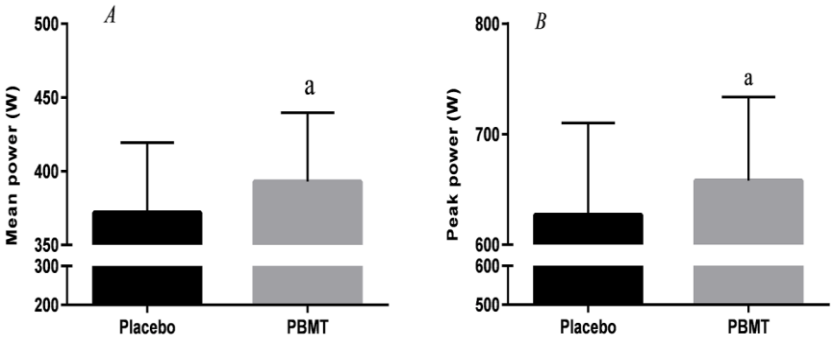

Figure 6. WG test performance results for PBMT and placebo, **(A)** mean power according to WG test performance after intervention; **(B)** peak power according to WG test performance after intervention.

Note: Data are means ± standard errors of the means. [a] $p < 0.05$ using paired *t*-test and compared with the placebo group.

4. Discussion

The objective of this research was to investigate the potential impact of PBMT on the recovery process following exhaustive exercise. The findings of our study indicate that PBMT can be an effective intervention for improving acute recovery. This was evidenced by a decrease in BL levels and HR, along with an enhancement in performance during the WG test. Studies have found long-term benefits of PBMT for physiological regulation in humans. Optimal wavelength and dose of PBMT have been shown to enhance cell function, including activation of anti-inflammatory factors [24], immunoglobulins [25], growth factors [26], interleukins [24,27]. One study evaluated the effect of PBMT and cryotherapy as a single or combination therapy on skeletal muscle recovery after eccentric contraction of the knee extensor muscle and found that PBMT as a monotherapy was the best way to enhance post-exercise recovery compared to PBMT, cryotherapy, cryotherapy + PBMT, PMBT + cryotherapy, or placebo [28]. Another study compared the short-term effects of cold water immersion therapy (CWIT) and light-emitting diode therapy (LEDT) with placebo LEDT on biochemical measures related to skeletal muscle recovery after high-intensity exercise, and found that LEDT had the potential to improve recovery after short-term exercise better than 5-min CWIT [29].

Research has shown that applying PBMT prior to exhaustive exercise can be both ergogenic and protective across various groups [6,29]. This is likely due to its interaction with cytochrome c oxidase [30], a key mitochondrial enzyme in the

respiratory chain that facilitates electron transfer between complexes III and IV, as well as its role in mitochondrial ATP production and enhancing metabolic adaptation to generate more ATP for cell function [10]. These factors collectively lead to better muscle performance, slower muscle fatigue, and reduced tissue damage. Increased ATP synthesis promotes faster resynthesis of creatine phosphate and muscle glycogen, thereby improving muscle endurance. PBMT before exercise can improve athletic performance and reduce exercise-induced fatigue and injury [31,32]. Studies have shown that pre-exercise PMBT also can improve muscle performance, muscle endurance and promote recovery from muscle strength and injuries [33]. One study indicated a potential for PBMT to improve acute recovery and muscle performance after fatigue, it demonstrated that PBMT significantly reduced BL levels at 10 and 15 min post-exercise when applied to the quadriceps after exhaustive exercise [12]. Our study results, which also show a decrease in BL at 10 min and 20 min post-exercise following PBMT (as depicted in **Figure 3**), align with these previous findings. It should be noted that while the dos Reis study utilized a gallium–aluminum arsenide laser at 830 nm, our study used a helium-neon laser at 635 nm, suggesting that PBMT at either wavelength can similarly affect BL levels during acute recovery post-exhaustive exercise. PBMT application after exercise fatigue to reduce BL is therefore not wavelength-dependent. Furthermore, the anti-fatigue and ergogenic effects of PBMT before fatigue are not wavelength-dependent [6,29].

Another interesting finding of the present study was that BL evaluated immediately after the WG test demonstrated more significant reductions (d = 1.55) than BL evaluated at 20 min after exercise (d = 1.18) and 10 min after exercise (d = 0.8) in the PBMT group compared with the placebo group (**Figure 3**). These results indicated that allowing more time to respond to light during the recovery process after exhausting exercise was more effective for reducing BL and also protected against fatigue due to subsequent 30 s sessions of supramaximal cycling (WG test). Moreover, our research indicated that PBMT can improve performance in the WG test, as measured by both mean (d = 0.50, **Figure 6A**) and peak power (d = 0.62, **Figure 6B**), when administered 20 min following an exhaustive exercise routine. This outcome, however, contrasts with findings from a prior investigation involving male professional soccer players, which suggested no significant difference in muscle performance post-exercise between the PBMT and placebo groups. That study assessed performance by the quantity and maximum load of repetitions at the 15-min mark post-fatigue [12]. Additionally, another study reported no positive impact of PBMT on strength performance 24 h post-exercise following plyometric exercises with maximal voluntary contractions [18]. The variability in responses could potentially be attributed to the timing of performance assessments. That is, the interval for the muscle's response to PBMT might have been either insufficient or excessive, thus affecting the observable benefits of PBMT on muscle performance post-fatigue for both the treatment and placebo groups. For example, in a study with mice, it has been shown that PBMT might be most effective when administered 6 h before the exercise bout [34].

The role of lactate levels in the development of skeletal muscle fatigue is controversial, however, it is one of the most studied biochemical markers of muscle fatigue [35,36]. Based on the available literature, PBMT may reduce BL before,

during, and after exercise; however, few studies have examined its mechanism. One possible mechanism, as indicated by the lower BL in this study, is the capability of PBMT to induce interstitial and vascular spaces of the exercised muscles and improve microcirculation [37,38], thereby promoting the removal of lactic acid [6]. Another possible mechanism of the reduction in BL by PBMT may be related to the lower concentration of cytosolic lactate dehydrogenase in musculoskeletal cells, which is considered pyruvate reductase and has a greater ability to transform pyruvic acid into lactic acid [39].

In the present study, we also evaluated the acute recovery of HR after exhausting exercise. To our knowledge, only a few studies have focused on the efficiency of PBMT for the HR response [37,40,41], which is the most common measurement used to estimate exercise-induced cardiac vago-sympathetic interaction and reduction of baroreflex sensitivity in humans [40,42]. Surprisingly, the current study found a significant decrease in HR during acute recovery with PBMT applied after a single exercise session compared to placebo (**Figure 4**). Paolillo et al. [37] demonstrated a faster recovery time of HR and lower HR in a group that received PBMT during high-intensity endurance training for 6 months than in a placebo group; these groups comprised postmenopausal women. In contrast to our study, Paolillo et al. [37] suggested that PBMT together with long-term endurance may help improve cardiovascular adaptations and exercise performance in postmenopausal women. However, the current study is the first to confirm the positive effects of PBMT applied after exhausting exercise on acute HR recovery.

HR adjustments are influenced by adrenoceptor reactions, which are triggered by sympathetic nervous system activity [43,44]. A study by Nagao et al. [40] reported positive outcomes where the stellate ganglion of the sympathetic nervous system, when exposed to PBMT for 10 min, resulted in a notable reduction in HR and an enhancement in blood flow through the right brachial artery in frogs. Other research has indicated the beneficial impact of PBMT on the dysfunction of sympathetic nerves and adrenoceptor reactions in patients with segmental vitiligo [45] and in hypertensive rats [46]. It is hypothesized that PBMT administered post-exercise might lead to a reduction in adrenoreactivity and sympathetic modulation, thereby accelerating the recovery of HR [37]. Nevertheless, additional research is needed to fully understand these mechanisms.

Despite the positive findings in the present study, limitations do exist, including the lack of evaluation of power density and intensity response characteristics. Indeed, the effects of PBMT are highly dependent on characteristics such as power intensity and density [6,47]. In addition, research in the Leal-Junior groups study investigated the positive effects of PBMT with varying wavelengths on improving skeletal muscle fatigue and preventing muscle damage, including wavelengths 660/850 nm light emitting diode [29], 810 nm infrared lasers [48], however, the procedures in their study differed from the present study used 635 nm helium-neon laser. Indeed, evidence supports a 635 nm helium-neon laser with deeper penetration compared to another power spectrum, thus, future research may focus on PBMT with varying power spectrum for the recovery process and ergogenic effects. Another limitation is the lack of evaluation soreness (e.g., visual analogue scale). Although we evaluated psychological load by RPE, no significant change was found during the 20-min

recovery period (**Figure 5**). In the same way, a major limitation should be kept in mind that we investigated only the effects of PBMT on very acute recovery, which possibly led to more insightful responses that have been neglected. Furthermore, considering the limited number of participants in our research, it is necessary to verify the initial findings through extensive research. This should incorporate assessments of biochemical indicators and evaluations of neuromuscular performance.

Author contributions: Conceptualization, YL and YT; methodology, YL; software, YT; validation, YL and YT; formal analysis, YL; investigation, YT; resources, YT; data curation, YL; writing—original draft preparation, YL; writing—review and editing, YL; visualization, YT; supervision, YL; project administration, YL; funding acquisition, YL. All authors have read and agreed to the published version of the manuscript.

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Ethical approval: The study was conducted in accordance with the Declaration of Helsinki, and approved by the Ethics Committee of Zhaoqing University (protocol code 20190010-01).

Conflict of interest: The authors declare no conflict of interest.

References

1. Armstrong, L. E., Bergeron, M. F., Lee, E. C., Mershon, J. E., & Armstrong, E. M. (2022). Overtraining syndrome as a complex systems phenomenon. Frontiers in Network Physiology, 1: 794392. https://doi.org/10.3389/fnetp.2021.794392
2. Carrard, J., Rigort, A. C., Appenzeller-Herzog, C., Colledge, F., Königstein, K., Hinrichs, T., & Schmidt-Trucksäss, A. (2022). Diagnosing overtraining syndrome: a scoping review. Sports Health, 14(5): 665-673. doi:10.1177/19417381211044739
3. Kwiecien, S. Y., & McHugh, M. P. (2021). The cold truth: the role of cryotherapy in the treatment of injury and recovery from exercise. European Journal of Applied Physiology, 121(8): 2125-2142.
4. Van Pelt, D. W., Lawrence, M. M., Miller, B. F., Butterfield, T. A., & Dupont-Versteegden, E. E. (2021). Massage as a mechanotherapy for skeletal muscle. Exercise and Sport Sciences Reviews, 49(2): 107-114.
5. Afonso, J., Clemente, F. M., Nakamura, F. Y., Morouço, P., Sarmento, H., Inman, R. A., & Ramirez-Campillo, R. (2021). The effectiveness of post-exercise stretching in short-term and delayed recovery of strength, range of motion and delayed onset muscle soreness: a systematic review and meta-analysis of randomized controlled trials. Frontiers in Physiology, 12: 677581.
6. Fisher, S. R., Rigby, J. H., Mettler, J. A., & McCurdy, K. W. (2019). The effectiveness of photobiomodulation therapy versus cryotherapy for skeletal muscle recovery: a critically appraised topic. Journal of Sport Rehabilitation, 28(5): 526-531.
7. González-Muñoz, A., Perez-Montilla, J. J., Cuevas-Cervera, M., Aguilar-García, M., Aguilar-Nuñez, D., Hamed-Hamed, D., Pruimboom, L., & Navarro-Ledesma, S. (2023). Effects of Photobiomodulation in sports performance: a literature review. Applied Sciences, 13(5): 3147. https://doi.org/10.3390/app13053147
8. Rageh, M. R. M., Yamany, A. A., Hamada, H. A., & Mohamed, R. R. (2021). Effect of different time intervals of light emitting diode therapy application on muscle fatigue. SPORT TK-Revista EuroAmericana de Ciencias del Deporte, 10(2): 214-233. https://doi.org/10.6018/sportk.489141
9. Borsa, P. A., Larkin, K. A., & True, J. M. (2013). Does phototherapy enhance skeletal muscle contractile function and postexercise recovery? A systematic review. Journal of Athletic Training, 48(1): 57-67.
10. Karu, T. (2010). Mitochondrial mechanisms of photobiomodulation in context of new data about multiple roles of ATP. Photomedicine and Laser Surgery, 28(2): 159-160.

11. Kim, H., Lee, H. Y., Abueva, C., Park, S. Y., Padalhin, A., Ryu, H. S., Chung, P. S., & Woo, S. H. (2023). Effect of 850 nm photobiomodulation on the adenosine diphosphate/adenosine triphosphate measure of apoptosis in geniculate ganglion neuronal cells in vitro. Medical Lasers; Engineering, Basic Research, and Clinical Application, 12(3): 183-190. https://doi.org/10.25289/ML.23.023
12. Dos Reis, F. A., da Silva, B. A. K., Laraia, E. M. S., de Melo, R. M., Silva, P. H., Leal-Junior, E. C. P., & de Carvalho, P. D. T. C. (2014). Effects of pre-or post-exercise low-level laser therapy (830 nm) on skeletal muscle fatigue and biochemical markers of recovery in humans: double-blind placebo-controlled trial. Photomedicine and Laser Surgery, 32(2): 106-112.
13. Fitts, R. H. (2008). The cross-bridge cycle and skeletal muscle fatigue. Journal of Applied Physiology, 104(2): 551-558.
14. Meyler, S., Bottoms, L., Wellsted, D., & Muniz-Pumares, D. (2023). Variability in exercise tolerance and physiological responses to exercise prescribed relative to physiological thresholds and to maximum oxygen uptake. Experimental Physiology, 108(4): 581-594. https://doi.org/10.1113/EP090878
15. Paolillo, F. R., Corazza, A. V., Borghi-Silva, A., Parizotto, N. A., Kurachi, C., & Bagnato, V. S. (2013). Infrared LED irradiation applied during high-intensity treadmill training improves maximal exercise tolerance in postmenopausal women: a 6-month longitudinal study. Lasers in Medical Science, 28: 415-422.
16. Tullberg, M., Alstergren, P. J., & Ernberg, M. M. (2003). Effects of low-power laser exposure on masseter muscle pain and microcirculation. Pain, 105(1-2): 89-96.
17. Kelencz, C. A., Munoz, I. S., Amorim, C. F., & Nicolau, R. A. (2010). Effect of low-power gallium–aluminum–arsenium noncoherent light (640 nm) on muscle activity: a clinical study. Photomedicine and Laser Surgery, 28(5): 647-652.
18. Fritsch, C. G., Dornelles, M. P., Severo-Silveira, L., Marques, V. B., Rosso, I. D. A., & Baroni, B. M. (2016). Effects of low-level laser therapy applied before or after plyometric exercise on muscle damage markers: randomized, double-blind, placebo-controlled trial. Lasers in Medical Science, 31: 1935-1942.
19. De Marchi, T., Ferlito, J. V., Ferlito, M. V., Salvador, M., & Leal-Junior, E. C. P. (2022). Can photobiomodulation therapy (PBMT) minimize exercise-induced oxidative stress? A systematic review and meta-analysis. Antioxidants, 11(9): 1671. https://doi.org/10.3390/antiox11091671
20. Servetto, N., Cremonezzi, D., Simes, J. C., Moya, M., Soriano, F., Palma, J. A., & Campana, V. R. (2010). Evaluation of inflammatory biomarkers associated with oxidative stress and histological assessment of low-level laser therapy in experimental myopathy. Lasers in surgery and medicine, 42(6): 577-583.
21. Al Haddad, H., Laursen, P. B., Chollet, D., Lemaitre, F., Ahmaidi, S., & Buchheit, M. (2010). Effect of cold or thermoneutral water immersion on post-exercise heart rate recovery and heart rate variability indices. Autonomic Neuroscience, 156(1-2): 111-116.
22. Borg, G., Domserius, M., & Kaijser, L. (1990). Effect of alcohol on perceived exertion in relation to heart rate and blood lactate. European Journal of Applied Physiology and Occupational Physiology, 60: 382-384.
23. Cohen, J. (1988). Statistical Power for the Social Sciences. Laurence Erlbaum and Associates, Hillsdale, N. J., USA.
24. da Cunha Moraes, G., Vitoretti, L. B., de Brito, A. A., Alves, C. E., de Oliveira, N. C. R., dos Santos Dias, A., Matos, Y. S. T., Oliveira-Junior, M. C., Oliveira, L. V. F., da Palma, R. K., Candeo, L. C., Lino-dos-Santos-Franco, A., Horliana, A. C. R. T., Júnior, J. A. G., Aimbire, F., Vieira, R. P., & Ligeiro-de-Oliveira, A. P. (2018). Low-level laser therapy reduces lung inflammation in an experimental model of chronic obstructive pulmonary disease involving P2X7 receptor. Oxidative medicine and cellular longevity, 2018(1): 6798238.
25. Skobelkin, O. K., Michailov, V. A., & Zakharov, S.D. (1991). Preoperative activation of the immune system by low reactive level laser therapy (LLLT) in oncologic patients: a preliminary report. Laser Therapy, 3(4): 169-175.
26. Luo, L., Sun, Z., Zhang, L., Li, X., Dong, Y., & Liu, T. C. Y. (2013). Effects of low-level laser therapy on ROS homeostasis and expression of IGF-1 and TGF-β1 in skeletal muscle during the repair process. Lasers in medical Science, 28: 725-734.
27. Oliveira Jr, M. C., Greiffo, F. R., Rigonato-Oliveira, N. C., Custódio, R. W. A., Silva, V. R., Damaceno-Rodrigues, N. R., Almeida, F. M., Albertini, R., Lopes-Martins, R. Á. B., de Oliveira, L. V. F., de Tarso Camillo de Carvalho, P., de Oliveira, A. P. L., Leal Jr, E. C. P., & Vieira, R. P. (2014). Low level laser therapy reduces acute lung inflammation in a model of pulmonary and extrapulmonary LPS-induced ARDS. Journal of Photochemistry and Photobiology B: Biology, 134: 57-63.
28. de Paiva, P. R. V., Tomazoni, S. S., Johnson, D. S., Vanin, A. A., Albuquerque-Pontes, G. M., Machado, C. D. S. M., Casalechi, H. L., de Carvalho, P. D. T. C., & Leal-Junior, E. C. P. (2016). Photobiomodulation therapy (PBMT) and/or cryotherapy in skeletal muscle restitution, what is better? A randomized, double-blinded, placebo-controlled clinical trial. Lasers in Medical Science, 31(9): 1925-1933.

29. Leal Junior, E. C., de Godoi, V., Mancalossi, J. L., Rossi, R. P., De Marchi, T., Parente, M., Grosselli, D., Generosi, R. A., Basso, M., Frigo, L., Tomazoni, S. S., Bjordal, J. M., & Lopes-Martins, R. Á. B. (2011). Comparison between cold water immersion therapy (CWIT) and light emitting diode therapy (LEDT) in short-term skeletal muscle recovery after high-intensity exercise in athletes—preliminary results. Lasers in Medical Science, 26: 493-501.
30. Hayworth, C. R., Rojas, J. C., Padilla, E., Holmes, G. M., Sheridan, E. C., & Gonzalez-Lima, F. (2010). In vivo low-level light therapy increases cytochrome oxidase in skeletal muscle. Photochemistry and Photobiology, 86(3): 673-680.
31. Antonialli, F. C., De Marchi, T., Tomazoni, S. S., Vanin, A. A., dos Santos Grandinetti, V., de Paiva, P. R. V., Pinto, H. D., Miranda, E. F., de Carvalho, P. D. T. C., & Leal-Junior, E. C. P. (2014). Phototherapy in skeletal muscle performance and recovery after exercise: effect of combination of super-pulsed laser and light-emitting diodes. Lasers in Medical Science, 29: 1967-1976.
32. Follmer, B., Dellagrana, R. A., Rossato, M., Sakugawa, R. L., & Diefenthaeler, F. (2018). Photobiomodulation therapy is beneficial in reducing muscle fatigue in Brazilian jiu-jitsu athletes and physically active men. Sport Sciences for Health, 14: 685-691.
33. Li, B. M., Qiu, D. Y., Ni, P. S., Wang, Z. Z., Duan, R., Yang, L., Liu, C. Y., Chen, B.Y., & Li, F. H. (2024). Can pre-exercise photobiomodulation improve muscle endurance and promote recovery from muscle strength and injuries in people with different activity levels? A meta-analysis of randomized controlled trials. Lasers in Medical Science, 39(1): 1-20.
34. Ferraresi, C., de Sousa, M. V. P., Huang, Y. Y., Bagnato, V. S., Parizotto, N. A., & Hamblin, M. R. (2015). Time response of increases in ATP and muscle resistance to fatigue after low-level laser (light) therapy (LLLT) in mice. Lasers in Medical Science, 30: 1259-1267.
35. Cairns, S. P. (2006). Lactic acid and exercise performance: culprit or friend?. Sports medicine, 36: 279-291.
36. Bartoloni, B., Mannelli, M., Gamberi, T., & Fiaschi, T. (2024). The Multiple Roles of Lactate in the Skeletal Muscle. Cells, 13(14): 1177. doi: 10.3390/cells13141177.
37. Paolillo, F. R., Corazza, A. V., Paolillo, A. R., Borghi-Silva, A., Arena, R., Kurachi, C., & Bagnato, V. S. (2014). Phototherapy during treadmill training improves quadriceps performance in postmenopausal women. Climacteric, 17(3): 285-293.
38. Dutra, Y. M., Claus, G. M., Malta, E. D. S., Seda, D. M. D. F., Zago, A. S., Campos, E. Z., Ferraresi, C., & Zagatto, A. M. (2021). Photobiomodulation 30 min or 6 h prior to cycling does not alter resting blood flow velocity, exercise-induced physiological responses or time to exhaustion in healthy men. Frontiers in Physiology, 11: 607302. https://doi.org/10.3389/fphys.2020.607302
39. de Brito Vieira, W. H., Bezerra, R. M., Queiroz, R. A. S., Maciel, N. F. B., Parizotto, N. A., & Ferraresi, C. (2014). Use of low-level laser therapy (808 nm) to muscle fatigue resistance: a randomized double-blind crossover trial. Photomedicine and Laser Surgery, 32(12): 678-685.
40. Nagao, M., Yamaguchi, S., & Okuda, Y. (2001). Effects of low reactive level laser, linear polarized light and Xenon-ray irradiation on the stellate ganglion in dogs. Masui. The Japanese Journal of Anesthesiology, 50(9): 958-963.
41. do Nascimento, A. P., de Oliveira, G. A., Bressanin, J. P. B., Aguirra, P., Ribeiro, A. S., Caldeira, L. F. S., Casonatto, J., Ferraresi, C., & Aguiar, A. F. (2024). Acute dose-response effect of photobiomodulation therapy on 5-km running performance in trained runners: a randomized, double-blind, placebo-controlled, crossover study. Lasers in Medical Science, 39: 145. https://doi.org/10.1007/s10103-024-04099-8
42. Miyamoto, T., Oshima, Y., Ikuta, K., & Kinoshita, H. (2006). The heart rate increase at the onset of high-work intensity exercise is accelerated by central blood volume loading. European journal of applied physiology, 96: 86-96.
43. Kliszczewicz, B. M., Esco, M. R., Quindry, J. C., Blessing, D. L., Oliver, G. D., Taylor, K. J., & Price, B. M. (2016). Autonomic responses to an acute bout of high-intensity body weight resistance exercise vs. treadmill running. The Journal of Strength & Conditioning Research, 30(4): 1050-1058.
44. Wu, C. S., Hu, S. C. S., Lan, C. C. E., Chen, G. S., Chuo, W. H., & Yu, H. S. (2008). Low-energy helium-neon laser therapy induces repigmentation and improves the abnormalities of cutaneous microcirculation in segmental-type vitiligo lesions. The Kaohsiung Journal of Medical Sciences, 24(4): 180-189.
45. Shuvaeva, V. N., Gorshkova, O. P., Kostylev, A. V., & Dvoretsky, D. P. (2011). Effect of laser irradiation on adrenoreactivity of pial arterial vessels in rats. Bulletin of Experimental Biology & Medicine, 151(1): 1-4.
46. Leal, E. C. P., Lopes-Martins, R. Á. B., Frigo, L., De Marchi, T., Rossi, R. P., de Godoi, V., Tmazoni, S. S., Silva, D. P., Basso, M., Filho, P. L., de Valls Corsetti, F., Iversen, V. V., & Bjordal, J. M. (2010). Effects of low-level laser therapy

(LLLT) in the development of exercise-induced skeletal muscle fatigue and changes in biochemical markers related to postexercise recovery. Journal of Orthopaedic & Sports Physical Therapy, 40(8): 524-532.

47. Lanferdini, F. J., Baroni, B. M., Lazzari, C. D., Sakugawa, R. L., Dellagrana, R. A., Diefenthaeler, F., Caputo, F., & Vaz, M. A. (2023). Effects of photobiomodulation therapy on performance in successive time-to-exhaustion cycling tests: A randomized double-blinded placebo-controlled trial. Journal of Functional Morphology and Kinesiology, 8(4): 144. https://doi.org/10.3390/jfmk8040144
48. Ramos, L., Leal Junior, E. C. P., Pallotta, R. C., Frigo, L., Marcos, R. L., de Carvalho, M. H. C., Bjordal, J. M., & Lopes-Martins, R. Á. B. (2012). Infrared (810 nm) low-level laser therapy in experimental model of strain-induced skeletal muscle injury in rats: effects on functional outcomes. Photochemistry and Photobiology, 88(1): 154-160.