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ORIGINAL ARTICLE

Whole-body photobiomodulation improves post-exercise recovery but does not affect performance or physiological response during maximal anaerobic cycling

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Abstract

This study aims to examine the effects of acute whole-body photobiomodulation (wbPBM), applied pre-exercise, on bouts of anaerobic cycling (Wingate) performances. Forty-eight healthy, active males and females participated in this single-blind, randomized, crossover study. Participants visited the laboratory three times to complete repeat (4×) Wingate testing, with one week between each visit. All participants completed baseline testing during their first visit and randomly received either the wbPBM or placebo condition before testing on the second visit, followed by the opposite condition on the third visit. There were no significant condition×time interactions for any variable (peak power, average power, power decrement, lactate, heart rate, ratings of perceived exertion, heart rate variability (HRV), root-mean square of differences between R-R intervals (rMSSD), power in the high-frequency range (HF) average, power in the low-frequency range (LF) average, total power, LF/HF, or power in the very-low-frequency range average). A main condition effect was only noted for heart rate, where peak heart rate was significantly higher for wbPBM (145, 141–148 bpm) than placebo (143, 139–146 bpm; $p=0.006$) and baseline testing (143, 140–146; $p=0.049$) throughout the entire testing session (i.e., collapsed across all timepoints). Furthermore, HRV (rMSSD) the following morning after testing was significantly higher for the wbPBM session compared to placebo ($p=0.043$). There were no differences in perceived recovery ($p=0.713$) or stress ($p=0.978$) scores between wbPBM and placebo. Implementing 20 min of wbPBM immediately prior to maximal bouts of anaerobic cycling did not improve performance (i.e., power output) or physiological responses (e.g., lactate). However, wbPBM elicited the ability to work at a higher heart rate throughout testing and seemed to enhance recovery through improved HRV the following morning.

Keywords Red and near-infrared light therapy · Wingate test · Muscle soreness · Fatigue · Power output · Heart rate variability

Introduction

Optimal physical performance is achieved through an effective balance of training demands and recovery to promote longitudinal performance adaptations and mitigate overtraining, burnout, and injury risks [1, 2]. Yet, high-performing populations (i.e., sport and tactical settings) require elite physical and psychological prowess, making intense training rigor necessary to prepare them for future competitions or occupational tasks [1, 3]. Recreationally

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active populations may also experience periods of unaccustomed physical demands that benefit from recovery modalities to promote greater improvements in anaerobic capabilities (i.e., strength) [4]. The anaerobic energy system's capability is often essential for sport and tactical settings, as well as improving quality of life and longevity, which requires training sessions that maximize power output and workload capacities [5–7]. Thus, a multidimensional approach is warranted to restore dampened physiological and psychological resources (e.g., heart rate, perceived stress, neuromuscular) from heightened training demands, which may be accomplished via engagement in recovery modalities [1, 3, 7].

The sports medicine and rehabilitation market is projected to reach $15.2 billion by 2027, a 47% increase from the $8.1 billion valuation in 2019 [8]. This rapid expansion stems from systemic pursuit of recovery strategies to decrease injury risk and increase performance during intensive time-restricted bouts of training and/or competition [9]. Resultantly, photobiomodulation (PBM) has exponentially increased in popularity over the last two decades [10, 11]. The combined red and near-infrared light therapy utilizes light-emitting diodes and/or low-level lasers at wavelengths ranging between 600 and 1100 nm to penetrate the skin and influence a series of intracellular activities [10, 11]. As it relates to human performance, combined red and near-infrared photons are absorbed by cytochrome *c* oxidase [11, 12] to stimulate mitochondrial activity [10, 11]. Subsequently, through improved electron transport chain efficiency and mitochondrial membrane potential, a cascade of events are initiated to promote energy substrate (i.e., adenosine triphosphate, ATP) production which enhance transients of calcium into the cell [10, 11]. Increased ATP and cyclic adenosine monophosphate production, with reduced reactive oxygen species and lactic acid production (via improved clearance rates), may serve to promote greater anaerobic power and less fatigue complications during training [11, 13]. Moreover, PBM may promote recovery by attenuating markers of muscle damage and oxidative stress, such as creatine kinase and lactate dehydrogenase, as well as muscular inflammation and soreness [10, 14–17]. Yet, the findings of PBM's effectiveness are uncertain due to variations in: environment (e.g., team/individual sport), training history, and performance endeavors (e.g., aerobic versus anaerobic energy systems) [16, 18, 19]. The recent influx of commercial technologies providing whole-body PBM (wbPBM) and targeted PBM (tPBM) demonstrates potential for applying PBM, but further investigation concerning methods for effectively implementing PBM are warranted.

The use of tPBM prior to exercise has demonstrated performance enhancement during aerobic weight-bearing (i.e., running) endurance events by prolonging time to exhaustion and increasing ventilatory oxygen kinetics (e.g., maximal oxygen consumption, VO_2max) [15, 20–22], while aerobic cycling literature is limited [23]. Pre-exercise tPBM has also shown improvements in local muscle performances through greater knee extensor maximal voluntary isokinetic forces and fatigue resistance [14], as well as improved post-exercise recovery [14, 16, 24]. Implementing tPBM prior to anaerobic sprint testing (~6.8-s trials) may decrease sprint times, lactate accumulation, and perceived fatigue [17], while tPBM prior to anaerobic cycling tasks (30–120 s) has yielded conflicting research with many finding no performance enhancement or physiological alterations (e.g., heart rate, lactate) from tPBM [25–28]. However, some have demonstrated positive ergogenic benefits from tPBM prior to anaerobic cycling tasks such as improved oxygen uptake [28, 29], prolonged time to exhaustion [29, 30], and decreased lactate accumulation [30, 31]. Moreover, recent literature reviews [10, 18, 19] have suggested that supporting evidence of PBM for performance and recovery enhancement is low to moderate with a lack of research regarding anaerobic training (i.e., maximal effort for ~30–120 s), which warrants further research to understand the efficacy of PBM across all energy systems.

Indeed, the majority of PBM research has utilized tPBM, which targets single localized muscle groups via custom-made light-emitting diode arrays [17]. However, recent developments from manufacturing companies enabled the ability to administer PBM to the entire human body, although very limited research has examined wbPBM [22, 32]. Previously, a 14-day wbPBM intervention improved 12-min run times in female basketball players [22], but a single wbPBM treatment pre-exercise did not significantly reduce creatine kinase levels following high-intensity resistance training in trained males [32]. The overall lack of research utilizing wbPBM warrants additional investigation to understand the general effectiveness of wbPBM, particularly as it pertains to anaerobic performance and recovery. Therefore, the purpose of this study was to examine the acute effects of wbPBM, applied pre-exercise, on fatigue and power output during repeated bouts of maximal anaerobic cycling, as well as post-exercise responses of recovery (i.e., lactate and heart rate metrics).

Methods

Experimental design

A randomized, single-blind, placebo-controlled, crossover design was employed to examine the effect of wbPBM on repeat Wingate cycle performances and post-exercise recovery (Fig. 1). The baseline session comprised familiarization, intake questionnaires, anthropometric

measurements, and baseline anaerobic cycle testing. Next, in random order, participants completed two experimental sessions in which they received either placebo or wbPBM immediately prior to performing repeat Wingate testing. Visits were separated by 7 days and occurred at the same time of day on the same weekday. The PBM room temperature and exercise testing facility was constantly monitored to ensure consistent ranges of 26.7–29.4 °C and 21.1–23.3 °C, respectively. An exit questionnaire was administered to determine whether participants were cognizant of and able to describe any perceived differences between wbPBM and placebo.

Participants

Healthy adult females ($n = 30$; age: 37 ± 12 years; body mass 64.2 ± 11.5 kg; height: 164.5 ± 7.2 cm; body fat percentage: $23.8 \pm 5.2\%$) and males ($n = 18$; age: 30 ± 10 years; body mass: 79.7 ± 9.3 kg; height: 179.8 ± 5.3 cm; body fat percentage: $12.9 \pm 5.0\%$) participated in this study. All participants were "low risk" according to the American College of Sports Medicine (ACSM) Risk Stratification and met ACSM's minimum physical activity guidelines of at least 75 min of vigorous or 150 min of moderate aerobic activity per week. Participants were recruited from running, triathlon, and other training groups in local and surrounding areas through Facebook groups, email lists, and word-of-mouth. All participants were asked to maintain their training, diet, and sleep patterns throughout the study, and refrain from supplementation and other ergogenic aids. Prior to initiating data collection, subjects were informed of the risks and benefits of the study and signed the institutionally approved informed consent document. All procedures were approved by the Institutional Review Board of West Virginia University (Protocol Number 1903492075) and were compliant with the Declaration of Helsinki guidelines.

Procedures

Familiarization and baseline testing

The first visit consisted of familiarization and baseline testing. Participants were first given a demonstration of all the study procedures (e.g., cycling and condition protocols). Next, participants' anthropometric and body composition measures were obtained. Body height and mass were measured via a professional beam-scale (Healthometer, Mississippi, USA) and a digital scale (Scaletronix; Welch Allyn, New York, USA), respectively. Body fat percentage was estimated via the 7-site skinfold method (Lange skinfold

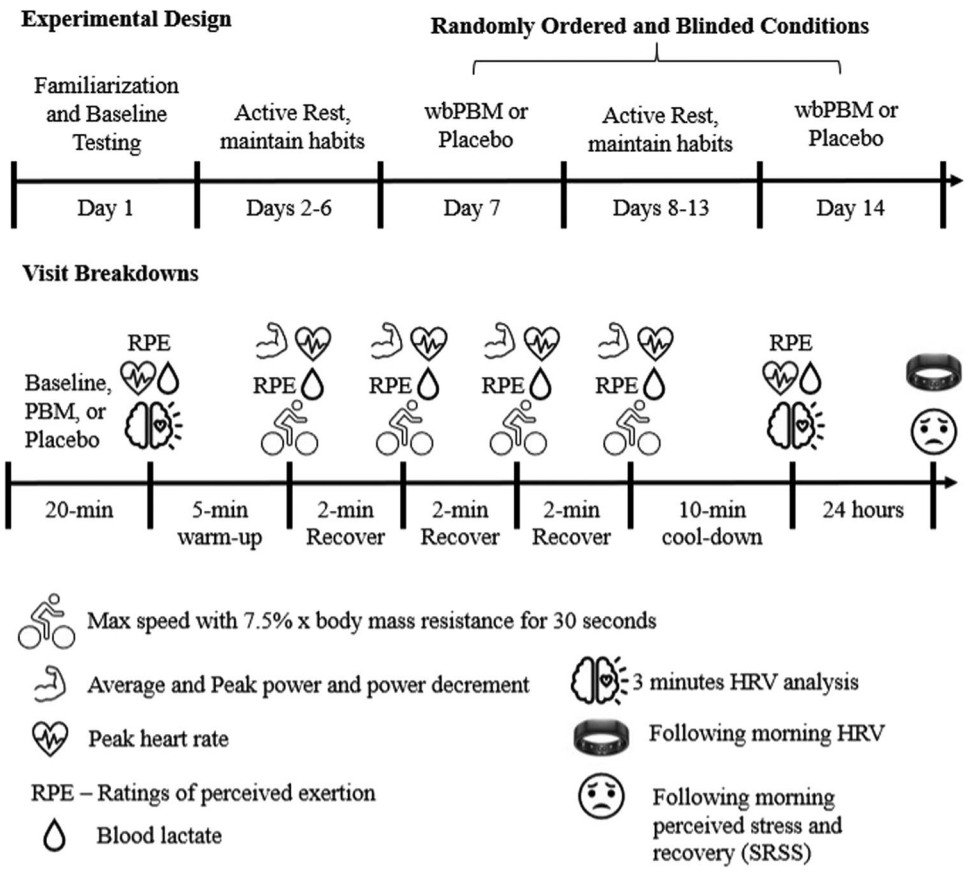

Fig. 1 Experimental study design diagram. wbPBM, photobiomodulation using a whole-body light bed (wavelengths of 660 and 850 nm and a power density of 28 $mW \cdot cm^{-2}$). Placebo, control condition; familiarization, familiarizing participants with procedures prior to baseline data collection

calipers; Beta Technology, California, USA). The average thickness of two measures at each site was used for analyses and the same trained study personnel executed the skinfold measurements to improve reliability. To obtain baseline measures, participants completed all study procedures without being exposed to placebo or wbPBM conditions prior to testing.

Conditions (wbPBM; placebo)

The NovaThor Whole Body Light Pod (THOR Photomedicine, London, UK) was used to administer light at wavelengths of 660 and 850 nm and a power density of 28 mW/cm^2 for 20 min immediately prior to anaerobic cycling. This wbPBM unit uniformly applies irradiance to the entire body and is not specifically targeted toward single anatomical locations. The placebo condition was conducted under the same procedures, except the wbPBM device was powered off. To create similar ambient temperatures as wbPBM (26.7–29.4 °C), space heaters and fans were turned on during the placebo condition. In addition, participants donned a blackout blindfold and noise-cancelling headphones during both conditions to block out light and noise generated by the wbPBM device. Clothing was standardized for participants (females, sports bra and shorts rolled up to 1 in. inseam; males, shirtless with shorts rolled up to 1 in. inseam).

Anaerobic sprint cycling (repeat Wingate testing)

Anaerobic power output and power decrement were assessed via a repeat (4 ×) Wingate test [33] performed on a cycle ergometer (894E Wingate Testing Bike Ergometer; Monark Exercise, Vansbro, Sweden). Seat height was set, for all sessions, to standing hip height, affirmed by visual inspection of the participant's leg fully extended while seated. Participants completed a 5-min warmup on the cycle ergometer at a self-selected pace, against no resistance. Next, Wingate testing was initiated by participants accelerating to maximum speed then adding a resistance of 7.5% of the participant's body mass. The participants pedaled at maximal effort for 30 s and were provided consistent verbal instruction (i.e., 15 and 5 s remaining marks) and encouragement. Then, the resistance was removed and a 2-min active recovery was permitted at a self-selected pace. The same series of testing and active recovery was repeated until four Wingate trials were completed. Then, participants completed a "light" 5-min active recovery at a self-selected cycle pace followed by a 5-min light walk on a turf track. Five-second epochs were used to calculate peak power (highest power obtained), average power (average of 6 epochs), and power decrement (((peak power − lowest power) / peak power)) × 100)) for each Wingate trial (Monark Anaerobic Test Software; Monark Exercise). To account for variations in body mass, relative (power/body mass) metrics were analyzed.

Measures immediately before, during, and after anaerobic cycling

The peak HR, ratings of perceived exertion (RPE), and lactate data were collected immediately prior to starting the warmup, within 30 s after completing each of four Wingate trials, and at the end of the 10-min cooldown. Heart rate monitors (Polar H10; Polar, Kempele, Finland) were positioned with the electrode placed tightly, but comfortably, just below the xiphoid process to record R-R intervals. RPE was assessed on the Borg scale from 6 (very, very light) to 20 (maximum exertion) [34]. Blood lactate was measured using a lactate meter and test strips (Lactate Plus; Nova Biomedical, Massachusetts, USA). Blood samples were obtained from the middle or ring finger, according to World Health Organization recommendations [35], via single-use 28-gauge 1.8-mm lancets (Unistik 3 Comfort; Owen Mumford, Oxford, UK). To confirm data quality and quality control, the lactate meter was calibrated using the level 1 and level 2 control solutions before testing. The fingertip was cleaned by an alcohol swab, the initial blood sample was wiped away with medical gauze, and the subsequent drop was used for analysis.

Testing day heart rate variability

During the baseline and experimental sessions, heart rate variability (HRV) was measured immediately prior to and 10 min following the completion of the repeat Wingate testing. The HRV data were recorded using the heart rate monitor (H10 chest strap; Polar) and application (Firstbeat Sports; Firstbeat, Jyväskylä, Finland) while participants laid in a supine position for 3 min. Participants were instructed to become comfortable then remain completely motionless while breathing naturally. The HRV metrics assessed were rMSSD, root-mean square of differences between R-R intervals in a specified time segment; VLF, power in the very-low-frequency range (< 0.04 Hz); LF, power in the low-frequency range (0.04–0.15 Hz); HF, power in the high-frequency range (0.15–0.4 Hz); and LF/HF, low frequency/high frequency ratio.

Morning HRV and subjective questionnaires

For the morning following each condition's testing, HRV was recorded as rMSSD using the Oura ring (ŌURA, Oulu, Finland) [36]. To ensure data integrity, participants were properly fitted for the Oura ring and downloaded the companion application on their smartphone during the initial

visit. Participants were instructed to wear the ring according to manufacturer guidelines (i.e., ring sensors oriented on the palmar side of the hand, same finger throughout). Upon awakening and while lying as still as possible, a 5-min "Moment" (Oura application function to permit spot measurements) was executed to measure morning HRV.

Participants completed the Short Recovery and Stress Scale (SRSS) questionnaire as a valid measure of perceived stress and recovery [37]. The SRSS was completed upon awakening the morning after each session. Questions consisted of eight items, rated on a 7-point system from 0 (does not apply at all) to 6 (fully applies), that pertained to the participants' current states of recovery and stress in relation to their highest state (i.e., most stressed, most recovered state).

Statistical analysis

All analyses were conducted using R software version 4.0.5 [38] with an alpha level of < 0.05. Data were considered normal according to Shapiro–Wilk testing. Distributions were adjusted using a natural log transformation for HRV data prior to analysis. Mixed-effects models were employed with participants nested within condition to account for variations in individual responses. There were four times (Wingate 4×) for cycling power and power decrement; six times (pre- and post-exercise; Wingate 4x) for lactate, RPE, and heart rate; and two times for HRV (pre–post). Any significant univariate (condition, time, or time × condition) results were followed by post hoc testing using Tukey's method for multiple comparisons. Recovery, via HRV and SRSS, was assessed on the morning after testing by comparing the difference from baseline testing to the wbPBM and placebo conditions using Wilcoxon signed-rank tests.

Results

Effectiveness of the placebo condition

Although 58.3% of participants stated they detected differences between conditions, only 29.0% of participants correctly identified the week they received wbPBM, suggesting an effective placebo condition.

Acute effects of photobiomodulation on cycling performance and physiology

There were no significant condition × time interactions or condition effects for cycling peak power, average power, or power decrement (Table 1, Fig. 2). There were no significant condition × time interactions for blood lactate, peak heart rate, or RPE (Table 1, Fig. 2). Lactate and RPE were not different across conditions throughout the entire protocol. There was a main condition effect on heart rate, where peak heart rate was significantly higher for wbPBM (mean, 145; $CI_{95\%}$, 141–148 bpm) than placebo (mean, 143; $CI_{95\%}$, 139–146 bpm; $p = 0.006$) and baseline testing (mean, 143; $CI_{95\%}$, 140–146; $p = 0.049$).

Acute effects of photobiomodulation on recovery

There were no significant main condition effects nor condition × time interactions for HRV metrics immediately pre- and post-exercise (Table 1, Fig. 3). However, as shown in Fig. 4, HRV (rMSSD) the morning after testing, compared to baseline, was significantly higher for wbPBM than placebo. There were no differences in recovery ($p = 0.713$) scores between placebo (mean $= -0.5$, $CI_{95\%}$, -8 to 8) and wbPBM (mean $= 0$, $CI_{95\%}$, -11 to 9) or stress scores ($p = 0.978$) between placebo (mean $= -1$, $CI_{95\%} = -8$ to 11) and wbPBM (mean $= 1$, $CI_{95\%} = -9$ to 13).

Discussion

The current aim was to determine the acute effects of wbPBM on anaerobic cycling performance and recovery. Contrary to our hypothesis of improved cycling performances, based on prior research [10, 19], wbPBM did not improve cycling power or fatigue indices. In prior literature, the implementation of tPBM prior to sprint testing elicited decreased average sprint times, fatigue indexes, lactate accumulation, and perceived fatigue in rugby athletes [17]. The aforementioned sprint times (~6.8-s trials) were shorter than the Wingate testing (30-s trials), which may explain the lack of significant performance improvements from the current study, as well as prior research using tPBM immediately before a Wingate test in volleyball players [27]. For longer anaerobic exercise, such as cycling to exhaustion (> 60–120 s), prior research found tPBM to prolong time to exhaustion, increase maximal oxygen consumption, and decrease lactate accumulation in competitive cyclists [30], but not in untrained male [25] or recreational cyclists [26]. Others found large effect sizes for increased maximal oxygen consumption and time to exhaustion during maximal effort cycling bouts in competitive male cyclists, but no statistical significance was reached [29]. Another group of untrained males and females demonstrated greater peak oxygen uptake but no improvement on cycling time to exhaustion [28]. In short, differences among the current and prior findings on anaerobic cycling performances may be a cumulative result of the cycling test (e.g., to exhaustion, for maximal power in shorter durations), population experience (e.g., untrained, recreational, competitive), and PBM modality (i.e., wbPBM, tPBM).

Table 1 Main univariate effects for photobiomodulation (wbPBM) for each variable assessed

Metric	Condition (placebo vs. wbPBM)	Trial (W1, W2, W3, W4)	Condition by trial
Peak power	2.08 (0.126)	91.54 (<0.0001)	0.99 (0.435)
Average power	2.06 (0.129)	306.17 (<0.0001)	0.72 (0.633)
Power decrement	2.41 (0.090)	5.73 (0.001)	1.23 (0.287)
Metric	Condition (placebo vs. wbPBM)	Time (pre, W1, W2, W3, W4, post)	Condition by time
Lactate	1.74 (0.176)	1000.75 (<0.0001)	0.67 (0.753)
Peak heart rate	5.21 (0.006)*	3259.27 (<0.0001)	0.46 (0.914)
RPE	0.15 (0.862)	1993.26 (<0.0001)	1.00 (0.441)
Metric	Condition (placebo vs. wbPBM)	Time (pre, post)	Condition by time
rMSSD	1.64 (0.195)	1220.47 (<0.0001)	0.34 (0.710)
HF average	0.74 (0.480)	965.25 (<0.0001)	1.01 (0.368)
LF average	0.84 (0.434)	661.85 (<0.0001)	0.89 (0.411)
VLF average	0.06 (0.943)	389.59 (<0.0001)	0.83 (0.437)
LF/HF	0.44 (0.642)	153.03 (<0.0001)	0.28 (0.757)

Values are *F* statistic (*p* value). * indicates statistical significance

RPE ratings of perceived exertion, *rMSSD* root-mean square of differences between R-R intervals, *VLF* very-low-frequency power (<0.04 Hz), *LF* low-frequency power (0.04–0.15 Hz), *HF* high-frequency power (0.15–0.4 Hz), *LF/HF* low frequency/high frequency ratio

Another potential explanation for the aforementioned discrepancies is that many of the positive PBM effects exist primarily within the aerobic (i.e., oxidative) energy system, such as increased maximal oxygen uptake [28], improved tissue oxygenation [28, 39, 40], and greater rates of ATP synthesis [10, 11, 15], thus the expected delayed requirement for ATP synthesis by the anaerobic energy systems, subsequently reducing production of lactate during exercise. Moreover, lower lactate accumulation following PBM is supported in theory by the improvements in nitric oxide bioavailability from PBM that would result in improved clearance of metabolic byproducts from increased vasodilation [41]. For example, improved maximal oxygen consumption and time to exhaustion were noted in physically active males following tPBM prior to an incremental treadmill test, which also resulted in reduced lactate 13–15 min, but not pre- or 0–11 min following training [20]. Meanwhile, male soccer players (aged 15–18) noted lower blood lactate in the tPBM condition 15 min after but not 3 min or 10 min following a single Wingate test coinciding with no improvement in cycling performances [31]. However, there were no differences in lactate responses throughout testing (following each Wingate test) or 10 min after testing in the current study. These findings are in line with prior literature that did not demonstrate improved lactate removal from tPBM prior to incremental cycling in untrained males and females despite improved oxygen extraction by peripheral muscles [28]. The discrepancies may be due to the timepoint of lactate collection following testing, where the aforementioned studies typically sampled > 10 min before noting differences in lactate levels. Another theory, due to the benefit to oxidative properties, is that PBM may delay the onset of fatigue to increase time to exhaustion, but not necessarily improve peak power output. However, in shorter duration tasks, such as sprint testing, tPBM resulted in lower blood lactate at 3, 10, 30, and 60 min after testing in high-level male rugby athletes [17]. Thus, the timeline of the effectiveness of PBM may be subject to the intensity and duration of the exercise in question, as well as the dose of PBM and the testing outcome metric.

For example, in moderately active males performing supramaximal running at 115% of their maximal oxygen consumption (8–10 min of testing), lactate at 3, 5, 7, and 10 min were not different following tPBM, but the difference between conditions gradually increased as time surpassed [42]. Therefore, with the supramaximal intensity and long duration, the effect of tPBM on lactate removal may not have been noted until after 10 min. Others have found a cumulative effect via multiple doses of tPBM, which suggests that more energy may need to be delivered to the utilized muscle tissue to induce performance and physiological benefits for more exertive movements (high intensity whole body) or in untrained individuals [25]. This may be particularly evident for tissue that is low in mitochondria, which has more difficulty responding to low doses of light, such as muscle tissue in the fast-twitch muscles recruited for high-power motions in the current study [43]. On the contrary, tissue with high degrees of mitochondrial density (i.e., likely noted

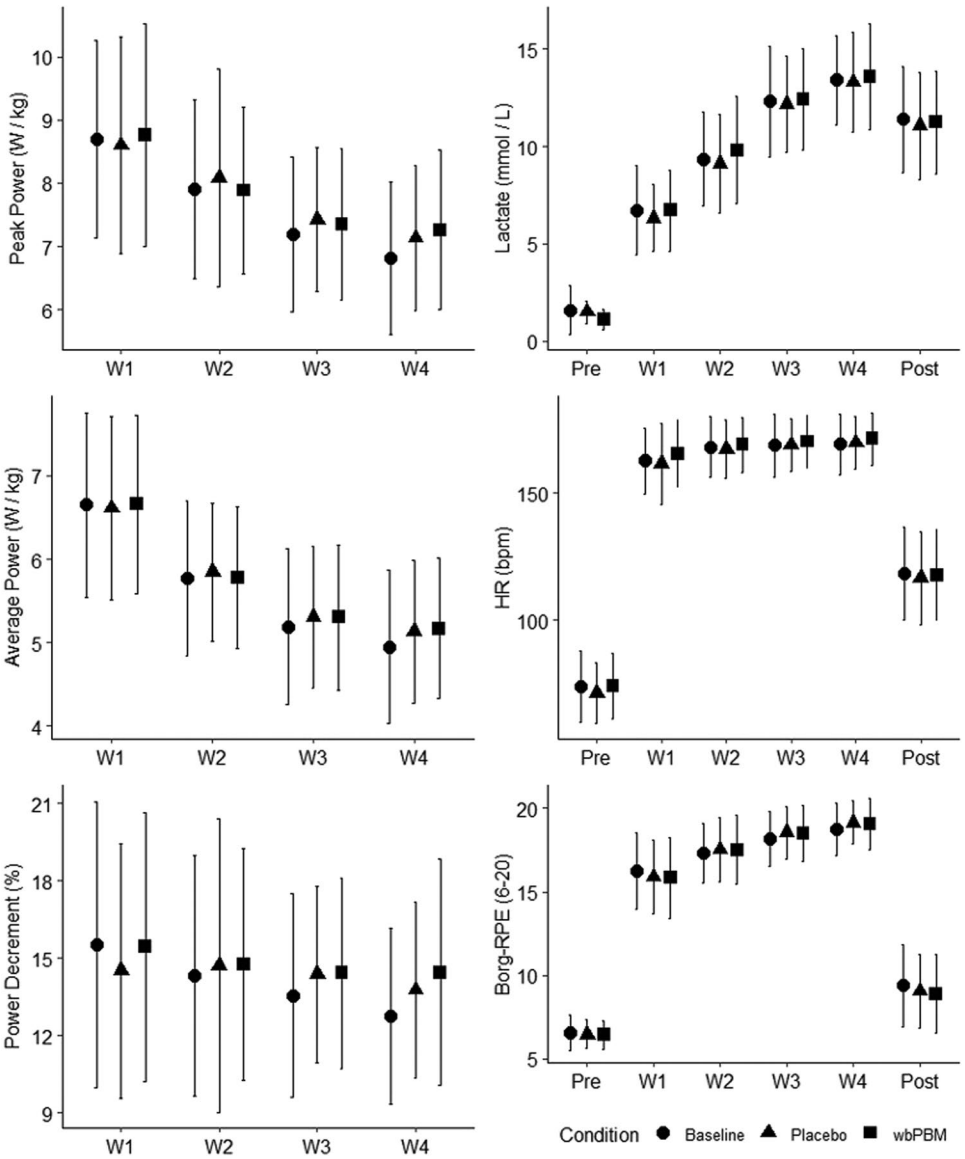

Fig. 2 Comparisons between whole-body photobiomodulation (wbPBM) and placebo group for relative to body mass peak power (PP), average power (AP), and power decrement (PD) across each Wingate trial, as well as lactate, peak heart rate (HR), and ratings of perceived exertion (RPE) across each Wingate trial and pre- and post-exercise. Pre = pre-exercise, W1 = immediately after first Wingate test, W2 = immediately after second Wingate test, W3 = immediately after third Wingate test, W4 = immediately after fourth Wingate test, 10 min post = 10 min following completion of fourth Wingate test

in competitive athletes) may experience a lack of ergogenic effect from PBM due to overdosing rather than underdosing [43]. Still, comparable research on incremental or maximal intensity cycling until exhaustion reported that no improvement in lactate removal existed from tPBM in untrained males [25], untrained males and females [28], and in male cyclists [26]. However, the present study utilized wbPBM, which was theorized to target a greater amount of muscle tissue. Thus, further research is necessary to identify optimal doses of wbPBM for performance enhancement and recovery, which may vary based on the population of interest (i.e., trained vs. untrained; aerobic vs. anaerobic training history).

Despite the lack of differences in power output during cycling and lactate responses, peak heart rate was significantly higher throughout cycling during the wbPBM testing session than the baseline and placebo conditions. This may allude to the ability of participants to work at a higher rate throughout the testing session, which consisted of maximal all-out effort 30-s bouts of cycling. Yet, due to the nature of the all-out cycling, the participants did not perceive any greater effort given during the wbPBM condition. Thus, the heart rate responses may not coincide exactly with RPE responses [44]. In previous literature, tPBM did not alter HR responses when applied prior to cycling [25], but did lower heart rate and RPE when applied prior to an incremental bout of treadmill running for recreationally active males [20]. Yet, heart rate and RPE were not altered by tPBM when moderately active males completed 8–10 min of treadmill running [42] or when untrained males and females completed maximal incremental cycling [28]. Further research is needed to understand the relationship between HR, RPE, and wbPBM.

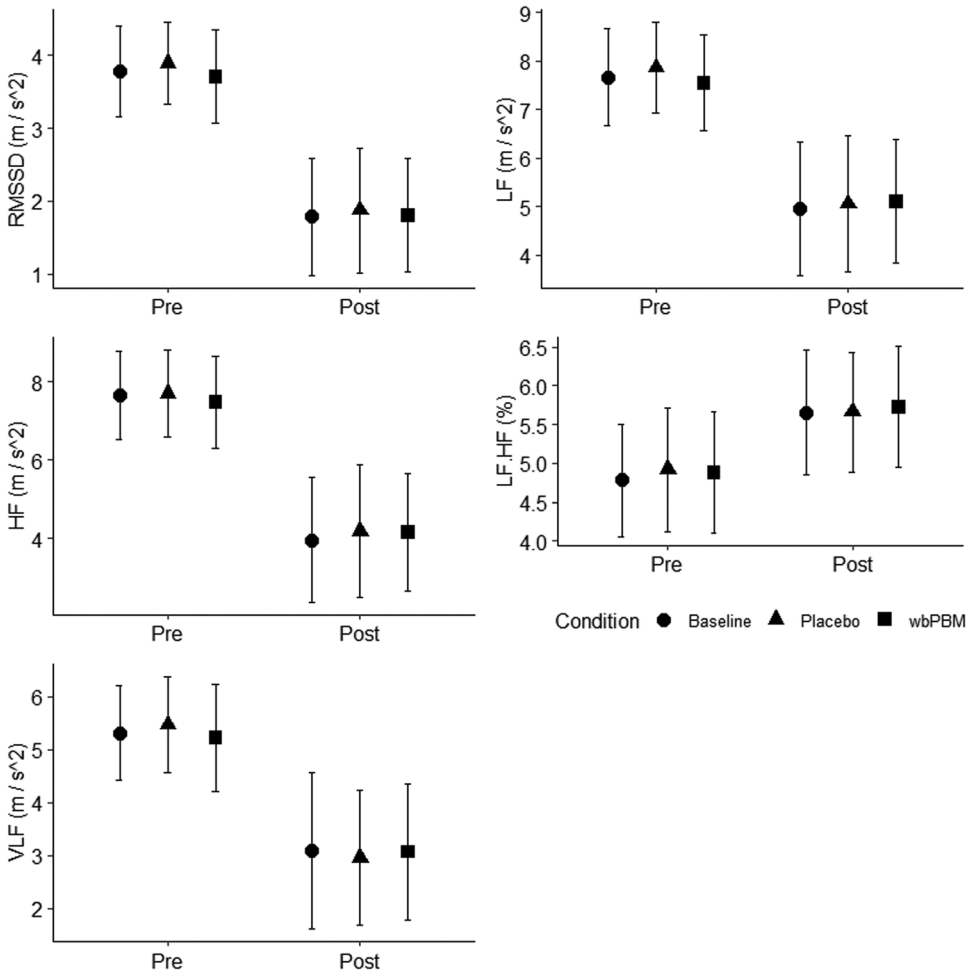

Fig. 3 Comparison of heart rate variability measures following whole-body photobiomodulation (wbPBM) or placebo conditions before exercise (Pre) and 10 min following completion of cycling (Post). HF = high-frequency band, LF = low-frequency band, VLF = very-low-frequency band, LF/HF = the ratio of low-frequency to high-frequency power

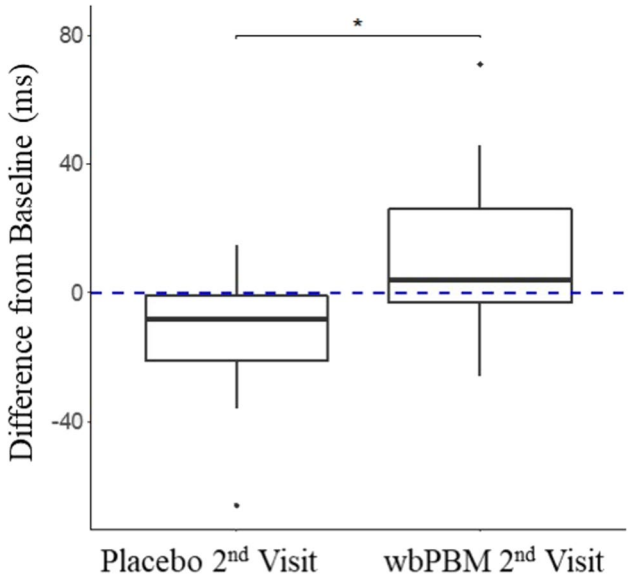

Fig. 4 Comparison between heart rate variability (rMSSD) from baseline on the morning following baseline testing to the morning following either placebo or whole-body photobiomodulation (wbPBM). *Statistically different at $p < 0.05$

Other physiological metrics, such as HRV, have been monitored for days leading into wbPBM testing sessions [32], as a means of controlling for confounding factors by determining stress on the body and preparedness to train, but not after cycling in response to wbPBM interventions. In the current study, the HRV responses were not statistically significantly different prior to cycling or 10 min after cycling, although the data were trending to lower HRV immediately after wbPBM and prior to cycling. However, daily fluctuations in HRV could have occurred prior to arriving at the laboratory for many reasons. Thus, we also assessed HRV the morning after placebo and wbPBM conditions in comparison to the baseline measure for more consistent comparisons of HRV [3]. The rMSSD (HRV) was higher the morning following wbPBM compared to the placebo group when comparing both to baseline measures, indicating improved recovery. Previous research reported that after two 40-min running time trials, HRV (rMSSD) was not different 24 or 48 h after the second running time trial, but there were lower perceptions of muscle soreness in the tPBM condition [45]. On the contrary, there were no differences in recovery or stress scores, during the current study, from baseline at the morning after PBM

and placebo conditions. It is possible that PBM may have a greater effect on post-exercise recovery responses (i.e., perceived soreness or HRV) when the exercise involved requires the entire body and a high level of demand (i.e., high intensity and/or duration) [32]. However, it is important to consider that the current results occurred in a fairly non-homogenous group of males and females from diverse backgrounds (i.e., age and training histories), which permits the ability to generalize the findings to a broader population interested in using these devices but may differ compared to results from homogenous highly trained populations.

Conclusion

In a group of healthy active adults, wbPBM, when compared to placebo, showed a significant improvement in recovery through an increase in morning HRV (rMSSD). These findings suggest that pre-conditioning with wbPBM prior to intense exercise may lead to improved recovery the following day. Regarding acute performance alterations, wbPBM did not improve power output or loss of power throughout maximal effort anaerobic cycling bouts. The lack of performance alterations may stem from the coinciding ineffectiveness on improving lactate removal in the current protocol. Although heart rate was elevated throughout the testing session, which may indicate increased physiological effort, no differences in RPE or HRV were noted during the testing session. According to these findings, wbPBM may not improve performance or physiological responses during maximal effort anaerobic cycling, but when applied prior to exercise, wbPBM may improve physiological recovery (according to HRV). The increased availability of wbPBM technologies and interest in accelerated recovery strategies in high performers is allowing for much more research to be generated, and we suggest continued studies to understand the performance impacts for all energy systems and a deeper understanding of physiological recovery in applied training environments.

Author contribution All authors have read and approved the manuscript. Conceptualization: J.D.F., J.D.S., M.D.S., and J.A.H.; methodology: J.D.F., J.D.S., M.D.S., R.D.B., and J.A.H.; formal analysis: J.D.F., J.J.M., J.D.S., and J.R.; investigation: J.D.F., J.D.S., J.J.M., and J.R.; resources: S.M.G., J.A.H.; data curation: J.D.F., J.D.S., J.J.M., and J.R.; writing—original draft preparation: J.D.F., J.D.S., and J.J.M.; writing—review and editing: M.D.S., J.R., S.M.G., R.W.B., and J.A.H.; visualization: J.D.F. and J.J.M.; project administration: S.M.G. and J.A.H. All authors have read and agreed to the published version of the manuscript.

Declarations

Ethical approval All procedures were approved by the Institutional Review Board of West Virginia University (Protocol Number 1903492075) for human participant research and were compliant with the Declaration of Helsinki guidelines.

Informed consent Prior to initiating data collection, subjects were informed of the risks and benefits of the study and signed the institutionally approved informed consent document.

Conflict of interest The authors declare no competing interests.

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