

**The Effects of Photobiomodulation (PBM) on Recovery: A
10-week trial comparing duration of DOMS before and after
the use of PBM with the use of BIODEX.**

By Lexie Spurr

As a fulfilment of the requirements of an MSc by research

TABLE OF CONTENTS

ACKNOWLEDGMENTS	3
ABSTRACT	4
LIST OF FIGURES	5
LIST OF TABLES / GRAPHS	6
LIST OF ABBREVIATIONS	7
INTRODUCTION	8
Delayed Onset Muscle Soreness (DOMS).....	10
Introduction to Photobiomodulation (PBM) Therapy	12
Previous Studies on Photobiomodulation and Muscle Recovery.....	14
DOMS Assessment Methodologies	17
Methodological Approaches in Previous PBM Studies.....	18
Limitations and Gaps in Existing Literature on PBM and DOMS	20
Menstrual Cycle and its Effect on Recovery	21
Aims of Research	23
METHODS	24
Participants.....	24
Menstrual Cycle.....	25
Study Protocol	25
Baseline Testing (laboratory visit one)	25
Inducing DOMS (laboratory visit two)	26
Questionnaire.....	29
Statistical Analysis	29
RESULTS	31
DISCUSSION	38
Limitations and Methodological Considerations.....	44
CONCLUSION	46
REFERENCES	48
APPENDIX	58

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ABSTRACT

This study examined the effects of photobiological phototherapy (PBM) on delayed onset muscle soreness (DOMS) in female collegiate athletes over a 10-week period. DOMS is a common side effect of intense exercise. Therefore, it can have a significant impact on athletic performance and training schedules. Although various rehabilitation strategies have been proposed, PBM therapy has emerged as a promising approach to improve muscle recovery and enhance performance. A randomized, double-blind, placebo-controlled crossover design was used. The study tested the efficacy of PBM in managing DOMS in female field hockey players. Participants received a DOMS-inducing exercise protocol followed by a PBM or placebo light treatment. Muscle strength was objectively measured using a Biodex isokinetic dynamometer, while subjective pain perception was assessed using the McGill Pain Questionnaire. Results suggest that PBM therapy may have a positive effect on recovery of muscle strength after DOMS-induced exercise was found to be significantly different between the placebo conditions (however, subjective pain scores showed no significant differences between PBMT and placebo conditions). This study contributes to increasing research on PBM in sports science, while also addressing the underrepresentation of female athletes in such studies. To account for any hormonal changes or effects on the recovery process, we controlled for menstrual cycle stages. Although our results point to the potential advantages of PBM for muscle recovery, they also emphasise the complexity of DOMS and the difficulties in evaluating it. To completely understand the processes underlying PBM's effects on DOMS and to develop specific treatment plans that work for a variety of athletic groups, more research is required.

LIST OF FIGURES

Figure 1: The Isokinetic Dynamometer Biodex System 3 PRO that was used throughout this study (Ekstrand, Lexell and Brogårdh, 2016).

Figure 2: A consolidated standards of reporting trials (CONSORT) diagram.

Figure 3: Average peak Torque (TQ) at Baseline, Placebo and PBM

Figure 4: Peak torque (TQ) comparing PBM and Placebo

Figure 5: Profile Plots

LIST OF TABLES / GRAPHS

Table 1: Participant characteristics in all study groups

Table 2: Descriptive Statistics

Table 3: Pairwise Comparisons

Table 4: Tests of Within-Subjects Effects

LIST OF ABBREVIATIONS

DOMS - Delayed Onset Muscle Soreness

NSAIDs - Nonsteroidal Anti-Inflammatory Drugs

PBM - Photobiomodulation

PBMT - Photobiomodulation Therapy

BST - Bangsbo Sprint Test

HRV - Heart Rate Variability

SJ - Squat Jump

IL-6 - Interleukin-6

CK - Creatine Kinase

LDH - Lactate Dehydrogenase

TNF- α - Tumor Necrosis Factor-alpha

EIMD - Exercise-Induced Muscle Damage

VAS - Visual Analog Scale

INTRODUCTION

The desire for more active lifestyles and optimal physical performance have made it necessary for individuals to look for more efficient ways to speed up recovery and improve training adaptation. One of the most frequent side effects of strenuous or unaccustomed exercise is delayed onset muscle soreness (DOMS). DOMS is a comprehensive term used to characterise post-exercise muscular discomfort, tenderness, and rigidity occurring in hours after exercise (Howatson & van Someren, 2008) and peaking one to three days later (Cheung *et al* 2003). The severity and duration of soreness, and subsequent impact on performance is highly variable between individuals, and DOMS has been found to be rated similarly in both highly trained and untrained individuals (Newton *et al* 2008), and impairing physical performance similarly by limiting range of motion, reducing muscle strength, and causing discomfort during exercise. For elite athletes, dealing with DOMS can interfere with finely tuned, periodised training schedules, and demands careful attention and management from teams (Pexa *et al* 2023).

When DOMS occurs changes in muscle recruitment and sequencing patterns can occur, putting abnormal strain on muscles, ligaments, and tendons (Cheung, Hume, Maxwell 2003). These compensatory mechanisms may unintentionally raise the risk of further injury, particularly if an athlete tries to return to activity too soon (Cheung, Hume, Maxwell 2003). However, with appropriate rest and recovery, the body returns to homeostasis (Pexa *et al* 2023), DOMS resolving by around 4-days after exercise (Damas *et al* 2016). It is generally recommended that athletes who train daily reduce the volume and intensity of their workouts for one to two days after engaging in activities that cause severe DOMS (Soligard *et al* 2016) but this is not always possible in elite settings. Finding an effective way to track and alleviate the effects of DOMS can empower athletes to engage in more rigorous training sessions, increasing possible training loads throughout the week and lower injury risk.. By accelerating the recovery process, athletes can return to full training earlier, which could benefit them in the long run, making them stronger, fitter, and overall better.

Numerous treatment strategies have been proposed to mitigate the severity of DOMS and expedite the recovery of maximal muscle function. The effectiveness of nonsteroidal anti-inflammatory medicines (NSAIDs) been shown to be beneficial (Morelli et al 2018), but its effectiveness may be dependent on the timing of administration and dose used (Cheung, Hume & Maxwell, 2012). A recent review paper by Dupuy et al (2018) concluded that “massage seems to be the most effective method for reducing DOMS and perceived fatigue” but the results of massage treatment for DOMS can differ, perhaps as a result of variations in the time and particular techniques used during the massage (Cheung, Hume and Maxwell, 2012). Other approaches, including electrical current modalities, homoeopathy, cryotherapy, stretching, compression, water immersion and ultrasound, have typically not been successful in reducing DOMS symptoms though they may effectively manage the corresponding perceived fatigue (Dupuy et al 2018). Active recovery, using exercise to alleviate DOMS has been the most commonly technique for over 30 years (Armstrong, 1984). However, the impact of active recovery may only be significant during a short period after exercise (Zainuddin et al., [2006](#)) and may be explained by enhanced blood flow in muscle tissue (Cheung 2003). With the lack of effective treatment, emerging modalities such as photobiomodulation (PBM) have garnered attention for their potential to more effectively manage DOMS, particularly within elite sport settings, where rest may not be a practical alternative.

Field hockey

Field hockey is a high-intensity game with higher recorded meter per minute distances than other comparable team sports (McMahon and Kennedy, 2019) and high recorded heart rates (McGuinness, Malone, Hughes *et al*, 2017) requiring a high level of fitness. Matches are characterised by intermittent sprinting, frequent changes of direction, hitting and dribbling the ball, jumping and diving which collectively classify hockey as high impact, high intensity exercise (McGuinness, Malone, Petrakos, & Collins 2017) and the semi-crouched required puts further pressure on both arm and leg muscles (Elferink-Gemser, *et al.*, 2004). Developing hockey skills in training places a significant emphasis on the muscular strength and endurance components of a players fitness (Elferink-Gemser, *et al.*, 2007). Elite field hockey players competing in sequential games within a multi-day tournament are found less able to sprint in the second and third games, with DOMS being a possible factor (Spencer *et al* 2005). Female

hockey players playing in the top two tiers of university hockey generally train or play 6 days a week. Lowering the risk and impact of DOMS during the hockey season would be a useful addition to a team's training plan.

Delayed Onset Muscle Soreness (DOMS)

DOMS is a complex physiological response involving several interconnected mechanisms. The current understanding suggests that the symptoms are caused by unaccustomed or intense exercise, particularly eccentric contractions, leading to micro-tears in muscle fibres and connective tissue, which disrupts the structural integrity of muscle cells. This damage triggers an inflammatory response, releasing mediators such as histamines, prostaglandins, and cytokines, increasing blood flow and attracting immune cells to the affected area. The muscle damage and inflammatory process also increases production of reactive oxygen species (ROS), contributing to oxidative stress. Damage to muscle cell membranes allows intracellular enzymes like creatine kinase (CK) and lactate dehydrogenase (LDH) to leak into the bloodstream, allowing both to be used as markers of muscle damage. These processes result in swelling, sensitizing nociceptors and altering neuromuscular activation patterns. The delayed peak of DOMS symptoms, typically occurring 24-72 hours post-exercise, is attributed to the time required for the full development of these physiological responses (Cheung et al., 2003; Howatson & van Someren, 2008).

In recent years, there's been an increase in research to investigate the different theories to understand why DOMS occurs and explore the variety of approaches that have been proposed to be easing its effects or prevent it altogether. The main areas of research have been into the use of cold or heat temperature, compression, massage and dietary change (Heiss et al., 2019). The effectiveness of cold and heat therapy to reduce DOMS remains inconclusive partly due to widely varying study protocols. A study by Petrofsky et al. (2015) involving 100 subjects found that both immediate and delayed cold or heat therapy after exercise reduced muscle damage. The control subjects lost 24% strength after exercise whereas the subjects with cold or heat therapy just after exercise only lost 4% strength ($p < 0.01$). Measurements were collected at 110° of knee flexion to determine the force required to flex the knee between 90 and 125 degrees. The data was adjusted for individual variations

(leg length and girth) by normalising them to the force needed for each subject to flex their knee prior to exercise. All groups required the same amount of force to stretch their legs one day following the workout. The force remained statistically consistent in all groups over the next day, but in the group that got heat or cold therapy immediately following exercise, the force remains statistically constant for the following 2 days. There is also some evidence for the effectiveness of cryotherapy/cryostimulation exposure after a physical exercise, Fonda et al. (Fonda and Sarabon, [2013](#)) found a positive effect of whole body cryotherapy (WBC) on DOMS after an exposure of 3 min exposure at -140 and -195°C and recent reviews by both Lombardi et al. (2017) and Dupuy et al. (2018) concluded that cryotherapy within 24h of muscle damage was likely to be effective in reducing DOMS.

In 2005, Zainuddin et al. looked into the effectiveness of massage in alleviating DOMS without affecting muscle function following eccentric exercise. The study utilized an arm-to-arm comparison model with two independent variables (control and massage) and six dependent variables to assess various aspects such as strength, range of motion, muscle soreness, and plasma creatine kinase activity. Ten subjects performed eccentric elbow flexor exercises, with one arm receiving 10 minutes of massage treatment three hours post-exercise while the contralateral arm received no treatment. The results showed that massage effectively reduced DOMS by approximately 30% and mitigated swelling, but it did not influence muscle function recovery.

Dietary supplements are frequently used in sports and exercise to improve performance and speed up recovery (Rodriguez et al 2009). As exercise-induced muscle damage (EIMD) is associated with inflammatory reactions, such as the release of cytokines and reactive oxygen species (ROS), as well as mechanical stress, anti-inflammatory and antioxidant supplements have been proposed to help prevent and lessen signs of muscle damage, including DOMS, and loss of muscle strength (Tanabe, Fujii and Suzuki, 2021). However, although several studies using supplements have shown a reduction in ROS, this has not been effectively linked to a significant reduction in DOMS. A 50 study Cochrane Review by Ranchordas et al. (2017) looking into the potential benefits of antioxidant-enriched meals and supplements for preventing and treating DOMS after exercise concluded that although there was some evidence of benefit this was weak, particularly when the poor study quality, and effect sizes

were considered. There are also some risks associated with high supplementary antioxidant intakes with evidence that they may prevent some of the physiological functions of free radicals that are needed for cell signalling. Therefore, higher dosages of antioxidants can hamper or prevent performance-enhancing and health-promoting training adaptation such as mitochondrial biogenesis, skeletal and cardiac muscle hypertrophy, and improved insulin sensitivity (Li et al 2022). This is also the case against using NSAIDs.

Supplementing with fruit derived polyphenols particularly those rich in anthocyanins; tart cherry juice, Pomegranate or New Zealand Blackcurrant have also been linked to positive effects in reducing muscle damage (Cook & Willems 2018) and self-reported muscle soreness (Souza et al 2022). As with other studies in this area the wide variety of different protocols, supplement doses and supplement types have made any strong conclusions of benefit impossible. However, studies do suggest that there may be some benefit with consistent smaller doses (Souza et al 2022). For example, in a study conducted in 2016 by Bell et al., sixteen male semi-professional soccer players were given a placebo or tart cherry juice concentrate to take for two 7-day periods followed by a 2-week washout. To replicate the action of a football match, participants completed a modified version of the Loughborough intermittent shuttle test. In comparison to the placebo group, the study indicated that ingesting Montmorency Tart Cherry Juice considerably reduced muscle soreness despite the blood markers for inflammation and muscle injury showing no discernible difference. This is because plasma cytokines don't reflect intramuscular ones (Bell et al., 2016).

Introduction to Photobiomodulation (PBM) Therapy

Photobiomodulation therapy (PBMT), originally known as low-level laser therapy, first came on the scene in the 1960s. The development of PBM can be traced back to Endre Mester, a Hungarian scientist. In 1967, Mester conducted experiments using a low-powered ruby laser on mice, initially attempting to replicate an experiment to determine if laser radiation might cause cancer. Unexpectedly, he observed that the laser treatment accelerated hair growth and wound healing in the mice (Hamblin, 2016). This serendipitous discovery laid the foundation for what would become PBM therapy. Throughout the 1970s and 1980s, research into the biological effects of low-level laser therapy expanded, with studies exploring its

potential in various medical applications, including wound healing, pain management, and inflammation reduction (Chung et al., 2012). The use of PBM in sports medicine and performance enhancement began to gain traction in the late 1990s and early 2000s. One of the earliest studies specifically examining PBM in a sports context was conducted by Lopes-Martins et al. in 2006. This animal study investigated the effects of low-level laser therapy on muscle fatigue development and possible mechanisms in rats (Lopes-Martins et al., 2006). The first randomized clinical trial (RCT) exploring the use of PBM for improving sports performance was reported by Leal-Junior et al. in 2008. This ground-breaking study demonstrated that applying PBM before an exercise session could enhance the performance of elite volleyball players by delaying muscle fatigue onset and preventing the expected increase in blood lactate levels (Leal-Junior et al., 2008). Since then, numerous studies have investigated the effects of PBM on various aspects of athletic performance and recovery, leading to its increasing adoption in sports medicine and elite athletics (Ferraresi et al., 2016).

Photobiomodulation involves the application of light to stimulate cellular processes, promoting tissue repair and reducing inflammation (Hamblin, 2016). At the cellular level, PBM has been shown to enhance mitochondrial function, increase ATP production, and modulate inflammatory responses (Ferraresi et al., 2012). These effects are thought to contribute to improved muscle performance and accelerated recovery from exercise-induced damage. PBM's influence extends beyond local effects, impacting various physiological processes from cellular development and repair to fundamental metabolism. It also has a favourable impact on key facets of cell signalling and growth factor synthesis (Crous & Abrahamse, 2021). Upon PBM exposure, cytochrome-c oxidase, a pivotal enzyme in the mitochondrial respiratory chain, absorbs NIR light, increasing enzymatic activity. This activation promotes electron transfer within the respiratory chain, elevating the mitochondrial membrane potential and augmenting ATP production. The rise in the mitochondrial membrane potential is associated with controlled production of ROS, which serve as crucial signalling molecules that further facilitate cellular proliferation and survival (Pan et al., 2022). These processes collectively initiate mitochondrial biogenesis, characterized by the replication of mitochondrial DNA and the growth and division of existing mitochondria. In the context of human adipose-derived mesenchymal stem cells, PBM-induced mitochondrial biogenesis significantly enhances stem cell proliferation, migration, and differentiation capabilities, thereby improving their efficacy

in tissue repair and regenerative therapies (Hamblin and Demidova, 2006; Karu, 2008). This procedure can be utilized to increase osteoblast proliferation, which will enable the creation of novel therapeutic strategies in which the effects of laser irradiation will be combined with an understanding of stem cell behaviour and targeted manipulation to expedite bone regeneration (Saito and Shimizu, 1997).

PBM has become a viable approach to shorten the duration of DOMS and speed up recovery, offering a fascinating field for further study and practical use. Enhancing the production of mitochondrial ATP (adenosine triphosphate), an energy currency in cells, is one of PBM's main effects. PBM uses light to increase mitochondria's ATP production which gives cells a greater ability to power all of their processes, from cellular development and repair to fundamental metabolism. PBM also has a favourable impact on important facets of cell signalling and growth factor synthesis (Crous & Abrahamse, 2021).

This research aims to investigate the benefits of PBM on reducing muscle soreness and improving recovery after intense exercise. The importance of this study is driven by the growing interest in active lifestyles and enhancing physical performance. After rigorous exercise, many people experience the discomfort of delayed onset muscle soreness (DOMS), making it crucial to find effective ways to alleviate it especially in an elite setting where recovery time is limited. This is particularly important for active team sport players where playing and training schedules may prevent sufficient rest and recovery between games. If PBM is proven to be useful in lowering DOMS, athletes may be able to return to their normal routines or training sooner after experiencing an intense period of exercise or physical exertion. DOMS can cause significant discomfort so by finding that PBM can reduce these symptoms could also provide individuals with a non-invasive method of pain management.

Previous Studies on Photobiomodulation and Muscle Recovery

Photobiomodulation (PMB) describes the use of red or near-infrared light to stimulate, heal and regenerate damaged tissue (Ferranesi, Ying-Ying & Hamelin 2016). Photobiomodulation treatment (PBMT) has demonstrated significant potential in enhancing athletic performance and accelerating recovery. In their 2016 review Ferraresi, Huang and Hamblin investigated

533 randomised controlled trials and case-control studies in healthy trained and untrained participants, including elite athletes. The purpose of their investigation was to gather as much information and then evaluate the total effects of PBM on a range of performance and recovery metrics, including fatigue, rep count, torque, muscle hypertrophy, and markers of muscle injury and healing such as DOMS and creatine kinase levels. The study conclusion suggested that PBM improved muscular function, increased muscle mass and decreased inflammation and lowered oxidative stress. (Ferraresi et al., 2016). However, the review did show some conflicting outcomes. While some studies reported no appreciable advantages, others indicated that PBM had a good impact on muscular performance and recovery. Ferraresi et al. pointed out that a number of variables, such as the particulars of the PBM application and the kind of exercise carried out, may affect how successful PBM is. They concluded that although PBM has the potential to improve muscular performance and recovery in top athletes, further research is required to determine the best practices and comprehend the underlying mechanisms.

A more recent systematic review by Ferlito et al in 2021 compared PBM and cryotherapy (CRT) and their effects on muscle recovery. According to the paper's findings, PBM significantly outperforms CRT in terms of the outcomes of muscle rehabilitation. Particularly in muscle strength, PBM showed a large positive effect compared to CRT (SMD = 1.73, 95% CI: 1.33 to 2.13, $p < 0.00001$). The study found no significant difference between PBM and CRT in oxidative stress and inflammatory levels. However, PBM demonstrated its superiority by significantly reducing DOMS by an average of 25.69% (95% CI: -34.42% to -16.97%, $p < 0.00001$), indicating a substantial reduction in post-exercise muscle soreness compared to CRT. The concentration of biomarkers associated with muscle damage was notably lower with PBM (SMD = -1.48, 95% CI: -1.93 to -1.03, $p < 0.00001$), indicating a significant reduction in muscle damage when compared to CRT (Ferlito et al., 2021).

In 2016 Pinto et al.'s examined recovery within elite rugby players. This study was a double-blind, crossover, randomised, placebo-controlled clinical research and aimed to assess PBMT's performance after muscle damage caused using the Bangsbo sprint test (BST), an anaerobic field test. Twelve elite male rugby players took part; they received no treatment during the familiarisation phase and a randomised pre-exercise PBMT or placebo therapy for

the remaining phases. Although not looking at DOMS, the results showed that PBMT considerably decreased tiredness and enhanced sprint performance. In particular, there was a significant improvement in the BST's average sprint time (3.98 ± 0.18 s for PBMT vs 4.32 ± 0.19 s for placebo, $p \leq 0.05$) and fatigue index (26.62% lower in the PBMT group, $p \leq 0.05$). PBMT also dramatically reduced post-exercise subjective fatigue and blood lactate levels. These results. Particularly, the PBMT group's percentage change in blood lactate levels was considerably lower ($p < 0.05$). This difference was particularly noticeable at 30 minutes after exercise ($15.28 \pm 1.73\%$ for PBMT vs. $28.40 \pm 1.67\%$ for placebo). This implies that super-pulsed laser, red LEDs, and infrared LEDs used in pre-exercise PBMT can improve sports performance and speed up recovery in real-world sports environments (Pinto et al., 2016).

In a similar study Zagatto et al. used full-body PBMT male water polo competitors' recovery with full-body PBMT during the 2019 Brazilian under-20 water polo championship. Water polo being an intermittent high intensity sport in which competitions are played with repeated games over two of more days. The study examined many signs of recovery, such as markers of inflammation and muscle injury, hormonal reactions (cortisol and testosterone), heart rate variability (HRV), maximal voluntary contraction, and squat jump (SJ) power. Following every match, all athletes received a neuromuscular evaluation and blood sample, after which they were given either a placebo or an effective PBMT medication. Testosterone, cortisol, TNF-alpha, interleukin-6, creatine kinase concentration, maximal isometric voluntary contraction, SJ test, and HRV did not significantly interact, according to the data. After the first match, there was a single, statistically significant drop in the LDH response ($p = 0.004$, post-hoc $p = 0.038$). These results imply that the full-body PBMT parameters employed during the tournament did not significantly improve recovery with respect to inflammation, muscle injury (apart from LDH), hormones, HRV, and neuromuscular responses (Zagatto et al., 2020).

A contrasting study conducted by Tsuk et al in 2020 but in healthy physical education students rather than athletes found no difference between performance of the two treatments: infrared light (B-cure laser) or sham light. In addition, the study found Photobiomodulation for ten minutes right before exercise did not enhance muscle recovery from exhaustion or increase muscular function and had little impact on muscle rehabilitation. The B-cure laser is a portable laser therapy device that stimulates ATP biostimulator to reduce pain and enhance

cell healing. It operates at low levels of infrared light, with a power range of 1 to 1000 mW. Tusk et al. carried out two independent crossover randomised double-blind placebo-controlled trials. Thirty-eight healthy students, ages 20 to 35, were enlisted (30 participants for each trial), of which 28 were men and 32 were women. For every experiment, participants executed two treatments in parallel at three quadricep regions (treatment energy of approximately 150J) or a sham (placebo) treatment. In the first experiment, an isokinetic dynamometer was used to measure the total work and peak torque of the muscles during five repetitions of knee extension. In the second experiment, muscle recovery was assessed by measuring the total work and peak torque during five repetitions of knee extension following the induction of muscular exhaustion. This study by Tsuk et al is interesting due to the results being non-significant. However, the participants were only given the infrared/sham light for 10 minutes before exercise which potentially could have been too short of exposure for the light therapy to work (Tsuk et al., 2020).

DOMS Assessment Methodologies

In the current study an isokinetic dynamometer was used, but several other methods can be employed to measure DOMS. According to Cheung et al. (2003), Visual Analog Scales (VAS) are widely used to assess subjective pain intensity associated with DOMS. The VAS typically consists of a 100 mm line with verbal anchors at each end, such as "no pain" and "worst pain imaginable". Participants mark a point on the line that corresponds to their perceived pain level, which is then measured in millimetres from the left end of the scale (Cheung, Hume and Maxwell, 2003). The VAS has been shown to have good reliability and validity for measuring pain intensity. Price et al. (1983) demonstrated that VAS scores were highly correlated with experimental pain intensity and could discriminate between different levels of pain. Furthermore, Bijur et al. (2001) found high reliability for the VAS in acute pain measurement, with a 90% chance that a patient's second VAS score would be within 9 mm of the first when taken 1 minute apart. However, as noted by Warren et al. (1999), while VAS is useful for assessing subjective pain, it lacks the objectivity required for assessing muscle function and strength changes. This limitation highlights the importance of using multiple assessment methods, including objective measures like dynamometry, to comprehensively evaluate DOMS.

Pressure algometry is another method used to quantify muscle tenderness. As described by Nussbaum and Downes (1998), this technique involves applying controlled pressure to a muscle and measuring the point at which pain is reported. However, it primarily assesses pain sensitivity rather than functional impairment (Nussbaum and Downes, 1998). Blood biomarkers such as creatine kinase (CK) and LDH are often used to assess muscle damage. Brancaccio et al. (2010) explained that elevated levels of these enzymes in the blood indicate muscle injury. However, these markers do not directly measure muscle function or strength, and blood sampling is an invasive procedure (Brancaccio, Lippi and Maffulli, 2010). Ultrasound imaging could also have been used to visualize muscle structure changes associated with DOMS. According to Nosaka and Clarkson (1996), ultrasound can detect muscle swelling and increased echogenicity. However, this method requires specialized equipment and expertise (Nosaka and Clarkson, 1996). Our decision to use an isokinetic dynamometer (BIODEX System 3) is consistent with the approach taken by Baroni et al (2010). They emphasise how it may be used to quantify muscular strength and performance precisely and objectively in controlled settings after exercise-induced muscle injury. Comprehensive evaluation of many performance metrics, such as peak torque, total work, and maximal voluntary isometric contraction of the quadriceps muscle can be measured (Baroni et al., 2010). It provides a complete approach for investigating the functional and subjective components of exercise-induced muscle injury and recovery when combined with qualitative measures like pain assessments.

Methodological Approaches in Previous PBM Studies

In Pinto et al. (2016), the effects of PBMT on performance were examined in an uncontrolled field test environment, generating the hypothesis that PBMT would improve performance, accelerate blood lactate clearance, and reduce subjective tiredness. The twelve elite male rugby players from the São José Rugby Club, ranging in age from 19 to 26, all finished the study without missing any days. Three test phases were provided to the participants: one week apart for the familiarisation phase and two experimental phases with either PBMT or placebo treatments. Athletes completed a BST, which simulates important rugby movements, during each phase to gauge anaerobic performance. Blood lactate levels, personal exhaustion, mean sprint time, best sprint time, and tiredness index were measured

as dependent factors. The blood lactate levels at different times (baseline, 3-, 10-, 30-, and 60-minutes post-test) and treatments (familiarisation, placebo, PBMT) were measured as independent variables. A portable lactate analyser was used to examine blood samples taken from the fingertips. Following standardised warm-up and stretching exercises, athletes received either active PBMT or placebo treatments prior to each BST. Red LEDs, infrared LEDs, and super-pulsed lasers were all emitted by cluster probes on an MR4 Laser Therapy Systems, which were used to apply PBMT. The course of treatment spanned seventeen locations on both lower limbs and took about 10 minutes. The average and best sprint timings as well as the fatigue index were used to measure performance, and a questionnaire was used to gauge perceived exhaustion. Researchers and participants were blinded to the treatment conditions, and randomization and blinding were enforced (Pinto et al., 2016).

Zagatto et al.'s 13 water polo athletes were 18 years old and were split into PBMT and placebo groups according to their position and technical ability. The study was conducted over the course of five days, during which each team played three matches in the 2019 Brazilian under-20 water polo tournament. Prior to every game, blood samples were taken for the measurement of interleukin-6 (IL-6), testosterone, cortisol, creatine kinase (CK), lactate dehydrogenase (LDH), and tumour necrosis factor-alpha (TNF- α). Squat jump (SJ) and maximal voluntary contraction (MVC) tests were used to evaluate neuromuscular responses. Placebo treatments involved fake irradiation with the device turned off. A two-way repeated-measures ANOVA was used in the data analysis to analyse the raw and percentage differences between the PBMT and placebo groups. The Sidak post-hoc test was used to identify confidence intervals for comparison of results. This approach guaranteed a thorough assessment of PBMT's influence on numerous performance and physiological indicators (Zagatto et al., 2020).

Pinto et al. (2016) and Zagatto et al. (2020) both employed photobiomodulation therapy in their studies, recognizing its potential to enhance athletic performance and recovery. However, their approaches to PBM application and the rationale behind its use differed based on their specific research objectives. Pinto et al. utilized PBMT with a combination of red LEDs, infrared LEDs, and super-pulsed lasers applied to specific locations on the lower limbs. This targeted approach was chosen to potentially enhance local muscle performance and recovery

in rugby players, a sport characterized by high-intensity, intermittent efforts. The researchers hypothesized that PBMT would improve anaerobic performance, accelerate blood lactate clearance, and reduce subjective fatigue, all crucial factors in rugby performance. In contrast, Zagatto et al. opted for a full-body PBMT application using the Joovv Elite system, which employed 900 LEDs to irradiate the entire body. This comprehensive approach was selected to address the systemic demands of water polo, a sport that involves whole-body exertion over multiple days of tournament play. The researchers aimed to investigate PBMT's effects on a broader range of physiological markers, including inflammatory cytokines, hormones, and muscle damage indicators, as well as neuromuscular responses. This holistic method was chosen to assess PBMT's potential in supporting overall recovery and maintaining performance throughout a tournament. The difference in PBM application methods between these studies reflects the researchers' understanding of the potential mechanisms by which PBMT might benefit athletes in different sports contexts. Pinto et al.'s localized application aligns with the theory that PBMT can enhance mitochondrial function and local blood flow, potentially improving muscle performance and recovery in the treated areas. Zagatto et al.'s full-body approach, however, suggests an interest in PBMT's systemic effects, including its potential to modulate inflammatory responses and support overall physiological recovery. Both studies contribute to the growing body of evidence on PBMT's efficacy in sports, with their methodological choices highlighting the versatility of PBM as a tool for potentially enhancing various aspects of athletic performance and recovery.

Limitations and Gaps in Existing Literature on PBM and DOMS

While research on PBM and its effects on DOMS has expanded recently, several limitations and gaps in the existing literature still exist. There is a lack of standardisation in PBM protocols across studies, with variations in wavelengths, power densities, treatment durations, and application sites, complicating direct comparisons. This inconsistency makes it challenging to determine optimal PBM parameters for DOMS management. Many studies have small sample sizes, limiting statistical power and generalizability. The heterogeneity of participant populations, from sedentary individuals to elite athletes, further complicates result interpretation and makes it difficult to establish universal guidelines for PBM application. There is also a scarcity of long-term studies investigating PBM's cumulative effects on DOMS and muscle adaptation over extended periods. Most research focuses on acute responses,

leaving questions about the long-term impact of regular PBM use on muscle recovery and performance unanswered. The mechanisms underlying PBM's potential effects on DOMS are not fully elucidated, with most studies focusing on outcome measures rather than exploring physiological pathways. This gap in mechanistic understanding hinders the development of more targeted and effective PBM interventions. Limited research exists on optimal PBM application timing relative to exercise for DOMS prevention or treatment. Studies vary in their approach, with some applying PBM before exercise, others immediately after, and some at various time points during recovery. This inconsistency makes it challenging to determine the most effective timing for PBM application. The interaction between PBM and other recovery modalities, such as cryotherapy, massage, or nutritional interventions, needs more investigation. Understanding these interactions could lead to more comprehensive and effective recovery strategies. There is also a gap in the literature concerning the effect of PBM therapy in female athletes ??

Menstrual Cycle and its Effect on Recovery

The menstrual cycle's influence on athletic performance and recovery is a major area of current sports science research and should be considered when evaluating interventions like PBM. Although the anabolic effects of androgenic hormones (principally testosterone) are well researched, the influence of ovarian hormones on muscle mass and recovery is less clear. In addition, whilst sex hormone levels are relatively stable in men from day to day they can vary throughout the menstrual cycle naturally cycling in women (Shea & Vitzthum 2020).

To address this variability, this study will span into 4-week intervention periods, encompassing a complete menstrual cycle. Although current consensus suggests that there is no influence of women's menstrual cycle phase on acute strength performance, adaptation to resistance exercise or muscle recovery (Colenso-Semple et al 2023) this approach allows us to account for possible inconsistencies in female strength and recovery capabilities throughout the cycle's phases. Research has demonstrated that the menstrual cycle can be broadly divided into two phases, each with distinct hormonal profiles and these have potentially different effects on athletic performance. According to Kissow et al. (2022), an

athlete's maximal anaerobic potential and maximal muscle strength occur during the follicular period, which coincides with the lowest oestrogen levels. This phase, occurring in the first half of the menstrual cycle, is characterized by relatively stable hormone levels, potentially creating an optimal environment for muscle performance and recovery. In contrast, the second half of the menstrual cycle, referred to as the luteal phase, experiences an increase in hormone levels, specifically oestrogen and progesterone, in preparation for menstruation or the possibility of pregnancy (Janse de Jonge, 2003). These hormonal shifts may alter muscle function and recovery dynamics, potentially influencing an athlete's response to exercise and subsequent recovery. Constantini et al. (2005) noted differences in body temperature and inflammation levels between the follicular and luteal phases, which could also affect the body's response to interventions like PBM.

Given these cyclical variations, ensuring measurements are taken at consistent points in participants' menstrual cycles is essential for standardizing results, accounting for individual variations, and enhancing research validity. This approach allows for more accurate conclusions about PBM effectiveness and could potentially lead to personalized treatment protocols optimized for specific cycle phases. Controlling for the menstrual cycle Phase, would help to address the historical underrepresentation of females in sports science research, which would contribute to more comprehensive and reliable study outcomes (Costello et al., 2014). In conclusion, by maintaining consistency in measurement timing relative to the menstrual cycle, we are reducing the chance of hormonal fluctuations introducing anomalies that could affect muscle recovery assessments. This methodological approach enhances the validity of our findings and contributes to the broader goal of developing more personalized and effective interventions for female athletes across different phases of their menstrual cycles.

To address these gaps, this study employs a standardized PBM protocol with specific parameters, focusing on female athletes to address population-specific effects, and spans a 10-week period to investigate longer-term impacts. We also consider the menstrual cycle's influence on recovery processes, using 4-week intervention periods to account for hormonal fluctuations. By using the BIODEX system for objective strength measurements, we aim to provide consistent and reliable outcome measures. While our study doesn't directly address

all identified gaps, it contributes to the growing body of evidence on PBM's efficacy in sports recovery and aims to provide insights into some of the understudied areas in PBM research.

Aims of Research

This study aims to investigate the effects of PBM on recovery from DOMS over a 10-week period, using the BIODEX isokinetic system for objective strength measurements. By comparing the duration, intensity and strength lost during the DOMS before and after PBM treatment, this research seeks to provide valuable insights into the efficacy of PBM as a recovery strategy for athletes.

Specifically, this study will:

1. Assess the impact of PBM on muscle strength recovery following DOMS-inducing exercise.
2. Evaluate the intensity of DOMS with and without PBM intervention.
3. Consider the influence of the menstrual cycle on recovery processes in female participants.
4. Compare the effects of PBM treatment to a sham light treatment to account for potential placebo effects.

The findings of this study have potential implications for athletes, coaches, and sports professionals, potentially leading to more effective recovery strategies and improved training protocols. By addressing the limitations in existing literature, including the lack of standardization in PBM protocols and the scarcity of long-term studies, this research aims to contribute to the growing body of evidence on PBM's efficacy in sports recovery.

METHODS

Participants

In this study the participant group comprised 17 female university athletes (age range 18-23, height ranged from 157cm-177cm, and weight ranged from 54kg-81kg). All participants were highly trained and selected for their extensive experience (> 6 years) and level of play in field hockey. Specifically, all participants had competed up to the national league level, demonstrating a high degree of skill, commitment, and athletic ability. This selection criterion ensured that the participants possessed a substantial background in competitive sports, which was essential for the reliability and relevance of the research findings. The age range was chosen to encompass the early adult years, a critical period for athletic development and peak performance. All participants gave informed consent before data collection. The study had Brooks University ethical approval.

The participants in this study were exclusively female due to the specific focus on using their menstrual cycles as a constant when introducing them to the infrared or sham light. This synchronisation with their cycles aimed to remove external hormone factors, which vary for each participant, and investigate its recovery effects. Focusing on female athletes allowed for precise analysis of the interaction between menstrual cycles and athletic performance, providing relevant insights for female sports science. To ensure accurate and consistent data collection, monitoring of the participants' menstrual cycles began at least one month prior to the commencement of the study. This preliminary tracking phase allowed for the establishment of baseline menstrual patterns for each athlete. Participants were required to maintain a diary of their menstruation phases, recording the start and end dates of their cycles. Digital tracking tools were also used to corroborate data of estimated start dates and enhance the accuracy of the tracking process. This comprehensive approach aimed to synchronize the timing of infrared light exposure with each participant's menstrual cycle phases.

Menstrual Cycle

Once the start dates of the participants' menstrual cycles were established, the exposure to the infrared or sham light exposure was synchronised for duration of their cycles. Light sessions being scheduled to align with every point of the menstrual cycle to eliminate potential variations with their progesterone and oestrogen hormone levels and that may impact recovery, susceptibility to injury or lower pain thresholds.

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Study Protocol

Baseline Testing (laboratory visit one)

Baseline testing was conducted to measure the participants' strength levels in Newton Metres before the introduction of infrared or sham light. This baseline assessment was essential for establishing a reference point against which the introduced factors could be compared. By evaluating the athletes' strength prior to any intervention, we ensured that any observed changes in performance could be attributed to the infrared light therapy rather than to pre-existing differences or natural variations in strength. To enhance the reliability of baseline strength testing, participants underwent a familiarisation session with the Biodex machine prior to the baseline testing. This session allowed participants to become comfortable with the equipment and testing procedures, minimizing the potential for performance improvements solely due to increased familiarity. By providing participants with the opportunity to practice and acclimate to the Biodex machine beforehand, any confounding effects related to learning or adaptation during the testing sessions should have been eliminated. This standardised familiarisation process helped ensure that the baseline strength measurements accurately reflected the participants' true physiological capabilities, providing a solid foundation for assessing the impact of subsequent infrared light therapy interventions. The baseline testing provided a clear picture of each athlete's starting condition, allowing for a more accurate assessment of the effectiveness of the infrared light treatment over the course of the study.

Once participants were happy with the protocol, they informed the research team when it was the first day of their cycle and were provided with either a red-light device emitting a

wavelength of 670 nm or a sham-red-light device, which emitted a low-intensity broad red-light spectrum. Participants were instructed how to use the device and asked to use it on their arm every morning for three minutes within the first four hours after waking up, for the duration of their menstrual cycle. Participants were randomized to either strand A (intervention first, followed by sham) or strand B (sham first, followed by intervention).

Inducing DOMS (laboratory visit two)

At the end of each individual's menstrual cycle and, following the light exposure DOMS was induced using a standardised protocol described by Pearcey et al. (2015). Using their dominant arm participants performed 10 sets of 10 repetitions of bicep curls using free weights, with the weight used being calculated by working out 60% of their 1RM, determined by the formula developed by Matt Brzycki: $\text{Weight} / (1.0278 - 0.0278 \times \text{repetitions})$. Participants had the option to reduce the weight as needed to ensure completion of all sets. This protocol is designed to induce muscle soreness reliably and consistently across all participants, allowing for controlled investigation of the effects of infrared light therapy on recovery..

Maximal Strength Testing (laboratory visit three)

Maximal strength testing was conducted on a Biodex system 3 Isokinetic Dynamometer three to four days post-DOMS induction to assess their recovery. The Biodex System 3 Isokinetic Dynamometer is known to provide reliable information on strength and muscle imbalances. The protocol employed was validated by Kang et al., 2018 and recognized as a reliable outcome measurement for this research area. The same laboratory and equipment were used for all participants, so conditions were kept consistent.

Maximal isometric strength was assessed using the Biodex machine through a series of five maximal isometric contractions, each held for 5 seconds with 60 seconds of rest between contractions. During the testing sessions, participants were seated in the Biodex System 3 Isokinetic Dynamometer with their non-dominant arm securely strapped in place. The positioning protocol required the participants' shoulders to be set at an angle of 20 degrees, while their elbows were maintained at a 90-degree angle. This specific positioning ensured that the angle between the forearm and the bicep was also at 90 degrees. Such alignment

was critical for accurately engaging and assessing muscle soreness in the biceps during the testing. This standardised posture not only facilitated consistent muscle activation across all participants but also minimized the risk of compensatory movements that could affect the reliability of the strength measurements. Consistent verbal cues were provided by the investigator to ensure uniformity across all sessions, with the same investigator at each session. Participants were instructed to pull the bar towards themselves with maximal effort during each contraction, and not to hold back. The starting signal consisted of a countdown from 3, 2, 1 followed by "go." Throughout the 5-second contractions, the principal investigator provided encouragement using verbal cues such as " keep going, keep going, keep going, almost there, and rest." The bar pull move corresponded to doing a bicep curl. Participants held the contraction for 5 seconds then rested for a minute. The protocol was repeated 5 times and results recorded.

An isokinetic dynamometer plays a key role in measuring DOMS. It gives clear and exact assessment of muscle strength and how well muscles work. The machine maintains the same speed as it moves, which allows precise reproduction of force and measures both total work done and time until peak force is reached. A full picture of how DOMS develops can be measured and the test is known to be valid and reproducible allowing results to be compared (Croisier et al. 2003, Engardt et al. 1995).

Figure 1 shows the correct set up position the participants were put in one visit 1 (familiarisation), 3 & 5



Figure 1: *The Isokinetic Dynamometer Biodesex System 3 PRO that was used throughout this study (Ekstrand, Lexell and Brogårdh, 2016).*

Cross-over : second light protocol (laboratory visit four)

On the first day of the following menstrual cycle participants received the alternative light to the one they had already received. The instructions given were identical to the first intervention: three minutes each morning on the arm within the first four hours of waking up, for the entirety of their cycle. After this intervention period, DOMS was induced a second time using the same standardized protocol of bicep curls on the dominant arm and participants were recalled to the lab after 3-4 days for maximal strength testing (laboratory visit five).

In crossover studies involving PBM interventions, the implementation of an adequate washout period is crucial to mitigate any potential carryover effects from the previous treatment phase. The washout period serves to eliminate residual physiological effects of the intervention, ensuring that subsequent measurements are not confounded by lingering benefits or adaptations from the previous treatment. Literature evidence suggests that a minimum washout period of 3 days is necessary to offset any potential benefits experienced due to red-light therapy (Leal-Junior et al., 2015). This recommendation is based on the

understanding of the temporal dynamics of PBM-induced cellular and molecular responses, which typically subside within 72 hours post-treatment (Hamblin, 2016). To enhance the robustness of our study design, a one-week washout period between the two intervention phases of our crossover study was used. This extended duration not only accommodates the minimum recommended time frame but also provides an additional buffer to account for potential individual variations in response to PBM treatment. The one-week interval allows for a more complete reversal of any physiological adaptations induced by the previous intervention, thereby minimizing the risk of sequence effects and ensuring a clear baseline for the subsequent treatment phase.

Regular check-ins were conducted to ensure adherence to the protocol and to address any issues or concerns that arose amongst the participants

Questionnaire

In addition to objective measures of muscle recovery, subjective assessments of discomfort and pain are crucial for a comprehensive evaluation of the DOMS. To this end, DOMS was assessed using a self-reported questionnaire based on the McGill Pain Questionnaire (Melzack, 1975). This well-established tool, previously used in many muscle soreness studies, provides valuable insights into the type and intensity of pain experienced by the participants. The questionnaire will be administered during visits 1 (baseline), 3 and 5 capturing detailed information on the athletes' pain perceptions. These visits will be done while the athletes are still in the muscle soreness window of 3-5 days. Assessing self-report discomfort within this time frame was done to ensure that participants would still have traces of DOMS meaning their answers will be accurate and current. Utilising a questionnaire in this way allows us to gather subjective data that complements the physiological measurements, potentially seeing correlation between the data sets.

Statistical Analysis

Comprehensive statistical analyses were performed to assess PBM's impact on muscle recovery. Peak torque values were evaluated in relation to light type (Baseline, Placebo, PBM) using a repeated-measures ANOVA. The repeated-measures ANOVA's sphericity assumption was tested using Mauchly's Test of Sphericity. For multiple comparisons, post-

hoc testing with Bonferroni correction were used to identify particular differences between conditions. The mean differences between each pair of conditions (Baseline vs. Placebo, Baseline vs. PBM, and Placebo vs. PBM) were analysed using pairwise comparisons. In addition, a one-way repeated measures ANOVA was conducted to evaluate the impact of the different lights at different time points.

RESULTS

Eighteen university field hockey players (20.5 ± 1.7 years, height 164.8 ± 5.7 cm and weight 67.5 ± 6.6 kg) were recruited. All participants were playing at tier 3 or above as assessed by McKay et al (2022) performance calibre framework and had >6years playing experience. One participant withdrew during the study with 17 included in the analysis. None of the participants were carrying an injury that would influence inclusion. Participant characteristics are shown in table 1 and the structure of the study and recruitment process is shown in Figure 2. A double-blind randomization process was employed, overseen by the study advisors, to allocate participants into groups.

Table 1: Participant characteristics in all study groups

	BASELINE, PBM AND PLACEBO (N=17)
AGE	20.5 (± 1.7)
HEIGHT	164.8 (± 5.7)
WEIGHT	67.5 (± 6.6)
LENGTH OF MENSTRUAL CYCLE*	27.8 (± 1.05)

*Length of menstrual cycle dictated how long each participant used the red light for.

Figure 2

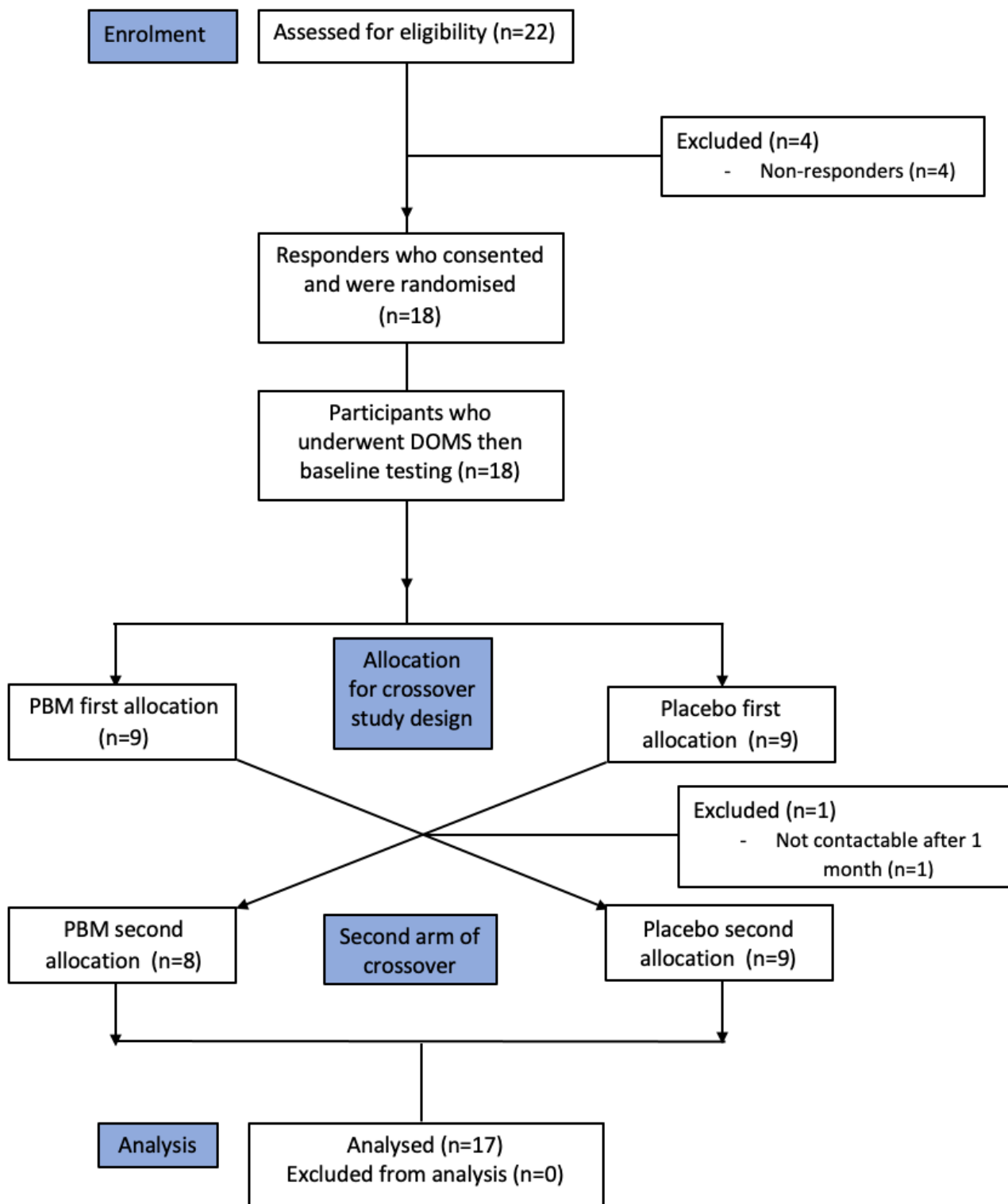


Figure 2: A consolidated standards of reporting trials (CONSORT) diagram.

The McGill Pain Questionnaire data analysis showed no major differences in how people felt pain across the two study conditions or over time. The most common words used to describe participants DOMS experience were "tight," "aching," "cramping," "tender," "dull," "sore," and "throbbing."

Figure 3

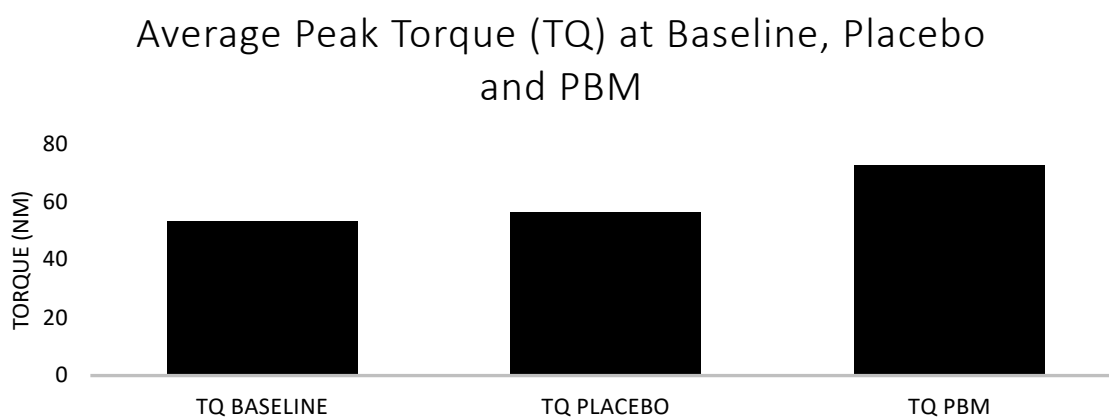


Figure 3: Average peak Torque (TQ) at Baseline, Placebo and PBM

Figure 3 shows average peak torque measurements across the three conditions: baseline, sham light treatment, and photobiomodulation (PBM) light treatment. The baseline condition showed the lowest average peak torque ($53.71 \pm 20.99\text{Nm}$), indicating participants' initial muscle strength before any intervention. There was a small non-significant increase in the sham- light condition (placebo – $56.82 \pm 20.49\text{ Nm}$) suggesting a potential placebo effect or natural variation in performance. A greater increase in performance was seen in the PBM condition where average peak torque increased significantly to $73.06 \pm 25.19\text{ Nm}$.

Figure 4.

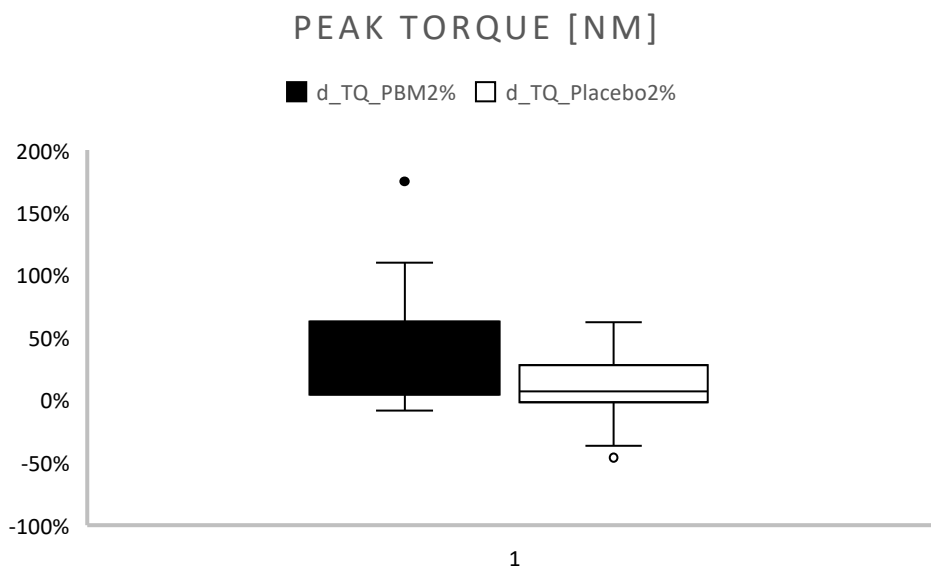


Figure 4: Peak torque (TQ) comparing PBM and Placebo

Figure 4 displays the percentage change in torque (TQ) after PBM or sham light treatment. The plot illustrates the distribution of muscle torque changes compared to baseline measurements following the application of either of the two different light therapies. The box plot shows the median, quartiles, and range of the data, with error lines extending to indicate variability outside the upper and lower quartiles. Notably, the plot reveals two outliers, suggesting that some participants experienced significantly different responses to the PBM, and sham light treatments compared to the majority. This representation allows for a comprehensive view of the central tendency, spread, and any unusual values in the dataset, providing insights into how PBM affects muscle strength or performance over time, particularly in the context of DOMS management in female athletes. The percentage change in torque was calculated using the formula $\text{d_TQ_PBM} = \frac{[\text{TQ_PBM}] - [\text{TQ_BASELINE}]}{[\text{TQ_BASELINE}]}$, which normalizes the change in torque relative to the baseline measurement.

A repeated-measures ANOVA was performed to evaluate the effect of light type on peak torque (TQ) value. The means and standard deviations for TQ values are shown in Table [2].

Table 2: Descriptive Statistics

	Mean	Std. Deviation	N
TQ BASELINE	53.60	22.996	15
TQ PLACEBO	58.60	21.567	15
TQ PBM	69.80	22.444	15

Mauchly's test indicated that the assumption of sphericity had been met, $\chi^2(2) = 2.503$, $p = .286$. The effect of light type on the measured variable was significant at the .05 level, $F(2, 28) = 10.867$, $p < .001$.

Table 3: Pairwise Comparisons

(I) Light Type	(J) Light Type	Mean Difference (I-J)	Std. Error	Sig. ^b	95% Confidence Interval for Difference	
					Lower Bound	Upper Bound
BASELINE	Placebo	-5.000	2.962	.341	-13.049	3.049
	PBM	-16.200*	3.391	<.001	-25.415	-6.985
PLACEBO	Baseline	5.000	2.962	.341	-3.049	13.049
	PBM	-11.200	4.210	.056	-22.642	.242
PBM	Baseline	16.200*	3.391	<.001	6.985	25.415
	Placebo	11.200	4.210	.056	-.242	22.642

Based on estimated marginal means

**. The mean difference is significant at the .05 level.*

b. Adjustment for multiple comparisons: Bonferroni.

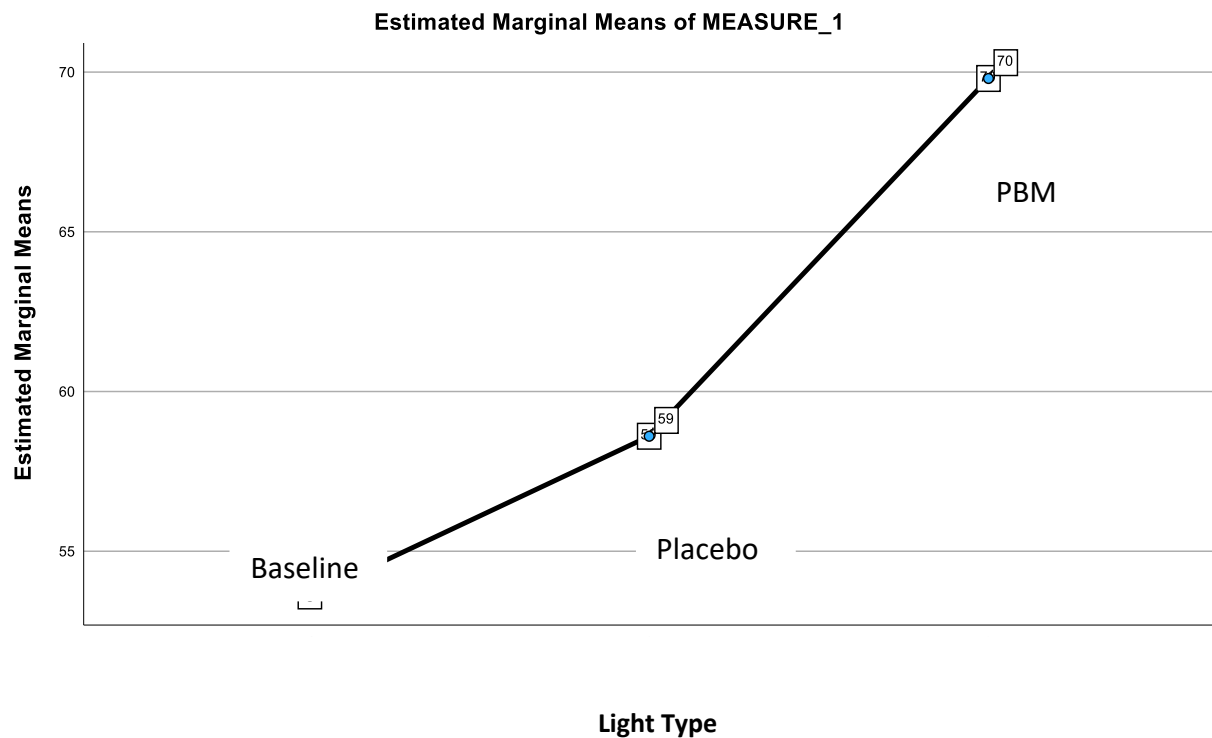
Post hoc tests using the Bonferroni correction revealed that there was a statistically significant increase in scores from Baseline to PBM (mean difference = 16.200, $p < 0.001$). No significant difference was found between Baseline and Placebo (mean difference = -5.000, $p = 0.341$). The difference between Placebo and PBM approached significance (mean difference = -11.200, $p = 0.056$), suggesting a trend towards an increase in scores between these conditions.

Table 4: Tests of Within-Subjects Effects

Source		Type III Sum of Squares	df	Mean Square	F
Light Type	Sphericity	2064.400	2	1032.200	10.867
	Assumed				
	Greenhouse- Geisser	2064.400	1.702	1212.966	10.867
	Huynh-Feldt	2064.400	1.913	1079.007	10.867
	Lower-bound	2064.400	1.000	2064.400	10.867
Error (Light Type))	Sphericity	2659.600	28	94.986	
	Assumed				
	Greenhouse- Geisser	2659.600	23.827	111.620	
	Huynh-Feldt	2659.600	26.785	99.293	
	Lower-bound	2659.600	14.000	189.971	

A one-way repeated measures ANOVA was conducted to compare the effect of the different lights used at different time points. Mauchly's Test of Sphericity indicated that the assumption of sphericity had been violated, $\chi^2(2) = [\text{value}]$, $p = [\text{value}]$. Therefore, a Greenhouse-Geisser correction was applied ($\epsilon = 1.702$). The results showed that the mean scores were statistically significantly different, $F(1.702, 23.827) = 10.867$, $p < 0.05$.

Figure 5: Profile Plots



The profile plot visually represents the changes in estimated marginal means across Baseline, Placebo, and PBM conditions. From Baseline to Placebo, there's a slight increase, consistent with the non-significant difference ($p = 0.341$) in pairwise comparisons. A more pronounced increase is observed from Baseline to PBM, supporting the statistically significant difference ($p < 0.001$). The Placebo to PBM transition shows a substantial increase aligning with the marginally significant result ($p = 0.056$).

DISCUSSION

The aim of this study was to investigate the effects of PBM on recovery from DOMS over a 10-week period. The results overall provide some compelling evidence for the efficacy of PBM in enhancing muscle recovery. The one-way repeated measures ANOVA conducted on SPSS revealed a statistically significant effect of light type on peak torque ($F(1.702, 23.827) = 10.867, p < 0.05$), indicating that the type of light treatment applied (baseline, placebo, or PBM) had a meaningful impact on muscle strength post DOMS induction, with a positive increase in average peak torque from baseline (53.60 ± 22.70 Nm) to PBM treatment (69.80 ± 22.44 Nm), a 30.2% improvement. This difference is statistically significant ($p < 0.001$), with a mean difference of 16.200 Nm (95% CI: 6.985 to 25.415). This improvement from baseline to PBM treatment supports the hypothesis that PBM has a positive effect on recovery and can be used within an athletic setting.

The McGill Pain Questionnaire data analysis showed no major differences in how people felt pain across the two study conditions or over time. Despite no changes being found it is noteworthy, that the most common words used to describe participants DOMS experience were "tight," "aching," "cramping," "tender," "dull," "sore," and "throbbing." These words match words used in previous studies to describe DOMS which suggests participants in this study felt the usual sensations that come with muscle soreness after exercise. The finding that there was no identifiable difference between the description of pain in the PBM and placebo groups suggests that how participants described their pain did not change between treatments. It is possible that the participants still felt the subjective sensation of DOMS as their muscle strength recovered but these findings may also imply that the words used are not descriptive enough to identify the degree of feeling rather than that there was no change. This finding is interesting because the readings from the Biodex dynamometer showed differences in strength between conditions as shown in Figure 3.

The overall improvement in peak torque after the use of PBM could be down to a number of different mechanisms, with mitochondrial function, oxidative stress reduction, inflammatory

modulation and muscle fibre recruitment all having the potential to influence the recovery process. PBM has been shown to enhance mitochondrial function by increasing the ATP production and with that, improving electron transport chain efficiency, as found by Ferraresi et al. in 2012. This increase could lead to improved energy availability for muscle contraction, improving recovery time and decreasing DOMS pain. Oxidative stress reduction could also be a factor with PBM reducing oxidative stress by modulating ROS production and enhancing antioxidant defence mechanisms. In their 2023 systematic review Flávia et al., 2023 concluded that PBM therapy could limit exercise-induced muscle damage, improve biochemical and functional recovery, and reduce inflammation and oxidative stress. The review included studies that measured oxidative stress markers such as CK, LDH, and lipid peroxidation products, showing significant reductions post-PBM treatment.

Previous studies have also shown that PBM has anti-inflammatory action, which could help in reducing DOMS-related inflammation and could therefore promote faster recovery. De Marchi et al. in 2017 investigated the effects of PBM therapy compared to cryotherapy on muscle recovery after high-intensity exercise. The study found that PBM therapy significantly reduced markers of inflammation, such as CK and interleukin-6 (IL-6), indicating its anti-inflammatory effects.

Finally, there is some information out there that suggests that PBM could enhance motor unit recruitment, which could potentially lead to improved muscle force production. Ailioaie and Litscher, 2021 conducted a study that showed that PBM enhanced maximal voluntary contraction (MVC) from immediately after to 96 hours after exercise with 10 or 30 J doses. This improvement in MVC could be related to enhanced motor unit recruitment, although the study doesn't explicitly state that this is the case.

The findings obtained in the present study are consistent with previous studies that have also used PBM for recovery. Ferraresi et al. (2016) looked into the effects of PBM on human muscle tissue in elite athletes and reported that PBM may improve muscular function and recovery metrics, including muscle hypertrophy and markers of muscle injury, while also decreasing oxidative stress and inflammation. The study we conducted reflects these findings but

focuses specifically on female athletes while managing their menstrual cycle throughout to reduce hormone change, which addresses a gap in the existing literature.

There was a slight increase in average peak torque from the baseline (53.60 ± 22.70 Nm) to the placebo (58.60 ± 21.57 Nm) a 9.3% improvement. While this difference was not statistically significant ($p = 0.341$), it is worth discussion as it is indicative of an effect and small differences can be practically significant in athletic performance contexts. It is possible that this change was due to hockey specific training outside of the study or may imply that the familiarisation with the equipment was inadequate. This observed difference could also have been a placebo effect or down to differences in natural recovery processes. The potential role of psychological factors in performance enhancement occurs due to preset expectations and beliefs about the treatment performance contributing to seen results, even in the absence of an active intervention. The observed placebo effect in this study on the use of the sham light shows the complex link between psychological and physiological factors in recovery from DOMS and aligns with broader research on recovery interventions. Nasser et al., 2023 found similar recovery outcomes when investigating cold water immersion and a thermoneutral water immersion with the placebo/sham condition, in both groups improving from the control. These findings do reinforce the critical importance of including placebo controls in PBM studies, as without, the improvements observed with PBM might be overestimated.

The testing was done on days 3 to 5 post DOMS induction, which is typically when DOMS symptoms are at their peak. However, this timing also means that some participants may have already begun the natural recovery process, potentially influencing the effects of the placebo treatment. , The response to the placebo/sham condition was not consistent across all participants, as evidenced by the outliers in the data. This suggests individual variability in both natural recovery and susceptibility to placebo effects.

The difference in average peak torque between the PBM and placebo/sham treatments was close to being statistically significant ($p = 0.056$), with PBM showing a higher average torque (69.80 ± 22.44 Nm compared to the placebo's 58.60 ± 21.57 Nm). The mean difference of 11.200 Nm (95% CI: -0.242 to 22.642) suggests that there was a substantial effect size, despite it not reaching the $p < 0.05$ threshold. While not statistically significant at the $\alpha = 0.05$ level,

the difference between PBM and placebo/sham treatments may still be clinically meaningful. The 19.1% improvement from placebo to PBM could still have performance benefits in real-world athletic contexts. There are a few factors that could have contributed to the marginal statistical significance. Sample size, treatment protocol and again, difference in participant recovery. There was a relatively small sample size ($N=17$), which may have limited the statistical power. A post-hoc power analysis was conducted but more participants would provide greater insights into the results. The specific details of the PBM protocol; the wavelength used, power density, and treatment duration, might have also affected the results. Fine-tuning these aspects of the study, may have resulted in bigger differences between how well PBM works compared to the placebo/sham light. Finally, the presence of outliers in the data, as shown in the box plot in figure 2, suggests that there was a high inter-individual variability in response to both the PBM light and placebo/sham light. This variability could have reduced the ability to detect statistically significant differences. This slight inconsistency in the results shows that we still need more research for a deeper understanding in PBM use for recovery.

There are several factors which may contribute to the observed individual variability in PBM response in this study. One of these factors is genetic variability with certain genotypes, or polymorphisms being associated with exercise-induced muscle damage; individuals with certain genetic make-up experiencing greater muscle damage, and requiring longer recovery, following strenuous exercise (Baumert et al. 2016). It is also possible that some gene variations will make an individual's mitochondria more or less responsive to the light therapy, participants therefore getting more or less benefit from PBMT, or that there are genetic differences in how the body manages inflammation that could play a role. If an individual's genes make them naturally prone to higher levels of inflammation, they could potentially need a stronger dose of PBM to see the same effects as someone else. These genetic factors are likely to be one of the reasons why we see such varied responses to PBM in studies. It's not just about the treatment itself, but also about the unique genetic blueprint of each person receiving it.

The 2021 systematic review by Ailioaie and Litscher, suggested that baseline fitness may also be potential source of variability in PBM benefit. Well-trained athletes may have muscles adapted to reoccurring muscle damage and become more efficient at recovering and adapting, so the effects of PBM might be much subtler for them, with less trained athletes showing a greater response. A greater understanding these differences between participants would give greater insight into how PBM can be best used in athletic populations to get the best results.

While this study focused on functional outcomes like average peak torque and a pain score, it is possible to measure muscle damage and muscle recovery using biochemical measures. To build on this work future research, could examine key biomarkers to get greater understanding of the underlying mechanisms. One of the markers commonly used in muscle damage studies is to track creatine kinase (CK) levels. By monitoring CK, it is possible to get a clearer picture of how PBM might be protecting or repairing muscle tissue. Measuring inflammatory cytokines such as IL-6 and TNF- α could establish if PBM is actually having an anti-inflammatory effect on the muscles. Markers of oxidative stress could also be examined, such as glutathione peroxidase and malondialdehyde could also be tracked. If glutathione peroxidase levels decrease after the use of PBM then this would confirm that PBM reduces oxidative stress. If malondialdehyde increases after the use of PBM then this would show that there is an enhanced antioxidant defence (Khedr et al., 2019). Lastly, near-infrared spectroscopy (NIRS) could have been used alongside the other biochemical tests, which would have helped us to look into what's happening within the muscles regarding oxygenation and blood flow during and after PBM treatment.

In this study, the PBM therapy significantly improved the recovery of muscle strength following DOMS induction. This improvement is on par with, and possibly more beneficial than, the cold and heat therapy results reported by Petrofsky et al. (2015). In contrast to the control/sham light group, which saw a 24% strength loss, study participants who received cold or heat therapy right after exercise only experienced a 4% strength loss. These findings show the potential of this therapies to reduce strength loss following exercise-induced muscle damage. In some participants, the PBM treatment not only prevented strength loss, but also increased strength above baseline, a finding not seen in Petrofsky's study suggesting that it

may have a better impact than cold and heat therapy in some individuals. It's key to remember that Petrofsky's research demonstrated that cold and heat therapy had long-lasting effects several days after exercise, with treated groups continuing to use the same amount of power. We cannot directly compare the duration of the effects, because this study only looked at one point in time after DOMS induction. The underlying processes in different recovery therapies may vary; PBM is thought to impact mitochondrial activity and oxidative stress, whereas cold and heat therapy largely affects blood flow and inflammation. Both strategies seem to provide considerable advantages for post-exercise muscle repair and strength maintenance, despite these mechanistic variations. A future study could see the effects of both these therapies being used together.

The present study focused only on female athletes, addressing a gap in the existing literature, which has predominantly involved only male participants. It was hypothesised that the observed effects may be influenced by sex-specific factors such as hormonal fluctuations across the menstrual cycle, differences in muscle fibre composition between males and females, or sex-specific differences in inflammatory responses and oxidative stress. We controlled for hormone fluctuations in this group of female athletes by making sure we tracked their menstrual cycle, ensuring they used the PBM (placebo or baseline) light at the same point of their cycle each time, while also inducing DOMS at the same point three times. The positive results observed in this all-female study suggested that PBM therapy is an effective tool for enhancing and improving recovery time in female athletes. However, further comparative research is needed to determine whether PBM protocols should be tailored differently for male and female athletes.

The improvement after the use of PBM in muscle strength while the participants had DOMS can be used in various application for athletes. In contexts of recovery, PBM could be integrated into post-exercise protocols to accelerate muscle repair and reduce DOMS effects. Additionally, it could be tactically used before competitions with a quick turnaround time (e.g at major games or tournaments) which could make an enhancement in muscle repair and therefore overall performance. Future, research could also look at how to optimise the PBM protocol, exploring different factors like light intensity, treatment frequency, and combinations with other recovery strategies such as cryotherapy or compression garments to

maximise effectiveness. While this study focused on acute effects, the long-term impacts of regular PBM use needs to be explored further. As exciting as the short-term benefits of PBM therapy are, we need to take a closer look at what happens with prolonged use (over years, not just months). It is possible that, like many interventions, the body adapts over time, reducing PBM's effectiveness. This adaptative response is found in other training and recovery methods, and it is important to investigate whether athletes using PBM for a long time continue to see the same level of improvements or if the benefits start to plateau. It is also important within this research to be vigilant about any potential risks or side effects that may happen with extended use. While PBM has shown a strong safety profile so far, high-performance athletes are a unique group pushing their bodies to the limits of power and endurance. A thorough, long-term safety assessment is essential to ensure that use is not risking future health for current gains.

Limitations and Methodological Considerations

One of the main limitations of this study is the smaller sample size ($N=17$). While the findings are promising, the limited number of participants does reduce the statistical power of the analyses and could potentially limit the generalizability of the results. If future research was to be done, it should aim to include larger sample sizes to increase the statistical power, allowing for more robust subgroup analyses and the detection of smaller effect sizes. By having a larger sample size, it would also allow for more detailed exploration of individual differences in response to PBM therapy, such as variations based on age, training status, or genetic factors.

Another limitation is although we employed a placebo/sham light control in our study, the effectiveness of participant blinding should be critically evaluated. Ensuring that participants are truly unaware of whether they are receiving the active treatment, or the placebo is crucial for maintaining the validity of the placebo comparison. We attempted to control this as much as we could, however with participants living together and comparing lights, they began to guess and assume. It's important to note that the placebo devices were also imperfect. The

visual nature of the treatment makes it quite difficult to create a placebo that mimics the appearance of an infrared light therapy without producing any physiological effects. Future studies should incorporate assessments of blinding effectiveness, such as asking participants to guess their group allocation at the end of the study. This can help determine whether any observed effects might be influenced by the participants' expectations or beliefs about the specific light they received.

The use of the BIODEX isokinetic dynamometer provided reliable measurements of muscle strength in this study. However, to gain more of a comprehensive understanding of PBM effects, future research should incorporate additional measures of muscle function. For instance, electromyography (EMG) could be employed to assess muscle activation patterns, while force plate analysis could offer insights into balance and power output. These additional measures would enable a more rounded assessment of PBM's influence on various aspects of muscle function and performance.

This study focused specifically on female athletes and a particular muscle group, which, while addressing a gap in the literature, limits the generalizability of our findings. Future studies should explore PBM's effects in diverse populations, including male athletes, non-athletes, and clinical populations. Additionally, examining PBM's impact on different muscle groups would help determine whether the observed benefits are consistent across various parts of the body. It also would be beneficial to consider longer follow-up periods and multiple assessment time points. This would allow for a more comprehensive evaluation of PBM's long-term effects and potential variations in its impact over time.

By investigating new and different PBM protocols, including variations in wavelength, power output, and treatment duration, it could help optimize the therapy for specific populations and muscle groups. Finally, by integrating more in-depth qualitative measures, such as participant feedback on perceived muscle function and performance, could provide valuable insights into the subjective experience of PBM treatment.

CONCLUSION

This study examined how photobiomodulation therapy (PBMT) affects delayed onset muscle soreness (DOMS) in female university athletes over a 10-week period. We used a crossover design and controlled for menstrual cycle phases to assess PBMT's effectiveness as a recovery strategy. These results indicate that PBM might help muscle recovery after DOMS-inducing exercise shown by better strength measurements and lower pain scores. The Biodex isokinetic dynamometer gave us reliable data on muscle strength recovery, while the McGill Pain Questionnaire provided useful insights into the subjective experience of DOMS. The study's design, which considered menstrual cycle changes, marks a big step in addressing the lack of female representation in this field and in sports science research. Monitoring menstrual cycle dates allowed us to control for hormone changes that could affect recovery processes making our results more valid.

However, we must consider the study's limits. The small sample size and focus on field hockey players might restrict how we can apply our findings and while we tried to control for placebo effects with a sham light treatment, we can't rule out the influence of the results that participants expected.

The current research adds to the growing evidence on PBM's potential as a recovery method in sports. The findings suggest that PBM could be a useful tool to optimize recovery and maintain performance during intense training or competition. But we need more research to understand how PBM affects DOMS and to determine the best treatment methods. Future studies should look at the long-term effects of regular PBM use on muscle adaptation and performance and explore how well it works in different sports and with various athlete groups. Research into how PBM interacts with other recovery methods could also help develop comprehensive recovery strategies.

Finally, this study offers promising evidence to support using PBM to manage DOMS in female field hockey athletes, while also highlighting the importance of considering sex-specific factors in sports science research. As the field of photobiomodulation grows, it has the

potential to enhance athletic recovery and performance calling for more investigation and improvement of application methods.

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APPENDIX

P 00 Number	Pain Score DOMS (1)	Pain Score 2	Pain Score 3
1	5	8	4
2	9	6	6
3	9	5	3
4	9	24	17
5	16	11	10
6	11	15	24
7	8	13	8
8	21	18	23
9	5	10	10
11	2	7	2
12	6	7	2
13	19	22	30
14	5	8	6
15	9	10	1
16	11	13	
17	12	8	12
18	13	13	
17 people in total. One drop out.			

Table showing how pain scores from the questionnaire was collected.



Graph showing how often the words came up to describe the participants DOMS.

Column1	Column2
constant	2
intermittent	8
brief	6
	16

Table showing the frequency of their pain. Collected through the questionnaire.