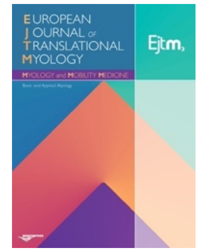
Neuromuscular performance after application of a wearable photobiomodulation device in young tennis athletes

European Journal of Translational Myology



pISSN: 2037-7452 eISSN: 2037-7460

https://www.pagepressjournals.org/index.php/bam/index

Eur J Transl Myol 2026 [Online ahead of print]

To cite this Article:

Grossi A, Fabris A, Campoli F, et al. **Preliminary pre-post changes in neuromuscular performance after application of a wearable photobiomodulation device in young tennis athletes.** *Eur J Transl Myol* doi: 10.4081/ejtm.2026.16043

Submitted: 29 July 2026 Accepted: 25 August 2026 Early access: 24 September 2026

Neuromuscular performance after application of a wearable photobiomodulation device in young tennis athletes

Preliminary pre-post changes in neuromuscular performance after application of a wearable photobiomodulation device in young tennis athletes

Alberto Grossi,[1,2] Andrea Fabris,[2] Francesca Campoli,[2] Lucio Caprioli,[2,3] Matteo Vitarelli,[1,2] Donatella Di Corrado,[4] Claudio Messina,[5] Domenico Cherubini,[6] Robert Nowak,[7,8] Elvira Padua,[2] Giuseppe Messina,[2,5*] Bruno Ruscello[2,9,10*]

[1]Department of Neurosciences, Biomedicine and Movement, University of Verona, Italy, [2]Department of Human Science and Promotion of Quality of Life, San Raffaele University, Rome, Italy; [3]Department of Sports Engineering Lab, "Tor Vergata" University, Rome, Italy; [4]Department of Sport Sciences, Kore University, Cittadella Universitaria, Enna, Italy; [5]Posturalab Research Institute, Palermo, Italy; [6]Facultad de Deporte, Catholic University of Murcia (UCAM), Murcia, Spain; [7]Institute of Physical Culture Sciences, University of Szczecin, Poland; [8]Department of Pathology, Pomeranian Medical University in Szczecin, Szczecin, Poland; [9]Department of Industrial Engineering, Faculty of Engineering, "Tor Vergata" University, Rome, Italy; [10]LUISS SportLab, Rome, Italy

[*]These authors contributed equally to this work.

Abstract

Athletes require effective recovery strategies to sustain performance, particularly in high-demand sports. Photobiomodulation (PBM) has emerged as a non-invasive approach capable of supporting muscle function without reported adverse effects. Wearable nanotechnology-based devices, such as Taopatch®, allow continuous and localized PBM delivery, representing a potential tool for sports applications. This pilot study investigated the acute effects of Taopatch® on neuromuscular performance in 28 young tennis players (11 females, 17 males; age 14.41 ± 2.60 years). Participants completed Squat Jump (SJ), Counter Movement Jump (CMJ), stiffness, and reaction time assessments before (T1) and after a 15-minute application period (T2). Taopatch® application was associated with pre–post increases in SJ flight time (unadjusted $p = 0.042$) and maximal pre-take-off velocity (Vmax; unadjusted $p = 0.012$), while CMJ concentric work also increased (unadjusted $p = 0.014$). Several effects remained significant after Benjamini–Hochberg false discovery rate correction, whereas none remained significant after the more conservative Holm–Bonferroni correction. Stiffness responses varied among subgroups, while reaction time remained unchanged. These preliminary findings suggest a potential association between Taopatch® application and acute changes neuromuscular performance. However, the statistical evidence was sensitive to the multiple-comparison correction applied, and controlled studies are required to confirm these exploratory observations.

Key words: photobiomodulation; tennis; youth athletes; explosive performance.

Athletic performance is strongly influenced by the ability to recover efficiently from exercise-induced fatigue and muscle damage. In high-performance sport, where training loads and competition frequency are continuously increasing, optimizing recovery strategies represents a critical determinant of both performance outcomes and injury prevention. Traditional recovery modalities, including Non-Steroidal Anti-Inflammatory Drugs (NSAIDs), massage therapy, and cold-water immersion, are widely adopted in athletic populations.[1,2] However, these approaches present several limitations. The chronic use of NSAIDs, for instance, has been associated with gastrointestinal, renal, and musculoskeletal side effects, as well as potential interference with muscle adaptation processes.[3] Similarly, other recovery strategies may require substantial time investment, specialized personnel, or may not be suitable for repeated use in dense, competitive schedules.[4,5]

With the advent of the modern era, growing attention has been directed toward wearable medical devices that enable personalized, topographically targeted treatment strategies.[6] In parallel, increasing attention has been directed toward non-invasive physical modalities capable of modulating physiological responses without pharmacological intervention. Different forms of externally applied physical stimulation have been investigated in clinical and rehabilitative settings, supporting growing interest in non-invasive technology-based approaches to physiological modulation.[7] Among these, Photobiomodulation (PBM) has emerged as a promising therapeutic approach. PBM is based on the absorption of light at specific wavelengths by intracellular chromophores, particularly cytochrome c oxidase, leading to increased mitochondrial activity, enhanced Adenosine Triphosphate (ATP) production, modulation of reactive oxygen species, and regulation of inflammatory pathways.[8,9]

Over the past decade, PBM has been increasingly investigated for its potential to enhance neuromuscular performance and accelerate post-exercise recovery. Evidence from systematic reviews and meta-analyses indicates that PBM can improve muscular endurance, delay fatigue, and reduce biochemical markers of muscle damage, such as Creatine Kinase (CK).[10] The most analyzed performance outcomes include the number of repetitions and time to exhaustion, which quantitatively increased by 5.47 (CI= 2.35–8.59; $p < 0.0006$) and 4.12 s (CI= 1.21–7.02; $p < 0.005$), in subjects treated with phototherapy, without significant heterogeneity (I^2= 0%).[11] Furthermore, PBM has demonstrated efficacy in managing sport-related musculoskeletal disorders,[12] particularly tendinopathies such as lateral epicondylitis (tennis elbow), with consistent short-term reductions in pain and improvements in functional outcomes reported.[13-16] Nevertheless, these benefits tend to diminish over longer follow-up periods, suggesting that PBM effects may be more pronounced during the acute or subacute phases of the condition.[17]

From a performance perspective, PBM has been shown to modulate electromyographic activity and enhance explosive strength, particularly when applied to large lower-limb muscle groups such as the rectus femoris, vastus lateralis, and vastus medialis.[18] Both pre- and post-exercise applications have been reported to accelerate the recovery of functional capacity without inducing adverse effects.[19] More recently, combined approaches such as PBM therapy associated with static magnetic fields (PBMT-sMF) have demonstrated additional benefits in preserving muscle strength and structural integrity, particularly in conditions of reduced training or detraining.[20]

Despite the growing body of evidence, responses to PBM appear to be influenced by several individual factors, including sex, age, training status, and neurophysiological conditions, highlighting the importance of personalized treatment approaches.[21-23] In parallel, technological advancements have facilitated the development of wearable medical devices designed to deliver continuous, low-intensity photobiomodulation in a targeted, user-friendly manner. These devices, often based on nanotechnology, enable localized stimulation without the need for external power sources, thereby expanding the practical applicability of PBM in real-world sports environments.[24]

Neuromuscular performance after application of a wearable photobiomodulation device in young tennis athletes

Among these innovations, wearable phototherapeutic patches such as Taopatch® have been proposed as tools capable of delivering multi-wavelength light stimulation across a broad spectrum (UV–NIR: 200–1200 nm). This emission range encompasses the wavelengths most associated with PBM efficacy (approximately 640–850 nm), which have been extensively used in experimental protocols aimed at improving muscular performance.[25] The reported spectral characteristics of the device derive from manufacturer-provided technical information and previous descriptions of the device rather than from an independent experimental characterization performed within the present study. Specifically, irradiance, power output, fluence, and spectral emission were not independently measured as part of the present experimental protocol. Therefore, the proposed PBM-related mechanism should be interpreted as a mechanistic hypothesis rather than as a directly demonstrated mechanism of action. Previous preliminary research involving Taopatch® during High-Intensity Interval Training (HIIT) has reported potential effects on metabolic responses, including reduced lactate accumulation and improved post-exercise glycaemic regulation.[26] However, these findings were obtained in a small pilot sample and were interpreted as hypothesis-generating evidence rather than definitive evidence of a specific mechanism of action. Accordingly, the present study does not assume a direct relationship between the reported optical characteristics of the device and potential physiological effects. The broader spectral output may also introduce complex tissue interactions that are not yet fully understood, underscoring the need for targeted experimental investigations.

Considering the available evidence and the growing interest in wearable photobiomodulation-based devices, there is a clear need for further experimental studies aimed at exploring the acute effects of this therapy on neuromuscular performance in sport-specific contexts.

Therefore, the present pilot study aimed to investigate pre–post changes in neuromuscular performance following the application of a photobiomodulation device (Taopatch®) in young tennis athletes, using a topographically targeted application. It was hypothesized that the application of this device may be associated with changes in neuromuscular efficiency and short-term performance outcomes, providing preliminary evidence for its potential role within sport-specific training and recovery protocols.

Neuromuscular performance after application of a wearable photobiomodulation device in young tennis athletes

Materials and Methods

Study design

Twenty-eight young tennis players (11 females and 17 males; age: 14.41 ± 2.60 years; body weight: 50.54 ± 13.44 kg; height: 164.1 ± 13.27 cm; body mass index [BMI]: 18.45 ± 2.58) with different levels of competitive experience (U12 = 4; U14 = 9; U16 = 5; U18 = 8; Senior = 2), were recruited for the study. Athletes trained 4 ± 1 times per week, with an average session duration of approximately 2 hours. All participants underwent the same neuromuscular assessment protocol based on jump tests (Optojump, Microgate, Italy) at two evaluation time points (T1 and T2). The protocol included an initial standardized warm-up consisting of 5 minutes of running, followed by three familiarization trials for each test. Familiarization trials were not included in the statistical analysis.

Experimental procedure

At baseline (T1), athletes completed four specific tests: Squat Jump (SJ), Counter Movement Jump (CMJ), Stiffness, and Reaction Time.

For the SJ and CMJ assessments, participants performed three recorded maximal trials, with approximately 60 s of recovery between consecutive attempts. The best performance was retained for subsequent analysis. Standardized verbal instructions were provided before each test, and participants were instructed to perform each jump with maximal effort. Hands were maintained on the hips throughout the execution to minimize the contribution of the upper limbs.

For the Squat Jump (SJ), participants started from a stationary semi-squat position, with the knees flexed to approximately 90°, and were instructed to perform a maximal vertical jump without any preliminary countermovement. For the Counter Movement Jump (CMJ), participants started from an upright standing position and performed a rapid self-selected countermovement immediately followed by a maximal vertical jump.

For the stiffness assessment, participants performed repeated vertical jumps according to the standardized Optojump testing protocol, with particular emphasis on maintaining consistent execution across T1 and T2. The repeated-jump assessment consisted of seven consecutive jumps performed with the legs extended and the arms maintained alongside the trunk. Participants were instructed to "jump as high and as quickly as possible." The recorded variables were automatically calculated by the Optojump software, and the values reported for each participant represent the mean of the seven

recorded trials. The test allowed the assessment of variables related to reactive and stretch-shortening cycle performance, including Reactive Strength Index (RSI), maximum power (Pmax), loading rate, time to maximum force (Time2Fmax), and time to maximum landing force (Time2FmaxLand).
The reaction-time assessment was performed using the Optojump system according to the same standardized procedure at T1 and T2. A predefined protocol consisting of three stimuli, visual and/or auditory, was administered by the software. During the assessment, participants maintained their gaze at eye level toward a screen displaying a red circle. For the visual condition, the stimulus consisted of a change in the circle color from red to green, which served as the cue to initiate the motor response. To increase ecological validity and approximate the demands of sport-specific performance, participants were instructed to perform a movement resembling a split step, *i.e.*, a preparatory double-leg jump characterized by short ground-contact and flight times, similar to the preparatory action performed in response to an opponent's shot. Because the movement was used as the motor response to the external stimulus, jump height and the other mechanical variables obtained during this task were not considered as outcome measures. The analysis was therefore restricted to the response time to the presented stimulus. The same testing conditions and standardized instructions were maintained across both assessment sessions to minimize procedural variability.
Participants were eligible for inclusion if they were actively engaged in regular tennis training and competitive activity and were able to complete the entire neuromuscular testing protocol. Participants were excluded in the presence of acute musculoskeletal injury, pain, or any other condition that could interfere with the safe and correct execution of maximal jumping tasks, as well as if they were unable to complete both assessment sessions.

Taopatch® application

Two Taopatch® devices (Taotechnologies S.R.L., Italy) were applied to the skin of each participant using a hypoallergenic adhesive patch, positioned posteriorly over the seventh cervical vertebra (C7) and anteriorly over the xiphoid process (diameter: 1.7 cm; area irradiated: 2.27 cm^2 for each device). These anatomical sites were selected according to the standardized application protocol adopted for the device and were maintained consistently across all participants and both assessment sessions. The C7 and xiphoid placements provided standardized posterior and anterior application sites. This placement was also selected in consideration of previous observations by Carbonari *et al.* (2021), who reported improvements in squat-jump height following application of the devices at the same anatomical sites.[27]

In the present study, this configuration was maintained consistently across participants to ensure standardized device placement. No independent measurements of irradiance, power output, fluence, or spectral emission were performed within the present study. After the 15-minute treatment period, conducted without additional cognitive or motor tasks, participants underwent a second assessment session (T2) using the same testing protocol. Participants were monitored throughout the experimental session for any adverse events, discomfort, or local skin reactions potentially associated with device application. No adverse events, discomfort, or skin reactions were observed or reported during the testing sessions. A sham- or placebo-controlled condition was not included, as the study was designed as an exploratory pilot investigation conducted within the athletes' regular training schedule, primarily to assess feasibility and generate preliminary hypotheses. No blinding procedures were implemented. To minimize potential expectancy effects, participants were not informed about the expected benefits of the device prior to testing.

Statistical analysis

The assumption of normality of data distribution was assessed using the Shapiro–Wilk test. Results are reported as mean ± standard deviation. Comparisons between the two assessment phases were performed using paired-sample t-tests. For variables that did not meet the normality assumption, the non-parametric Wilcoxon signed-rank test was applied, and results are reported as median and Interquartile Range (IQR). Subgroup analyses according to competitive category were considered exploratory. Inferential subgroup analyses were restricted to categories including at least four participants (U12, U14, U16, and U18), whereas the Senior category (n = 2) was excluded from inferential analyses because of the insufficient sample size. Given the small sample sizes within individual categories, subgroup effect estimates should be interpreted as exploratory and hypothesis-generating rather than confirmatory. Analysis Of Variance (ANOVA) was performed to verify whether the observed changes were dependent on playing category. In addition, multiple linear regression analysis was conducted to identify models explaining variability in significant performance changes. Given the exploratory nature of this pilot study, individual variables were not prospectively designated as formal primary outcomes. Whole-sample pre–post comparisons constituted the principal analyses, whereas subgroup analyses, analyses according to competitive category, and regression models were considered exploratory and hypothesis-generating All statistical analyses were performed using JASP version 3.0 (JASP Team, Amsterdam, Netherlands). Multiple-comparison corrections were performed using RStudio (version 4.5).

Results

Squat jump

Exploratory pre–post differences were observed in selected Squat Jump (SJ) test variables following device application. At the nominal unadjusted significance level, flight time increased by 0.009 s (raw $p = 0.042$; $d = 0.403$), while maximum velocity before take-off (Vmax) increased by 0.11 m/s (raw $p = 0.012$; $d = 0.509$). Jump height showed a borderline pre–post difference (raw $p = 0.050$; $d = 0.376$). These findings should be interpreted in conjunction with the multiple-comparison-adjusted analyses reported below (Table 1 and Figure 1).

Exploratory subgroup analyses suggested potential differences across training categories. Among Under-12 athletes, a significant increase in concentric work (WorkConc: $p= 0.003$; $d= 4.35$) was observed. In Under-18 athletes, significant positive changes were detected in both flight time ($p= 0.007$; $d= 1.34$) and jump height ($p= 0.011$; $d= 1.22$). In Under-16 athletes, these parameters showed only a trend toward statistical significance ($p= 0.057$ and $p= 0.056$, respectively). Confidence intervals indicated a general tendency toward higher post-intervention values. However, these findings should be interpreted with caution and do not allow confirmation of a systematic effect of the intervention.

Counter movement jump

Exploratory analysis of the CMJ showed a nominal pre–post difference in concentric work (WorkConc), with the median increasing from 7.85 J/kg at T1 (IQR = 2.11) to 8.36 J/kg at T2 (IQR = 1.64; median difference = +0.51 J/kg; raw $p = 0.014$; $r = 0.532$; Wilcoxon signed-rank test) (Table 1, Figure 1).

Subgroup analysis suggested heterogeneous patterns within specific categories, although these were not always statistically significant. In the Under-12 category, device application showed a tendency toward reductions in both the rate of force development (RFD) and eccentric work (WorkEcc), although these changes did not reach statistical significance ($p= 0.073$; $d= -1.353$ for both). In Under-14 athletes, a significant increase was observed in maximum velocity (Vmax: $p= 0.036$; $d= 0.836$). No significant changes were detected in the Under-16 category. Finally, in the Under-18 category, a statistically significant reduction in RFD was observed ($p= 0.003$; $d= -1.539$).

Stiffness test

Stiffness analysis did not show statistically significant differences for the entire team. However, subgroup analysis revealed potentially relevant variations within individual categories. In Under-12 athletes, a significant reduction was observed in the time to reach peak strength from the start of the concentric phase (Time2Fmax: $p= 0.041$; $d= -1.725$), whereas in Under-14 athletes, a significant increase was detected in the time to reach maximum force from initial ground contact after the jump (Time2FmaxLand: $p= 0.009$; $r= 1.00$; Wilcoxon). In the Under-16 category, significant increases were observed in maximum velocity (Vmax: $p= 0.048$, $d= 1.256$) and maximum power before take-off (Pmax: $p= 0.006$, $d= 2.426$). In addition, loading rate during the landing phase increased significantly ($p= 0.034$, $d= 1.420$), while time to maximum landing force (Time2FmaxLand) was reduced ($p= 0.036$, $d= -1.391$). In Under-18 athletes, significant increases were observed in Pmax ($p= 0.013$; $d=1.177$), Reactive Strength Index (RSI) ($p= 0.018$; $d= 1.084$), and Time2Fmax ($p= 0.021$; $d=1.046$).

Reaction time test

The reaction time test did not show significant changes in the variable studied, either in the team-level analysis or in the subgroup analyses.

Associations between baseline characteristics and changes in neuromuscular performance in jump tests

To further explore predictive factors for the observed changes, a multiple linear regression model was constructed that included anthropometric parameters, sex, age, Body Mass Index (BMI), and pre-test motor performance values. The analysis revealed that, for the change in maximum velocity in the SJ test (Vmax), the overall model was not significant ($F=0.70$; $p=0.669$; $R^2=0.20$; adjusted $R^2= -0.08$). None of the included predictors showed significant associations (all $p > 0.05$). Conversely, for the change in flight time, the regression model was significant ($F= 2.62$; $p= 0.043$), explaining 47.8% of the variance (R^2=0.48; adjusted R^2=0.30). Among the predictors, only the baseline flight time was significantly associated with the observed changes (β= −0.54; p= 0.015). Similarly, for changes in concentric work (WorkConc) in the CMJ test, the model was significant (F= 3.17; p= 0.020), explaining 52.6% of the variance (R^2= 0.53; adjusted R^2= 0.36). Baseline WorkConc (β=0.71; p=0.002) and age (β= 0.44; p= 0.036) were significant predictors. Finally, ANOVA analysis for the dependent variables Vmax and Flight Time in the SJ test, and WorkConc in the CMJ test, did not reveal significant differences in relation to the training category (Vmax: F=0.574; p= 0.684; Flight Time: F= 2.292; p= 0.090; WorkConc: F= 1.682; p= 0.188).

Multiple-comparison corrections

To control for inflation of the Type I error rate due to multiple comparisons, p-values were post-hoc adjusted using both the Benjamini–Hochberg (BH) procedure and the Holm–Bonferroni correction. At the nominal significance level ($p < 0.05$), several variables were statistically significant before adjustment. However, the application of multiple-comparison corrections substantially altered the overall interpretation of the results (Table 2). The Benjamini–Hochberg procedure identified a subset of variables that remained statistically significant after correction for multiple comparisons under False Discovery Rate (FDR) control. In contrast, the more conservative Holm–Bonferroni correction resulted in no statistically significant comparisons, with no effects remaining significant under Family-Wise Error Rate (FWER) control (Figure 2). Overall, the findings suggest a coherent pattern of differences across neuromuscular variables, assessment constructs, and subgroups. The strength of the evidence depends on the correction method applied. The FDR-based approach supports the interpretation of potentially relevant effects, whereas the Holm–Bonferroni adjustment does not confirm any differences at the individual test level. Therefore, the results should be interpreted as indicative rather than conclusive.

Performance changes

Considering the sample as a whole, post-treatment improvements of 2,23 % in flight time and 4,6% in maximum velocity (Vmax) in the Squat Jump test, as well as a 9,7% increase in concentric work

(WorkConc) in the Counter Movement Jump test, were observed (Table 3 and Figure 3). However, the wide confidence intervals and high coefficients of variation indicate marked inter-individual variability.

Discussion

The present study investigated pre–post changes in neuromuscular performance in young tennis athletes following the use of a wearable PBM device.

The main findings of this study suggest that PBM was associated with selective changes in explosive performance variables, particularly in SJ kinetics and concentric work during the CMJ, whereas no generalized effects were observed across all neuromuscular domains. At the same time, responses appeared highly variable across individuals and performance domains.

These results are partially consistent with previous literature indicating that PBM does not uniformly enhance performance outcomes but rather induces task-specific, variable responses depending on the neuromuscular demands of the movement and the characteristics of the athletes.[25,28,29] In the present study, the most evident changes were observed in flight time and maximal velocity during the SJ, suggesting modifications in movement efficiency and force-application dynamics rather than in maximal output. This interpretation aligns with findings reported by Ferraresi *et al.*, who demonstrated that PBM enhances muscle performance primarily through improvements in contractile efficiency and metabolic support rather than peak strength.[30]

The selective change in concentric work observed in the CMJ further supports the hypothesis that PBM may be associated with adaptations in contractile and metabolic components of muscle function. Indeed, systematic reviews and meta-analyses have shown that PBM is particularly effective in supporting muscular endurance and delaying fatigue, rather than directly enhancing explosive or elastic performance components.[24] This may explain why, in the present study, parameters associated with the stretch–shortening cycle did not show consistent improvements.

Another relevant point concerns the temporal dynamics of PBM effects. The relatively modest improvements observed immediately after application may reflect only the initial phase of a time-dependent physiological response. Previous studies have reported that PBM-induced performance changes may become more evident several hours or days after treatment. For instance, De Marchi *et al.* observed time-dependent improvements in jump performance following LED therapy, with significant effects emerging at 24–72 hours post-intervention.[31] This suggests that PBM may act through photochemical and metabolic pathways, including increased mitochondrial activity and modulation of oxidative stress, which require time to translate into measurable functional outcomes.[32,33]

The present findings are also consistent with studies by Leal-Junior and colleagues, who demonstrated that PBM administered before exercise can enhance performance and reduce fatigue, particularly when combined with repeated training sessions.[2,18] In these studies, more pronounced effects were observed under conditions of high metabolic demand or muscle fatigue, supporting the idea that PBM is more effective when the physiological system is sufficiently stressed.

Interestingly, the magnitude of post-intervention increases observed in this study falls within the lower range reported in the literature. Previous studies have documented performance enhancements ranging from approximately 2% to over 50%, depending on the protocol, population, and outcome measures.[11]

In the study by Zagatto *et al.*[34] involving water polo athletes, no significant differences were observed between the laser and placebo groups in 200-m performance before and after the one-week intervention. However, small to moderate effects emerged in 30 consecutive jumps (30-CJ), with effect sizes progressively increasing over time only in the Low-Level Laser Therapy (LLLT) group. Additionally, a meta-analysis by Qiu *et al.*[35] reported that PBM improves muscular endurance, delays the onset of fatigue, and reduces post-exercise muscle damage in ball-sport athletes. Notably, performance adaptations appeared sport-specific, with increased repetitions observed in volleyball players and significant reductions in CK levels in soccer players. These findings are further supported by Leal-Junior *et al.*,[36] the first study comparing LEDT with another active treatment (Cold Water Immersion Therapy, CWIT), in young futsal player.

From a mechanistic perspective, PBM is known to stimulate mitochondrial respiration by activating cytochrome c oxidase, thereby increasing ATP production and improving cellular metabolism.[30] Additionally, PBM may reduce muscle damage and inflammation, thereby facilitating recovery and preserving neuromuscular function.[18,37] However, translating these cellular effects into performance outcomes appears to depend on multiple interacting factors, including exercise type, timing of application, and individual responsiveness.

From a practical standpoint, the present findings suggest that the application of wearable PBM devices may be associated with changes in neuromuscular performance and may represent a potential adjunct strategy in sports characterized by repeated explosive actions such as tennis. However, the variability in responses and the lack of a controlled design indicate that these observations should be interpreted with caution, and no causal inference regarding the device's efficacy can be drawn. Taken together, these findings should be interpreted as early exploratory observations associated with device application rather than evidence of a causal treatment effect. The uncontrolled pre–post design does not allow the observed changes to be distinguished from potential learning, familiarization, expectancy, or other time-related effects. Further controlled studies are required to clarify optimal application parameters and support the development of individualized protocols tailored to athlete-specific responses.

Limitations

A full physical characterization of the device, including irradiance, power output, fluence, and an independently verified emission spectrum, was not available within the present study protocol. Therefore, a quantitative comparison with standard PBM dosimetry reported in the literature was not possible, and mechanistic interpretations should be considered with appropriate caution. In addition, subgroup analyses were based on relatively small and heterogeneous samples, which may have limited the statistical power to detect subgroup-specific effects. Accordingly, inferential statistics, including hypothesis tests and effect size estimates, should be interpreted in consideration of the sample size and exploratory nature of these analyses.

Another limitation is the absence of a sham- or placebo-controlled condition, which limits the extent to which the observed pre–post changes can be attributed specifically to the intervention. Furthermore, no blinding procedures were implemented. Although participants were not informed about the expected benefits of the device to minimize potential expectancy-related bias, the influence of nonspecific effects cannot be completely excluded. After Holm correction, none of the variables remained statistically significant, whereas some retained significance after Benjamini–Hochberg adjustment, warranting cautious interpretation of the findings.

Nevertheless, the present study contributes an initial characterization of acute changes in neuromuscular performance following the intervention under standardized, real-world conditions. These findings provide preliminary insights into the potential acute effects of the intervention and highlight the need for future sham-controlled, blinded studies to further investigate its efficacy and underlying mechanisms.

Future directions

To confirm the feasibility of sport-specific protocols, future research should prioritize randomized, controlled crossover designs with sham or placebo conditions implemented under double-blind procedures. In addition, a rigorous characterization of dosimetry and, consequently, of the dose–response relationship is required through two distinct experimental phases: i) bench-top characterization of emission parameters to define delivered dose, and ii) repeated outcome assessments across short- and long-term time windows to evaluate acute and chronic adaptations (time-dependent dose–response relationships). Furthermore, the inclusion of repeated testing sessions across phases would help to disentangle potential learning and fatigue effects associated with performance assessments. Mechanistic interpretation may also benefit from integrating muscle damage and fatigue-related biomarkers, providing complementary evidence alongside biomechanical performance outcomes. Similarly, the inclusion of subjective measures of perceived exertion, such as the Borg Rating of Perceived Exertion (RPE), could further enrich the interpretation of changes in performance. Finally, methodological considerations such as dropout rates (0% in the present study), adverse event reporting, and the definition of intra- and inter-measurement variability thresholds should be incorporated in future designs. However, the use of arbitrary dichotomization of continuous performance variables (e.g., fixed percentage thresholds for “responders” *vs*. “non-responders”) should be approached with caution and justified a priori when applied.

Conclusions

The present study provides preliminary evidence that the acute application of a wearable PBM device may be associated with selective improvements in neuromuscular performance in young tennis athletes. Changes were observed in kinetic variables associated with explosive performance, such as flight time and maximal velocity in the Squat Jump, as well as concentric work in the Counter Movement Jump.

The relatively modest magnitude of the observed changes, together with evidence from previous literature, indicates that PBM effects may follow a time-dependent trajectory, with early responses potentially representing only the initial phase of a broader physiological adaptation. Therefore, the exploratory findings of this study should be interpreted within the context of short-term exposure and warrant further investigation.

Overall, wearable PBM devices such as Taopatch® may represent a potential complementary tool for supporting neuromuscular performance. However, the present findings do not support causal inference regarding their efficacy.

Future research should prioritize randomized controlled trials, larger sample sizes, standardized reporting of PBM dosimetry, and the inclusion of time-course analyses and biochemical markers of muscle damage and recovery. Such approaches would provide a more comprehensive understanding of PBM mechanisms and its potential role in sports performance optimization.

Abbreviations

ATP, adenosine triphosphate
ANOVA, analysis of variance
BH, Benjamini–Hochberg
BMI, body mass index
CK, creatine kinase
CI, confidence interval
CMJ, counter movement jump
CWIT, cold water immersion therapy
FDR, false discovery rate
FWER, family-wise error rate
IQR, interquartile range
LEDT, light-emitting diode therapy
LLLT, low-level laser therapy
NSAIDs, non-steroidal anti-inflammatory drugs
PBM, photobiomodulation

Neuromuscular performance after application of a wearable photobiomodulation device in young tennis athletes

PBMT-sMF, photobiomodulation therapy associated with static magnetic fields

Pmax, maximum power

RFD, rate of force development

RPE, rating of perceived exertion

RSI, reactive strength index

SJ, squat jump

T1, baseline assessment

T2, post-intervention assessment

UV, ultraviolet

NIR, near infrared

Vmax, maximum velocity

WorkConc, concentric work

WorkEcc, eccentric work

Time2Fmax, time to maximum force during the concentric phase

Time2FmaxLand, time to maximum force after landing

U12, Under-12 category

U14, Under-14 category

U16, Under-16 category

U18, Under-18 category

Corresponding Author

Francesca Campoli
Department of Human Science and Promotion of Quality of Life, San Raffaele University, via di Val Cannuta, 247, 00166 Rome, Italy
francesca.campoli@uniroma5.it
0009-0004-1342-5881

Alberto Grossi

alberto.grossi@uniroma5.it

Neuromuscular performance after application of a wearable photobiomodulation device in young tennis athletes

0000-0002-2832-1960

Andrea Fabris
andrea.fabris@uniroma5.it
0009-0001-2054-1811

Lucio Caprioli
lucio.caprioli@uniroma5.it
0009-0005-4049-5225

Matteo Vitarelli
matteo.vitarelli@uniroma5.it
0009-0003-4294-7497
Donatella Di Corrado
donatella.dicorrado@unikore.it
0000-0001-8223-6671

Claudio Messina
claudio.messina@studenti.uniroma5.it

Domenico Cherubini
dcherubini@ucam.edu
0000-0002-5207-7558

Robert Nowak
robert.nowak@usz.edu.pl
0000-0003-3037-644X

Elvira Padua:
elvira.padua@uniroma5.it
0000-0001-5227-2567

Neuromuscular performance after application of a wearable photobiomodulation device in young tennis athletes

Giuseppe Messina
giuseppe.messina@uniroma5.it
0000-0003-2774-4950

Bruno Ruscello
bruno.ruscello@uniroma5.it
0000-0002-5381-9146

Contributions

Conceptualization, Alberto Grossi, Giuseppe Messina and Bruno Ruscello; methodology, Alberto Grossi, Francesca Campoli, Donatella Di Corrado, Giuseppe Messina and Bruno Ruscello; formal analysis, Alberto Grossi, Francesca Campoli, Andrea Fabris and Lucio Caprioli; investigation, Alberto Grossi, Francesca Campoli, Andrea Fabris, Matteo Vitarelli, Claudio Messina and Domenico Cherubini; resources, Giuseppe Messina and Bruno Ruscello; data curation, Lucio Caprioli, Matteo Vitarelli and Claudio Messina; writing – original draft preparation, Alberto Grossi, Francesca Campoli, Andrea Fabris and Lucio Caprioli; writing – review & editing, Elvira Padua, Donatella Di Corrado and Robert Nowak; Supervision, Giuseppe Messina and Bruno Ruscello; project administration, Giuseppe Messina and Bruno Ruscello. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

The authors declare no conflicts of interest. The principal authors are actively engaged in research on photobiomodulation and wearable devices, and their previous publications in this area reflect scientific continuity and domain-specific expertise. Accordingly, prior work involving the same or similar devices should be interpreted as part of an ongoing research line rather than as evidence of a conflict of interest. The authors further clarify that they have no commercial, financial, employment, or other contractual relationship with the device manufacturer. The device manufacturer had no role in the study design, participant recruitment, data collection, statistical analysis, interpretation of the results, preparation of the manuscript, or the decision to submit the manuscript for publication.

Neuromuscular performance after application of a wearable photobiomodulation device in young tennis athletes

Ethics approval

The study was approved by the Internal Research Board of the University of Enna "KORE", Prot. N°: 2574, 08 February 2024. All the procedures involved in this study were in accordance with the Declaration of Helsinki.

Informed Consent Statement

Informed consent was obtained from all subjects involved in the study (and from their legal guardians, given the participants' ages).

Availability of data and material

The data presented in this study are available on request from the corresponding author.

Funding

This research received no external funding.

Declaration of generative artificial intelligence and artificial intelligence-assisted technologies in the writing process

The authors did not use generative artificial intelligence or artificial intelligence-assisted technologies in the writing process of this manuscript.

Acknowledgments

The authors would like to thank all the athletes who participated in this study.

References

1. Heiss R, Lutter C, Freiwald J, et al. Advances in delayed-onset muscle soreness (DOMS)—part II: treatment and prevention. Sportverletz Sportschaden 2019;33:21–9.
2. Leal-Junior ECP, Lopes-Martins RÁB, Bjordal JM. Clinical and scientific recommendations for the use of photobiomodulation therapy in exercise performance enhancement and post-exercise recovery: current evidence and future directions. Braz J Phys Ther 2019;23:71–75.

3. Mandić M, Gustafsson T, Lundberg TR. NSAIDs and muscle hypertrophy: methodological concerns and alternative interpretations. J Physiol 2026.
4. Dupuy O, Douzi W, Theurot D, Bosquet L, Dugué B. An evidence-based approach for choosing post-exercise recovery techniques to reduce markers of muscle damage, soreness, fatigue, and inflammation: a systematic review with meta-analysis. Front Physiol 2018;9:403.
5. Ko GWY, Clarkson C. The effectiveness of acupuncture for pain reduction in delayed-onset muscle soreness: a systematic review. Acupunct Med 2020;38:63–74.
6. Sirolli S, Guarnera D, Ricotti L, Cafarelli A. Triggerable patches for medical applications. Adv Mater 2024;36:e2310110.
7. Benkov AA, Nagornev SN, Frolkov VK, Reps VF, Edelev DA, Fesyun AD, Yakovlev MY, Tumanova NF, Sanina NP, Maccarone MC, Masiero S. Simultaneous application of transcranial magnetic stimulation and low-frequency electrostatic field as treatment of carbohydrate and lipid disorders in patients with metabolic syndrome. Eur J Transl Myol 2022;32:10351.
8. Leal-Junior ECP. Photobiomodulation therapy in skeletal muscle: from exercise performance to muscular dystrophies. Photomed Laser Surg 2015;33:53–54.
9. Amato A, Messina G, Feka K, Genua D, Ragonese P, Kostrzewa-Nowak D, Fischetti F, Iovane A, Proia P. Taopatch® combined with home-based training protocol to prevent sedentary lifestyle and biochemical changes in MS patients during COVID-19 pandemic. Eur J Transl Myol 2021;31:9877.
10. Ferraresi C, Huang YY, Hamblin MR. Photobiomodulation in human muscle tissue: an advantage in sports performance? J Biophotonics 2016;9:1273–1299.
11. Leal-Junior ECP, Vanin AA, Miranda EF, De Tarso Camillo De Carvalho P, Corso SD, Bjordal JM. Effect of phototherapy (low-level laser therapy and light-emitting diode therapy) on exercise performance and markers of exercise recovery: a systematic review with meta-analysis. Lasers Med Sci 2015;30:925–939.
12. Ailioaie LM, Litscher G. Photobiomodulation and sports: results of a narrative review. Life (Basel) 2021;11:1339.
13. Tumilty S, Munn J, McDonough S, Hurley DA, Basford JR, Baxter GD. Low level laser treatment of tendinopathy: a systematic review with meta-analysis. Photomed Laser Surg 2010;28:3–16.
14. Stasinopoulos D, Stasinopoulos I, Pantelis M, Stasinopoulou K. Comparing the effects of exercise program and low-level laser therapy with exercise program and polarized polychromatic non-coherent light (Bioptron Light) on the treatment of lateral elbow tendinopathy. Photomed Laser Surg 2009;27:513–520.
15. Stergioulas A. Effects of low-level laser and plyometric exercises in the treatment of lateral epicondylitis. Photomed Laser Surg 2007;25:205–213.
16. Bjordal JM, Lopes-Martins RA, Joensen J, Couppe C, Ljunggren AE, Stergioulas A, Johnson MI. A systematic review with procedural assessments and meta-analysis of low-level laser therapy in lateral elbow tendinopathy (tennis elbow). BMC Musculoskelet Disord 2008;9:75.
17. Campoli F, Iovane A, Fabris A, Francavilla V, Proia P, Caprioli L, Bonaiuto V, Annino G, Padua E, Messina G. Acute effects of nanotechnological devices for the muscle and joint pain treatment. Eng Methodol Med Sports 2024:86–96.
18. Leal-Junior ECP, Lopes-Martins RÁB, Dalan F, Ferrari M, Sbabo FM, Generosi RA, et al. Effect of phototherapy (low-level laser therapy) on exercise-induced skeletal muscle fatigue and biochemical markers of muscle damage: a randomized double-blind placebo-controlled trial. Clin J Sport Med 2010;20:1–7.

19. Luo W, Lee C, Tam K, Huang T. Effects of low-level laser therapy on muscular performance and soreness recovery in athletes: a meta-analysis of randomized controlled trials. Sports Health 2022;14:687–693.
20. De Paiva PRV, Tomazoni SS, Machado CDSM, Pereira AL, Ribeiro NF, Lino MMA, Dias LB, de Oliveira MFD, de Araújo-Silva OM, Dorneles MP, et al. Effects of photobiomodulation therapy combined with static magnetic field on training adaptations and detraining responses: a randomised placebo-controlled trial. BMJ Open Sport Exerc Med 2025;11:e002799.
21. Gutiérrez-Menéndez A, Rodríguez-Fernández L, Zorzo C, Martínez JA, Arias JL. Safety of 810 nm photobiomodulation in the developing brain: no evidence of glial reactivity or pro-inflammatory cytokine expression in rats. Lasers Med Sci 2025;40:409.
22. Rodríguez-Fernández L, Zorzo C, Arias JL. Photobiomodulation in the aging brain: a systematic review from animal models to humans. GeroScience 2024;46:6583–6623.
23. Chamkouri H, Liu Q, Zhang Y, Chen C, Chen L. Brain photobiomodulation therapy on neurological and psychological diseases. J Biophotonics 2024;17:e202300145.
24. Vanin AAV, Verhagen E, Barboza SD, Costa LOP, Leal-Junior ECP. Photobiomodulation therapy for the improvement of muscular performance and reduction of muscular fatigue associated with exercise in healthy people: a systematic review and meta-analysis. Lasers Med Sci 2018;33:181–214.
25. Aguirra P, do Nascimento AP, Casonatto J, Ribeiro AS, Pacagnelli FL, de Oliveira RG, Aguiar AF. A systematic review and meta-analysis of the acute effects of photobiomodulation therapy on the maximum number of repetitions in resistance exercise in young adults. Lasers Med Sci 2025;40:184.
26. Boatta A, Pagliaro A, Messina G, Alioto A, Mingrino O, Kostrzewa-Nowak D, Nowak R, Proia P. Metabolic and neuromuscular responses to high-intensity training with and without Taopatch® nanotechnology: a pilot randomized control study. Cent Eur J Sport Sci Med 2025;52:57–65.
27. Carbonari B, Balducci F, Cesaretti G, Cesanelli L, Botticelli D, Messina G. Performance, balance and posture variations with Occlusal Splint and Taopatch® devices: a retrospettive cross-over study. J Sports Med Phys Fitness 2021;61:317–323.
28. Machado AF, Leal-Junior ECP, Batista NP, Espinoza RMCP, Hidalgo RBR, Carvalho FA, Micheletti JK, Vanderlei FM, Pastre CM. Photobiomodulation therapy applied during an exercise-training program does not promote additional effects in trained individuals: a randomized placebo-controlled trial. Braz J Phys Ther 2022;26:100388.
29. Machado AF, Micheletti JK, Vanderlei FM, Nakamura FY, Leal-Junior ECP, Netto J, Pastre CM. Effect of low-level laser therapy (LLLT) and light-emitting diodes (LEDT) applied during combined training on performance and post-exercise recovery: protocol for a randomized placebo-controlled trial. Braz J Phys Ther 2017;21:296–304.
30. Ferraresi C, Hamblin MR, Parizotto NA. Low-level laser (light) therapy (LLLT) on muscle tissue: performance, fatigue and repair benefited by the power of light. Photonics Lasers Med 2012;1:267–286.
31. De Marchi T, Leal-Junior ECP, Bortoli C, Tomazoni SS, Lopes-Martins RAB, Salvador M. Low-level laser therapy (LLLT) in human progressive-intensity running: effects on exercise performance, skeletal muscle status, and oxidative stress. Lasers Med Sci 2012;27:231–236.
32. Hamblin MR. Mechanisms and mitochondrial redox signaling in photobiomodulation. Photochem Photobiol 2018;94:199–212.
33. Chung H, Dai T, Sharma SK, Huang YY, Carroll JD, Hamblin MR. The nuts and bolts of low-level laser (light) therapy. Ann Biomed Eng 2012;40:516–533.

34. Zagatto AM, Dutra YM, Lira FS, Antunes BM, Faustini JB, Malta ES, Lopes VHF, de Poli RAB, Brisola GMP, Dos Santos GV, et al. Full body photobiomodulation therapy to induce faster muscle recovery in water polo athletes: preliminary results. Photobiomodul Photomed Laser Surg 2020;38:766–772.
35. Qiu D, He J, Li B, Ni P, Zhao Z, Lv R, Li F. The effect of photobiomodulation therapy on muscle performance in volleyball and football players: a meta-analysis of randomized controlled trials. Sports Health 2026;18:496–506.
36. Leal EC, De Godoi V, Mancalossi JL, Rossi RP, De Marchi T, Parente M, Grosselli D, Generosi RA, Basso M, Frigo L, et al. Comparison between cold water immersion therapy (CWIT) and light-emitting diode therapy (LEDT) in short-term skeletal muscle recovery after high-intensity exercise in athletes—preliminary results. Lasers Med Sci 2011;26:493–501.
37. Padoin S, Zeffa AC, Molina Corrêa JC, de Angelis TR, Moreira TB, Barazetti LK, de Paula Ramos S. Phototherapy improves muscle recovery and does not impair repeated bout effect in plyometric exercise. J Strength Cond Res 2022;36:3.

Table 1. Descriptive statistics of jump height, flight time, and Vmax in SJ test and concentric work in the counter movement jump test.

Outcome	Time	Mean	95% CI Lower	95% CI Upper	SD	CV	Median	IQR	Min	Max
SJ – Jump Height [cm]	Pre	23.4	21.2	25.1	5.70	0.24	–	–	14.1	36.3
	Post	24.3	22.2	26.4	5.44	0.22	–	–	15.3	36.0
SJ – Flight Time [s]	Pre	0.43	0.41	0.46	0.05	0.12	–	–	0.34	0.54
	Post	0.44	0.42	0.46	0.05	0.11	–	–	0.35	0.54
SJ – Vmax [m/s]	Pre	2.40	2.30	2.50	0.26	0.11	–	–	1.78	2.89
	Post	2.51	2.38	2.65	0.34	0.14	–	–	1.89	3.38
	Pre	7.68	7.03	8.34	1.69	0.22	7.85	2.11	4.29	10.7

CMJ – WorkConc [J/kg]	Post	8.19	7.67	8.72	1.35	0.17	8.36	1.64	5.58	11.7

Table 2. Raw and adjusted p-values (Benjamini–Hochberg and Holm-Bonferroni corrections for multiple comparisons).

Outcomes	**p_value**	**BH**	**Holm**	**signBH**	**signHolm**
Vmax - SJ	0.012	0.034	0.192	*	Ns
WorkConc - CMJ	0.014	0.034	0.196	*	Ns
WorkConc_U12 - SJ	0.003	0.029	0.066	*	Ns
Time2FmaxLand_U14 -STIFF	0.009	0.034	0.162	*	Ns
Pmax_U16 - STIFF	0.006	0.031	0.114	*	Ns
Flight Time_U18 - SJ	0.007	0.031	0.126	*	Ns
JumpHeigh_U18 - SJ	0.011	0.034	0.187	*	Ns
RFD_U18 -CMJ	0.003	0.029	0.066	*	Ns
Pmax_U18 - STIFF	0.013	0.034	0.195	*	Ns

RSI_U18 - STIFF	0.018	0.040	0.234	*	Ns
Time2Fmax_U18 - STIFF	0.021	0.042	0.252	*	Ns

Table 3. Descriptive statistics of mean percentage differences for the parameters showing significant changes in SJ and CMJ tests.

Outcomes	**Mean**	**95% CI Lower**	**95% CI Upper**	**SD**	**CV**
% Difference mean_ Flight Time [s]	2.23	0.27	4.19	5.06	2.27
% Difference mean_Vmax [m/s]	4.60	1.28	7.92	8.57	1.86
% Difference mean_ WorkConc [J/Kg]	9.65	0.73	18.6	23.0	2.38

Neuromuscular performance after application of a wearable photobiomodulation device in young tennis athletes

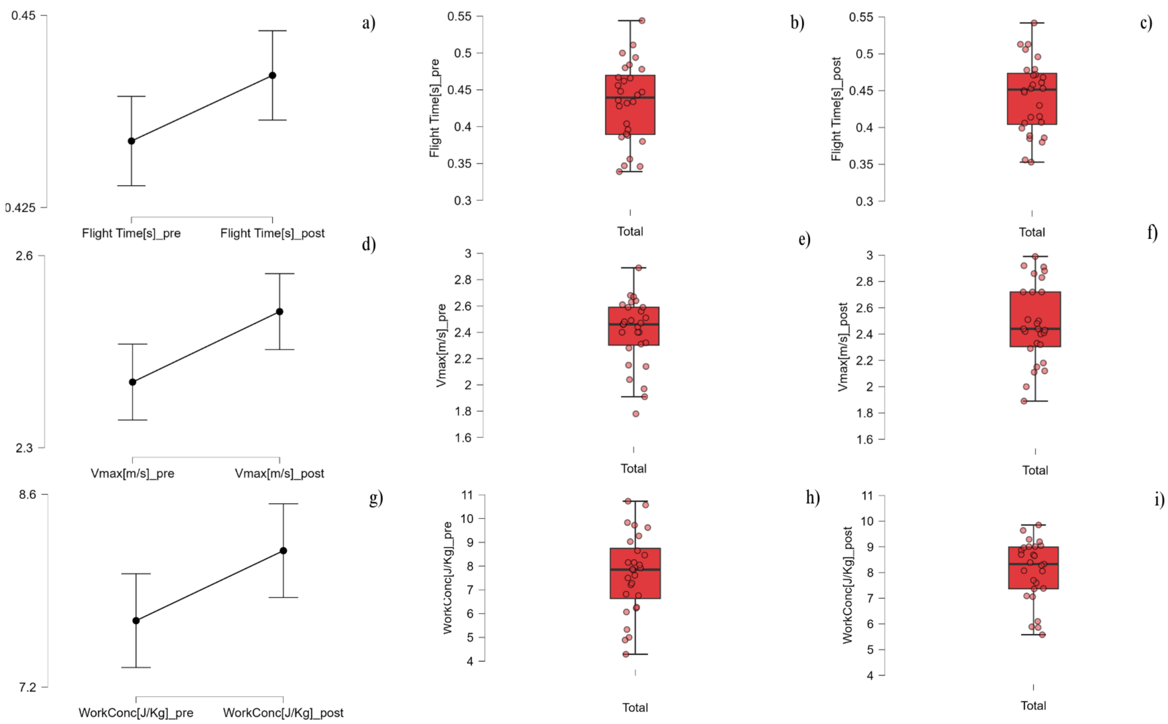


Figure 1. Pre–post comparison of performance variables in SJ and CMJ tests. a-d- g) mean values ± standard error. b–c) Flight Time pre and post. e–f) Vmax pre and post. h-i) WorkConc pre and post. Boxplots show median, quartiles, and individual data points.

Neuromuscular performance after application of a wearable photobiomodulation device in young tennis athletes

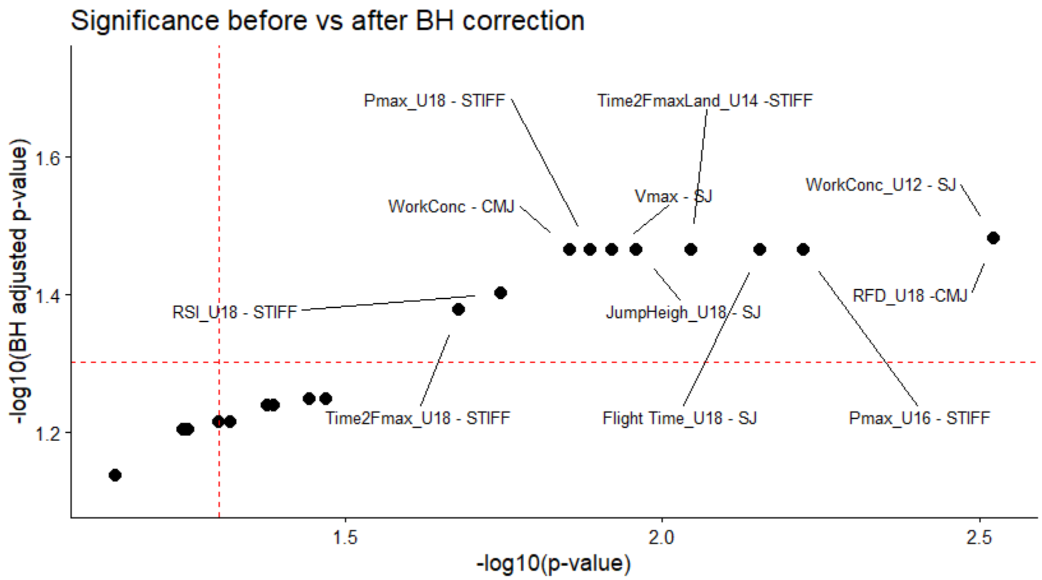


Figure 2. Comparison of statistical significance before and after Benjamini–Hochberg (BH) correction. The x-axis shows unadjusted −log10(p-values), and the y-axis shows BH-adjusted −log10(p-values). The red dashed line indicates the significance threshold corresponding to p = 0.05. Variables above the threshold line remain significant after correction, whereas those below the threshold are not significant after correction and are not labeled in the figure.

Neuromuscular performance after application of a wearable photobiomodulation device in young tennis athletes

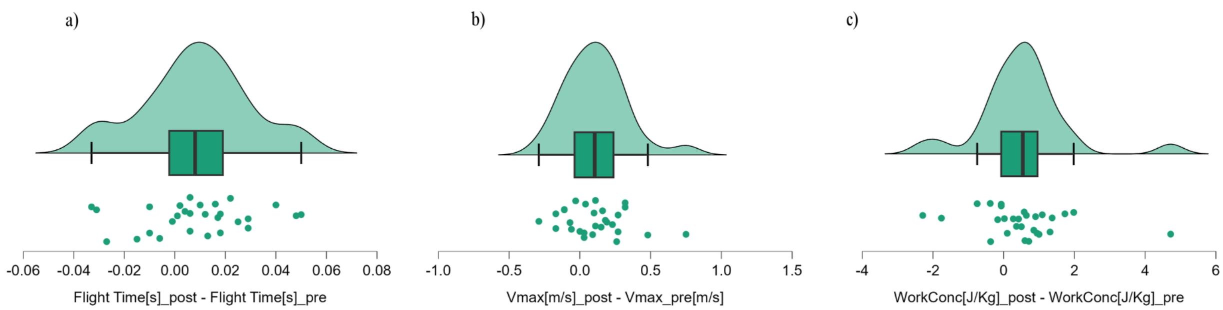


Figure 3. Post-pre differences in significant parameters in SJ and CMJ tests: a) Flight Time; b) Maximum Velocity; c) Concentric Work. Positive values indicate an increase after the intervention, while negative values indicate a decrease. The plot displays individual data points, the distribution of changes, and boxplots to provide a complete and transparent representation of the results.