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ORIGINAL ARTICLE

A pilot study on the effects of far-infrared-emitting fabric on neuromuscular performance of knee extensor and male fertility

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Abstract
The aim of this study was to evaluate the time course of the effects of far-infrared emitting fabric (FIR) on neuromuscular performance of knee extensor over 120 h and to investigate whether the use of FIR affects semen. This is a crossover, randomized, double-blind, and placebo-controlled trial split into neuromuscular and fertility assessments. Four (28.8 ± 4.7 years old) and six (29 ± 3.9 years old) healthy, resistance-trained males completed all neuromuscular and fertility assessments, respectively. In neuromuscular assessments, for five consecutive days, the participants underwent neuromuscular tests in an isokinetic dynamometer (maximal isometric voluntary contraction (MVC) and fatigue test) every 24 h in both conditions (FIR and Placebo). In fertility assessments, participants performed three semen collections: Baseline, FIR, and Placebo. FIR and Placebo collections were performed after five consecutive days of use of the pants. Conventional parameters and sperm DNA fragmentation were evaluated. In the FIR condition, the participants showed significant differences in total work at 96 h ($p < 0.001$; Cohen's $d = 3.73$), 120 h ($p = 0.01$; Cohen's $d = 2.65$), and pre-MVC at 120 h ($p = 0.02$; Cohen's $d = 2.15$) when compared to Placebo. FIR did not significantly ($p > 0.05$) affect the conventional semen parameters or sperm DNA fragmentation compared to Baseline or Placebo. FIR improved the knee extensor neuromuscular performance of healthy resistance-trained individuals, with 112.4 ± 7.8 h accumulated, and did not affect their seminal parameters (conventional or sperm DNA fragmentation), with 113.1 ± 10.2 h accumulated.

Keywords Exercise · Low-level light therapy · Photobiomodulation · Muscle fatigue · Time factors

Introduction

According to Anders, Lanzafame, and Arany [1], photobiomodulation therapy (PBMT) is a form of light therapy based on the use of different nonionizing light sources within the visible and infrared (IR) spectrum capable of triggering photochemical and photophysical events at different biological levels with positive therapeutic effects.

Since the pioneering study by Vinck et al. [2] that investigated the effects of photobiomodulation (PBM) on neuromuscular parameters, studies with PBMT and physical performance have grown considerably. Currently, we know that muscle conditioning (pre, during, and/or post-session) through PBMT is able to improve physical performance [3] within certain recommendations [4]. However, we know that the effects of PBM are not limited to red light and near IR [5]. Far-IR also has biological effects [6] and potential ergogenic effects, although the data are still inconclusive [7].

Albeit the main far-IR photoreceptor is the water cluster [8, 9], we can observe very similar effects to red light and near-IR mediated by cytochrome c oxidase (CCO) [10] that could improve physical performance, for example, improvement in mitochondrial ATP biosynthesis [11], nitric oxide production [12], and endothelial function [13] and delay onset of muscle fatigue [14]. Some volcanic lava granites and oxide minerals are capable of radiating far IR [15] when excited. These elements can be processed into nanoparticles and such particles can be incorporated into textile materials [6], ensuring PBM effects in a versatile, practical, and energy-independent way, becoming an alternative to

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traditional modes in PBMT (lasers and/or LED). However, far-IR irradiation through ceramic materials incorporated in textile materials could impose longer radiation exposure times due to the low amount of energy carried by the far-IR [6], given the biphasic dose–response PBM effect depending on the radiated energy [16].

Recently, some studies with far-IR-emitting fabric have shown positive effects on physical performance when there is a build-up of at least 4 days of use [17–20]. Silva et al. [18], by almost entirely replicating the protocol proposed by Baroni et al. [21], found significant increases for pre-MVC and post-MVC and a trend toward increased total knee extensor work (fatigue test) compared to placebo after the participants had accumulated 82 ± 19 h with far-IR-emitting fabric.

Thus, the aim of this study was twofold: first, to evaluate the time course of the effects of far-IR-emitting fabric (FIR) on neuromuscular performance of knee extensor in voluntary contractions over 120 h in healthy resistance-trained males and, second, to investigate whether the use of FIR affects semen parameters since the genital region would be being irradiated, and traditional PBMT has been used in the treatment of male infertility [22] and presents promising results [23–25].

Materials and methods

The study was a crossover, randomized, double-blind, placebo-controlled trial. The study was split into neuromuscular and fertility assessments. First, the participants performed all neuromuscular assessments in both conditions (FIR and Placebo). Afterwards, a washout of at least one week was given, and the participants were invited to perform the seminal collections in both conditions.

Participants

Four young healthy resistance-trained males (age: 28.8 ± 4.7 years; body mass: 81.1 ± 5.6 kg; height: 174.8 ± 2.9 cm; body mass index: 26.6 ± 2.3 kg/m^2; RT experience: 12 ± 6 years) and six young healthy resistance-trained males (age: 29 ± 3.9 years; body mass: 79.1 ± 11.7 kg; height: 174.8 ± 4.8 cm; body mass index: 25.8 ± 3 kg/m^2; RT experience: 12.7 ± 5.4 years) volunteered as subjects to participate in this study in neuromuscular and fertility assessments, respectively. The subjects were recruited from a university population and local gym (convenience sample). The inclusion criteria were as follows: (1) male individuals between 18 and 34 years old, (2) undergoing RT three or more times a week for 1 year continuously, and (3) a declared willingness to participate in the experimental procedures. The exclusion criteria were as follows: (1) musculoskeletal and/or joint injuries in the dominant lower limb up to 6 months prior to the study, (2) not wearing the pants, (3) exhibiting some muscle discomfort and/or joint during the neuromuscular test (just to neuromuscular assessment), (4) using steroids and/or another ergogenic aid, (5) having trained lower limbs up to 6 h before the test (just to neuromuscular assessment), (6) being a cyclist (practice/train cycling frequently and continuously), and (7) being a smoker. This study was approved by the local ethics committee and was conducted according to the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. All subjects were informed of the inherent risks and benefits prior to signing an informed consent form.

The sample approved by the local ethics committee was 14 participants based on Silva's study [18]. However, the coronavirus pandemic has affected our recruitment, and therefore, the present study must be considered as a pilot study.

Randomization and blinding procedures

The initial conditions (FIR and Placebo) were randomly drawn from opaque sealed envelopes (simple randomization). The groups were balanced and matched based on the numbers of participants in each initial condition. Two randomizations were performed, one for neuromuscular and one for fertility assessments. Neither participant nor evaluators knew if pants were FIR or Placebo during data collection and analysis. The only identification of pants was different tags to avoid confounding conditions, which were only revealed at the end of the study after analyzing all the data.

Far-infrared-emitting fabric (FIR)

The FIR is composed of a fabric with EMANA® technology (Rhodia Poliamida Especialidades LTDA) and emissive properties within the far-IR (> 3 µm). For more details about this fabric, see Silva et al. [18]. Placebo fabric is similar to FIR but does not have emissive properties. In addition, we used the same equations proposed by Silva et al. [18] to estimate the energy density and total irradiated energy.

Procedures

Neuromuscular

Neuromuscular assessments were carried out at the Galileo Hospital and Maternity (Valinhos, São Paulo, Brazil) between June and August 2021. All sanitary protocols were respected. The tests were performed on the isokinetic dynamometer Cybex® Isokinetic System (Cybex Division of Lumex Inc., Ronkonkoma, New York, USA). At this time, we evaluated the time course of the effects far-IR emitted by fabric (FIR) on neuromuscular performance of the knee extensor of healthy resistance-trained males.

First, the participants completed a familiarization and baseline session, separated by at least 48 h. Then, the participants underwent five successive experimental sessions (initial condition) separated by 24-h intervals, which were identical to the familiarization and baseline sessions. The participants were instructed to wear the FIR or Placebo pants continuously, for as long as possible, during the experimental 5-day period, removing them only for physical activity and personal hygiene. The experimental sessions began on Monday (24 h) and ended on Friday for a total of 120 h. Participants were instructed to start wearing the pants on Sunday so that on Monday, they had accumulated approximately 24 h of use before the first experimental session. The experimental protocol and all procedures have previously been described in detail [18]. In short, the participants were submitted to the maximal isometric voluntary contraction (MVC) test and fatigue test every 24 h, in which we evaluated the peak torque (Nm), total work (J), and fatigue index (%) of the knee extensor muscles. After the first five experimental sessions, a washout period of 1 week was given to reverse the conditions and repeat the procedures. All participants were instructed to maintain their physical activity pattern (upper limbs) and diet during the study period; for the lower limbs, participants were asked not to perform any additional/different exercise than usual, and if they trained on the day of the experimental session, they had to plan their training routine so that there was at least 6 h of rest between their training session and the experimental session, but no participants trained their lower limbs during the study. The CONSORT flowchart of neuromuscular assessment is shown in Fig. 1.

Fertility

All collections were carried out at the "Fertility and Life" Clinic (Campinas, São Paulo, Brazil) between August and September 2021. All sanitary protocols were respected. No participant reported loss of seminal sample during collections. All samples were discarded at the end of the analysis. In addition, before the collections, the participants answered a questionnaire about a history of fever, mumps, sexually transmitted diseases, cryptorchidism, vasectomy, consumption of drugs, alcoholic beverages and tobacco products, and exposure to toxic materials to control for confounding factors. At this time, we investigated whether the use of FIR affects the semen parameters of healthy resistance-trained males.

Initially, a semen sample was collected (self-masturbation) to characterize the participant's baseline (Baseline). Then, another semen collection was performed after the participant wore the pants (FIR or Placebo) for five consecutive days. Participants were instructed to accumulate as many as hours as possible pre-collection wearing their pants and should only remove them for physical activity and personal hygiene. After collection, a washout week was granted to reverse the condition, and the participant performed a new semen collection in the other condition. For semen collections, the participant was asked to abstain from sex and/or masturbation and alcohol consumption for at least 24 h (1 day) before collection. An experienced andrologist blinded to the conditions evaluated liquefaction, semen

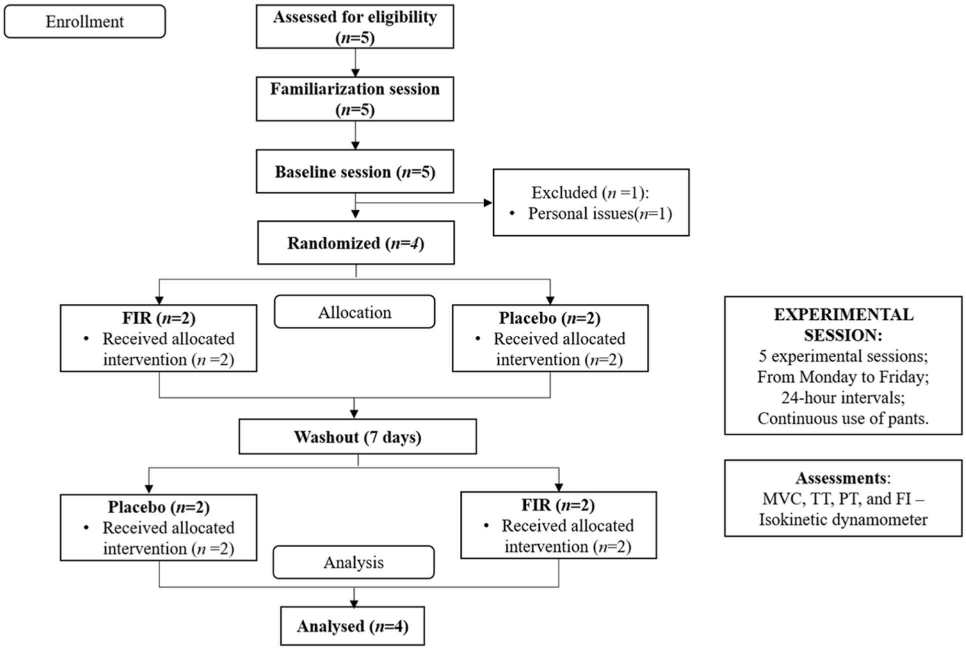

Fig. 1 CONSORT flowchart of neuromuscular assessment. FI, fatigue index in the fatigue test; MVC, maximal isometric voluntary contraction; PT, peak torque in the fatigue test; TT, total work in the fatigue test

volume, sperm concentration, total sperm number, motility, pH, morphology, vitality (i.e., conventional parameters), and sperm DNA fragmentation (Halosperm HT-HSG2 kit; Halotech®, Madrid, Spain).

A sterile plastic bottle was provided for the participant to collect their entire semen sample. The flask was kept between 20 and 37 °C and then placed on a heated plate at 37 °C inside the flow so that the semen liquefied and was then analyzed. Briefly, conventional parameters and sperm DNA fragmentation were processed as described by the World Health Organization (WHO) guidelines [26] and Fernández et al. [27], respectively. The CONSORT flowchart of fertility assessment is shown in Fig. 2.

Statistics

Despite the possible low statistical power due to the low number of participants, standardized statistical methods were used. The normality of the data was evaluated with the Shapiro–Wilk test. The homogeneity of variance was evaluated with the Levene test. For neuromuscular assessments, we used a one-way variance analysis (ANOVA) of repeated measures with Geisser-Greenhouse correction for analysis of the time effect and paired *t* test within moments (i.e., 24 h, 48 h, 72 h, 96 h, and 120 h) between conditions (i.e., FIR vs. placebo) to identify possible differences. In addition, the effect size for ANOVA is reported as eta-square (η^2) and interpreted as no effect (<0.01), small (0.01–0.04), medium (0.04–0.11), or large effect (>0.11) [28]. The effect size for the paired *t* test is reported as Cohen's *d* and interpreted according to Rhea [29] considering highly trained individuals: trivial: <0.25, small: 0.25–0.5, moderate: 0.5–1, and large effect: >1. Baseline neuromuscular parameters were compared between initial conditions using an independent *t* test. For fertility assessments, we used one-way repeated-measures ANOVA with Geisser-Greenhouse correction followed by Tukey's post hoc test, when necessary, for the analysis of parametric variables (semen volume, sperm concentration, progressive motility, total motility, immotile spermatozoa, sperm morphology, and fragmentation) and the Friedman test to analyze nonparametric variables (liquefaction, pH, total sperm number, vitality, and abstinence). A paired *t* test was used to verify possible differences in accumulated hours between conditions. Microsoft® Excel® 2016 software (Microsoft Corporation, Redmond, WA, USA) together with the supplement Real Statistics Resource Pack—Release 7.8 (Copyright 2013–2021; Charles Zaiontz. www.real-statistics.com) were used for all statistical analyses. Data are presented as the mean and standard deviation (SD), and the significance level adopted for all comparisons was $p < 0.05$.

Results

Neuromuscular

Initially, five participants ($n = 5$) started the study. However, one participant left after baseline collection, due to personal issues, did not finish the study. Therefore, the final sample analyzed was composed of four participants (age: 28.8 ± 4.7 years; body mass: 81.1 ± 5.6 kg; height: 174.8 ± 2.9 cm; body mass index: 26.6 ± 2.3 kg/m^2; RT experience: 12 ± 6 years). There were no significant differences in baseline neuromuscular parameters between initial conditions (Table 1). There was no significant difference ($p > 0.05$) for the total hours accumulated between conditions (FIR: 112.4 ± 7.8 h; Placebo: 114.8 ± 5.1 h;

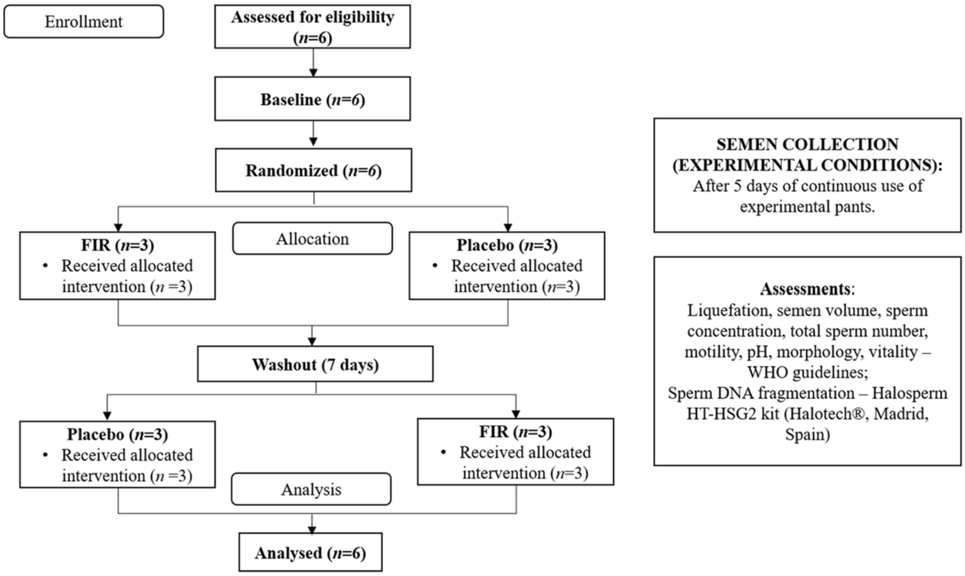

Fig. 2 CONSORT flowchart of fertility assessment

Table 1 Baseline neuromuscular parameters

Parameter	All ($n=4$)	FIR ($n=2$)	Placebo ($n=2$)	p value
Pre-MVC (Nm)	301.8 ± 28.8	306.7 ± 16.2	297 ± 46.1	0.81
Post-MVC (Nm)	257.9 ± 50.4	277.2 ± 69.7	238.7 ± 35.9	0.56
ΔMVC (%)	− 14 ± 17	− 8.9 ± 27.5	− 19.6 ± 0.4	0.68
TT (J)	4070.3 ± 521.3	3727.5 ± 244	4413 ± 534.6	0.24
PT (Nm)	167.1 ± 27.5	163.7 ± 22.6	170.4 ± 41.3	0.86
FI (%)	26.2 ± 8.7	24.5 ± 6.4	34 ± 8.5	0.33

FI, fatigue index; *pre-MVC*, maximal isometric voluntary contraction pre-fatigue test; post-MVC, maximal isometric voluntary contraction post-fatigue test; *PT*, peak torque in fatigue test; *TT*, total work in fatigue test; *ΔMVC*, delta between pre-MVC and post-MVC. Independent *t* test

All data are reported as the mean ± SD

$p=0.28$). On average, the participants wore FIR for 22.5 ± 1.8 h/day and Placebo for 23 ± 1.4 h/day. In the FIR condition, we estimate that the participants accumulated a total of 433.6 ± 30.2 kJ energy and a density of 54.2 ± 3.8 J/cm^2 (see Table 2).

There was no time effect in the pre-MVC to FIR ($F=3$; $p=0.12$; $\eta^2=0.5$, large effect) or Placebo condition ($F=0.62$; $p=0.58$; $\eta^2=0.17$, large effect). However, there was a significant difference between FIR vs. Placebo at 120 h ($p=0.02$; Cohen's $d=2.15$, large effect) (see Table 3). At 24 h, 48 h, 72 h, and 96 h, two out four participants showed improvements in the FIR condition compared to Placebo condition. At 120 h, all participants showed improvements in the FIR condition compared to Placebo condition.

In the post-MVC, we did not find time effect on FIR ($F=0.14$; $p=0.83$; $\eta^2=0.05$, medium effect) or Placebo condition ($F=0.62$; $p=0.57$; $\eta^2=0.17$, large effect). The paired T test did not identify any significant differences between conditions (see Table 3). The same behavior was observed for Δ%MVC. There was no time effect on FIR ($F=3.54$; $p=0.11$; $\eta^2=0.54$, large effect) or Placebo condition ($F=1.11$; $p=0.37$; $\eta^2=0.27$, large effect), or in differences between conditions (see Table 3).

In the fatigue test, no time effect was found in the TT to FIR ($F=1.01$; $p=0.41$; $\eta^2=0.25$, large effect) or Placebo conditions ($F=0.96$; $p=0.43$; $\eta^2=0.24$, large effect). Nevertheless, there was a significant difference between FIR vs. Placebo at 96 h ($p<0.001$; Cohen's $d=3.73$, large effect)

Table 2 Estimate of total irradiated energy and energy density over 5 days ($n=4$)

Parameter	24 h	48 h	72 h	96 h	120 h
Total irradiated energy (kJ)	89.5 ± 8.5	175.8 ± 16.8	261.9 ± 16.3	349.4 ± 20.8	433.6 ± 30.2
Energy density (J/cm^2)	11.2 ± 1.1	22 ± 2.1	32.7 ± 2	43.7 ± 2.6	54.2 ± 3.8
Accumulated hours (h)	23.2 ± 2.2	45.6 ± 4.4	67.9 ± 4.2	90.5 ± 5.4	112.4 ± 7.8

All data are reported as the mean ± SD

Table 3 Neuromuscular parameters ($n=4$)

Parameter	Condition	24 h	48 h	72 h	96 h	120 h	Time effect		
							F	p	η^2
Pre-MVC (Nm)	FIR	323.3 ± 65.6	329.2 ± 40.7	331.8 ± 47.8	332.2 ± 54.8	366.9 ± 51*	3	0.12	0.5
	P	321 ± 23.7	325.8 ± 34.2	336.5 ± 23.2	337 ± 37.1	326.4 ± 53.2	0.62	0.58	0.17
Post-MVC	FIR	304.6 ± 70.6	300.2 ± 42.6	305.2 ± 53.5	302.3 ± 58.5	309.9 ± 72.8	0.14	0.83	0.05
	P	296.9 ± 62	300.4 ± 51.8	297.6 ± 65	296.6 ± 53.3	307.5 ± 62.9	0.62	0.57	0.17
ΔMVC (%)	FIR	−5 ± 14	−9 ± 11	−8 ± 12	−9 ± 9	− 16 ± 11	3.54	0.11	0.54
	P	−8 ± 17	−8 ± 11	− 12 ± 14	− 13 ± 10	−5 ± 11	1.11	0.37	0.27
TT (J)	FIR	4677.8 ± 759.1	4670.3 ± 740.9	4680.3 ± 836.5	4833 ± 820.9*	4848.8 ± 829.6*	1.01	0.41	0.25
	P	4599.3 ± 539.7	4634.5 ± 580.3	4700 ± 792.4	4556.3 ± 815.5	4445.5 ± 801.9	0.96	0.43	0.24
PT (Nm)	FIR	173.8 ± 14.8	174.2 ± 9.8	176 ± 8.8	169.3 ± 9.3	174.4 ± 13.1	0.49	0.62	0.14
	P	170.1 ± 17.1	166.3 ± 21.8	172.8 ± 20.8	168.6 ± 21.2	169 ± 16	0.52	0.6	0.15
FI (%)	FIR	28.1 ± 5.6	27.3 ± 6.1	29 ± 6.5	26.8 ± 4.7	28.1 ± 6.2	0.37	0.61	0.11
	P	26.2 ± 9.8	27.4 ± 11.7	28.8 ± 6.6	26.5 ± 10.7	28.8 ± 4.2	0.34	0.72	0.10

FI, fatigue index; *pre-MVC*, maximal isometric voluntary contraction pre-fatigue test; *post-MVC*, maximal isometric voluntary contraction post-fatigue test; *P*, Placebo; *PT*, peak torque in fatigue test; *TT*, total work in fatigue test; *ΔMVC*, delta between pre-MVC and post-MVC

*Indicates a significant ($p<0.05$) difference between conditions (FIR vs. Placebo; paired *t* test)

All data are reported as the mean ± SD

and at 120 h ($p=0.01$; Cohen's $d=2.65$, large effect) (see Table 3). At 24 h, 48 h, and 72 h, two out four participants showed improvements in the FIR condition compared to Placebo condition. At 96 h and 120 h, all participants showed improvements in the FIR condition compared to Placebo condition.

There was no time effect in the PT to FIR ($F=0.49$; $p=0.62$; $\eta^2=0.14$, large effect) or Placebo condition ($F=0.52$; $p=0.6$; $\eta^2=0.15$, large effect), or in differences between conditions (see Table 3). For FI, again, there was no time effect on FIR ($F=0.37$; $p=0.61$; $\eta^2=0.11$, medium effect) or Placebo condition ($F=0.34$; $p=0.72$; $\eta^2=0.10$, medium effect), or in differences between conditions (see Table 3).

Data from neuromuscular performance assessments are shown in Table 3.

There were no serious adverse occurrences related to FIR.

Fertility

Three out of four participants of neuromuscular assessments participated in this moment, and another three new participants were recruited. Therefore, six participants composed the final sample (age: 29 ± 3.9 years; body mass: 79.1 ± 11.7 kg; height: 174.8 ± 4.8 cm; body mass index: 25.8 ± 3 kg/m^2; RT experience: 12.7 ± 5.4 years). For baseline collection, participants reported sexual abstinence of 2.5 ± 1.4 days and had normal semen samples (i.e., normozoospermia) [26] (see Table 4).

There was no main effect for liquefaction ($Q=0.11$; $p=0.95$), semen volume ($F=0.4$; $p=0.65$; $\eta^2=0.07$, medium effect), pH ($Q=1.08$; $p=0.58$), total sperm number ($Q=1$; $p=0.61$), sperm concentration ($F=0.005$; $p=0.99$; $\eta^2=0$, no effect), total motility ($F=0.06$; $p=0.93$; $\eta^2=0.01$, small effect), progressive motility ($F=0.89$; $p=0.43$; $\eta^2=0.15$, large effect), immotile spermatozoa ($F=0.06$; $p=0.93$; $\eta^2=0.01$, small effect), vitality ($Q=2.7$; $p=0.26$), sperm morphology ($F=4.07$; $p=0.06$; $\eta^2=0.45$, large effect), or abstinence ($Q=0.8$; $p=0.67$) (see Table 3).

There was a main effect for fragmentation ($F=4.81$; $p=0.04$; $\eta^2=0.49$, large effect); however, in Tukey's post hoc test, no significance difference was identified between FIR vs. Baseline ($p=0.2$), FIR vs. Placebo (0.7), and Placebo vs. Baseline ($p=0.07$).

Participants reported sexual abstinence of 2.1 ± 1 and 2.3 ± 1 days and accumulated 113.1 ± 10.2 and 114.6 ± 9.1 h (pre-collection) under FIR and Placebo conditions, respectively, with no significant difference between conditions ($p=0.7$). Under FIR condition, we estimated that the total irradiated energy and energy density were 436.5 ± 39.4 kJ and 54.6 ± 4.9 J/cm^2 (accumulated values), respectively.

Regardless of condition, all samples had parameters within the normal ranges (i.e., normal samples; normozoospermia). There were no serious adverse occurrences related to FIR.

Discussion

Neuromuscular

The main finding was that far-IR irradiated by textile material (FIR) over 120 h improved some neuromuscular parameters of the physical performance of knee extensor

Table 4 Spermogram ($n=6$)

Parameter	Baseline	FIR	Placebo	Time effect		
				F or *Q*	*p*	η^2
Liquefaction (min)*	13.7 ± 4.8	13.3 ± 2.6	12.5 ± 2.7	0.11	0.95	-
Semen volume (ml)#	3.2 ± 0.6	3.1 ± 1	3.5 ± 1	0.4	0.65	0.07
pH*	8 ± 0.2	8.2 ± 0.4	8.1 ± 0.1	1.08	0.58	-
Total sperm number (10^6 per ejaculate)*	346.7 ± 237.9	302.6 ± 184.7	350.8 ± 154.3	1	0.61	-
Sperm concentration (10^6 per ml)#	101.7 ± 54.4	100.8 ± 61.2	99.7 ± 24.3	0.005	0.99	0
Total motility (PR + NP, %)#	70.3 ± 6.5	69.2 ± 8.2	69.8 ± 5.5	0.06	0.93	0.01
Progressive motility (PR, %)#	62.2 ± 9	57.2 ± 7.8	59.2 ± 8.2	0.89	0.43	0.15
Immotile spermatozoa (%)#	29.7 ± 6.5	30.8 ± 8.2	30.2 ± 5.5	0.06	0.93	0.01
Vitality (live spermatozoa, %)*	82.2 ± 8.6	85 ± 11.8	90.2 ± 8.6	2.7	0.26	-
Sperm morphology (normal forms, %)#	5.8 ± 1.5	7.8 ± 1.5	8.7 ± 2.3	4.07	0.06	0.45
Fragmentation (%)#	12.3 ± 5.9	7.8 ± 4	6.3 ± 2.8	4.81	0.04	0.49
Abstinence (days)*	2.5 ± 1.4	2.1 ± 1	2.3 ± 1	0.8	0.67	-

NP, nonprogressive motility; *PR*, progressive motility

*Nonparametric data (Friedman test); #parametric data (one-way ANOVA)

All data are reported as the mean ± SD

(pre-MVC and TT) of resistance-trained males when compared to Placebo.

Over 120 h (5 days), participants accumulated 112.4 ± 7.8 h (433.6 ± 30.2 kJ; 54.2 ± 3.8 J/cm^2) with the FIR. Depending on the parameter evaluated, for example, TT, we can observe performance improvements with 90.5 ± 5.4 h accumulated (349.4 ± 20.8 kJ; 43.7 ± 2.6 J/cm^2). However, after accumulation for 112.4 ± 7.8 h (433.6 ± 30.2 kJ; 54.2 ± 3.8 J/cm^2), the participants showed performance improvements in two out of four parameters evaluated. Therefore, it seems that the participant should accumulate at least 112.4 ± 7.8 h with the FIR to optimize the neuromuscular performance of the knee extensor in short-duration and high-intensity tasks (study protocol). These findings are corroborated by Silva et al. [18], in which participants accumulated 82 ± 19 h with the FIR (317 ± 74 kJ; 40 ± 9 J/cm^2) and showed significant improvements for pre-MVC and post-MVC and a tendency to TT compared to Placebo.

Other studies that investigated the effect of far-IR irradiation by ceramic and/or textile materials on physical performance and other physiological markers, which show positive effects, also point to at least 80 h of far-IR exposure [17, 19, 20], consistent with the dose-dependent PBM effect of irradiated energy [16] since far-IR has a longer wavelength compared to the other subdivisions of the IR, consequently carrying a smaller amount of energy [6] and demanding a longer exposure time.

We did not find a significant effect for post-MVC, PT, or FI. It is interesting to highlight that PT represents the peak torque in the fatigue test, that is, the highest torque peak among the 30 contractions. If we look at the behavior of each contraction, we could observe a higher torque peak in the FIR condition in a greater number of contractions compared to Placebo, but not significantly different (data not shown), corroborating the higher TT.

Recently, some studies radiating energy in the thousands of Joules in relatively short time intervals, 15 min [30] and 5 min [31], reported the absence of PBMT effects on physiological markers and physical performance. Disregarding the limitations of the irradiation methods used that are known to affect the effects of PBM, we can speculate that, in addition to the dose of total irradiated energy, the time window in which this energy is supplied (energy deposition rate) is also very important, given our findings and other studies that used similar technology in which the radiated energy was distributed for longer periods of time, consistent with the Arndt–Schulz law and the effect of homeostatic facilitation caused by PBMT. It is worth mentioning that our sample was composed of highly trained individuals, that is, any intervention capable of improving performance in this population is extremely significant, given its lower adaptability.

The main mechanism investigated and associated with improved physical performance linked to PBMT is the optimization of mitochondrial energy metabolism mediated by CCO [10]. However, after photon absorption by photo acceptors (e.g., CCO, porphyrins, flavins, water), there is the activation of numerous key enzymes, which amplify the effects of PBM, altering redox status and cellular permeability, modulating ionic concentrations, among other effects [32] capable of affecting physical performance.

Looking at the physical demand in pre-MVC and the moment of its occurrence (i.e., beginning of the experimental session), we believe that the main mechanism associated with PBMT and performance improvement is improvement in Ca^{2+} bioavailability [12] through a direct effect on Ca^{2+} and/or indirect channels mediated by ATP and ROS [33]. Regarding the fatigue test, in which we identified significant increases for TT, it is possible that the optimization of mitochondrial metabolism [11], associated with an improvement in peripheral microcirculation by NO-related pathways [34], and consequently better nutritional intake and removal of metabolic residues, and a reduction of oxidative stress [35], may have favored the production of work and/or delayed/mitigated the process of neuromuscular fatigue [14].

In summary, 112.4 ± 7.8 h accumulated (433.6 ± 30.2 kJ) with FIR optimized the neuromuscular performance of knee extensor in high-intensity and short-duration tasks (pre-MVC and TT) of resistance-trained males. However, some limitations should be noted. First, our sample size, although we found significant differences with effect sizes ranging from small to large, more studies with a larger sample size are needed since, with the reduction of the sample size, there is an increase in the probability of occurrence of type II error. Second, FIR is a relatively recent technology, and there is no recommendation of any kind as to the time of use. Here, with 112.4 ± 7.8 h accumulated, the performance of knee extensor of resistance-trained males was optimized. Nevertheless, it is possible that such exposure may vary according to the participant's conditioning status, type of physical demand, and/or the combination of both factors. Third, no type of molecular analysis was performed.

Fertility

To our knowledge, this is the first study to investigate whether the use of FIR affects semen parameters. The main finding was that far-IR irradiation by FIR did not affect the semen quality of healthy resistance-trained individuals of reproductive age, but without evidence of fertility, after accumulating 113.1 ± 10.2 h (436.5 ± 39.4 kJ; 54.6 ± 4.9 J/cm^2). However, FIR proved to be safe within parameters irradiated and accumulated, as it did not present adverse effects on the seminal parameters. All conventional parameters showed values within the normal range [26] and DNA fragmentation below the threshold of 20% [37].

It is expected that mitochondrial function and pathways modulated by ATP availability are preserved in normal semen samples, consequently sperm motility as well, since flagellum movement is highly dependent on mitochondrial energy metabolism and intracellular calcium modulation [25, 38]. Thus, if we consider that one of the main effects observed under PBMT is the improvement of mitochondrial energy metabolism [39], the absence of effects of FIR on participant semen quality is reasonable. It is interesting to note that in our study, due to the characteristics of FIR, PBMT should mainly affect tissues involved in spermatogenesis and perhaps spermatozoa stored in the vas deferens and epididymis, but not semen, unlike studies that apply PBMT directly to sperm samples. Furthermore, due to the effect of abstinence time on DNA fragmentation [40], participants were asked to abstain from sex and/or masturbation for at least 24 h (1 day) pre-collection. Thus, although they accumulated 113.1 ± 10.2 h of use over five consecutive days, the effective accumulated energy dose on the sample spermatozoa (FIR) could be lower, despite the epididymis not being completely emptied in one ejaculation. Therefore, if spermatozoa show a dose–response curve equal to neuromuscular performance, it is plausible that the energy dose accumulated in our study is below the minimum threshold of the therapeutic window since normal samples may also show improvements in motility and energy metabolism, although the effects in abnormal samples are more evident [23–25].

Currently, sperm DNA fragmentation is recognized as an important factor for male infertility [37]. According to Santi et al. [37], 20% is a sensitive and specific cutoff threshold between fertile vs. infertile men. Fragmentation greater than 30% is incompatible with the initiation and/or maintenance of pregnancy [27]. We did not identify effects of far-IR on sperm DNA fragmentation rate in agreement with studies that used other wavelengths [23–25]. Taking into account that sperm are susceptible to damage caused by ROS and other spermatogenesis processes [41], which can damage sperm DNA and consequently its viability, the far-IR irradiation by the FIR of our study shows that this therapeutic modality is safe in terms of damage to sperm DNA.

Juho et al. [42], when investigating the effects of the use of the FIR (underpants) on penile blood flow and sexual satisfaction in subjects with erectile dysfunction, improvement in blood flow was observed, although it did not reach a significant difference compared to the control (Placebo) and in sexual satisfaction (erectile quality) of individuals, particularly among those with severe erectile dysfunction. Although the authors did not perform any seminal evaluation, this study also corroborated prior studies with regarding to the safety of this therapeutic modality from long-term (three months) and functional perspectives.

In short, 113.1 ± 10.2 h accumulated with FIR (436.5 ± 39.4 kJ; 54.6 ± 4.9 J/cm^2) did not affect semen quality (conventional parameters) or sperm DNA fragmentation rate of healthy resistance-trained individuals of reproductive age but without evidence of fertility. Nevertheless, the work has some limitations that must be recognized. First, our sampling constraint. Despite the fertility sample ($n = 6$) being larger than the neuromuscular sample ($n = 4$), it is still small. Second, even though our samples were classified as normal according to WHO criteria [26], two to three baseline collections are recommended to obtain a better-quality average baseline given the large intra- and inter-individual variation, something unfeasible in our work due to our budget constraint. Third, if there is truly an effect of FIR on tissues involved in spermatogenesis, our intervention was too short to observe any effect since the whole process can last up to 74 days. Finally, no analysis of molecular mechanisms was performed. It would be interesting to investigate the effects of far-IR on semen quality from a molecular perspective, as red light and near IR are able to optimize some aspects of semen, and wavelengths can impact cells and tissues differently.

Practical applications

The FIR is able to optimize the neuromuscular performance of knee extensors (pre-MVC and TT) in high-intensity and short-duration tasks (study protocol) after 112.4 ± 7.8-h use (accumulated) and does not affect male fertility up to 113.1 ± 10.2-h use (accumulated) by healthy resistance-trained males of reproductive age, but without evidence of fertility.

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Author contributions All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Manoel Silva, Arthur Gáspari, João Barbieri, Danilo Caruso, Jonatas Nogueira, André Andrade, and Antônio Moraes. The first draft of the manuscript was written by Manoel Silva and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability The authors declare that the data supporting the findings of this study are available within the article.

Declarations

Ethics approval This study was approved by the Ethics Committee of Medicine School of UNICAMP (CAAE: 26420319.2.0000.5404) and was conducted according to the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all individual participants included in the study.

Conflict of interest There are no outside funding and no conflicts of interest to report with regard to this scientific investigation.

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