

Improvement in exercise capacity and delayed anaerobic metabolism induced by far-infrared-emitting garments in active healthy subjects: A pilot study

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Abstract

Background: Far-infrared-emitting garments have several biological properties including the capability to increase blood perfusion in irradiated tissues.

Design: The aim of the study was to evaluate whether far-infrared radiation increases exercise capacity and delays anaerobic metabolism in healthy subjects.

Methods: With a double-blind, crossover protocol, a maximal cardiopulmonary exercise test was performed in 20 volunteers, wearing far-infrared or common sport clothes, identical in texture and colour.

Results: Comparing far-infrared with placebo garments, higher oxygen uptake at peak of exercise and longer endurance time were observed (peak oxygen uptake 38.0 ± 8.9 vs. 36.2 ± 8.5 ml/kg/min, endurance time 592 ± 85 vs. 570 ± 71 seconds; $P < 0.01$); the anaerobic threshold was significantly delayed (anaerobic threshold time 461 ± 93 vs. 417 ± 103 seconds) and anaerobic threshold oxygen uptake and anaerobic threshold oxygen pulse were significantly higher (25.3 ± 6.4 vs. 20.9 ± 5.4 ml/kg/min and 13.3 ± 3.8 vs. 12.4 ± 3.3 ml/beat, respectively). In 10 subjects the blood lactate concentration was measured every 2 minutes during exercise and at peak; lower values were observed with far-infrared fabrics compared to placebo from the eighth minute of exercise, reaching a significant difference at 10 minutes (3.6 ± 0.83 vs. 4.4 ± 0.96 mmol/l; $P = 0.02$).

Conclusions: In healthy subjects, exercising with a far-infrared outfit is associated with an improvement in exercise performance and a delay in anaerobic metabolism. In consideration of the acknowledged non-thermic properties of functionalised clothes, these effects could be mediated by an increase in oxygen peripheral delivery secondary to muscular vasodilation. These data suggest the need for testing far-infrared-emitting garments in patients with exercise limitation or in chronic cardiovascular and respiratory patients engaged in rehabilitation programmes.

Keywords

Far-infrared-emitting fabrics, muscular perfusion, peripheral oxygen delivery, exercise performance, cardiopulmonary exercise test, anaerobic metabolism, anaerobic threshold

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Introduction

Far-infrared radiation (FIR)-emitting fabrics are claimed to be biologically active textiles.^{1–3} Such garments are derived from traditional textile fibres by the incorporation of ceramic particles, which are natural minerals with peculiar electromagnetic absorption and emission properties. After absorbing incoming infrared radiation from the human body, FIR-emitting

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materials re-emit radiative energy at a longer wavelength between 4 and 16 μm , reflecting it back to the body.^{4,5} The emissivity of such engineered textile is a function of the percentage mass of bioceramics embedded into the fabric.⁶

In the band of infrared radiation, only FIR transfers energy in the form of gentle radiant heat with high penetrability in most biological material, up to 4 cm beneath the human skin, where it is perceived by local thermoreceptors.^{4,7,8} In human cells, there are charged groups located at specific molecule sites and associated with water molecules. The interaction between FIR and biological structures determines a vibrational and rotational stimulation of intra-molecular bonds,⁹ thus exerting an influence on the structure and behaviour of the whole molecule, which is proportionate to the water content.⁴ This phenomenon increases the molecular kinetic energy which finally results in local (skin and muscular) temperature rise,^{4,10} tissue vasodilation and therefore the enhancement of blood microcirculation in targeted regions of the body, such as exercising muscles. The same vasodilating effect is also induced by the non-thermic biological properties of FIR.^{1-4,7,8,11}

By the Fick equation, oxygen consumption (VO_2) = cardiac output * arteriovenous oxygen (O_2) difference ($\Delta a-v\text{O}_2$).¹² Consistently, enhanced muscular perfusion could increase peripheral oxygen delivery and thereby improve maximal VO_2 and prolong aerobic metabolism. However, previous studies report contrasting effects of local vasodilation both on global exercise capacity and exercising muscle performance.¹³⁻¹⁶

Therefore, the aim of our study was twofold: (a) to evaluate the timing of anaerobic metabolism; and (b) to assess exercise capacity with a ramp incremental exercise in normal subjects wearing FIR-emitting tissues, as analysed by cardiopulmonary exercise test (CPET).¹⁷

Methods

This is a double-blind, randomised crossover, prospective study comparing the effects on exercise performance of two kinds of sport outfit in healthy volunteers, each of them serving as his or her own control. The outfit consisted of a T-shirt and shorts; one made of polyamide fabrics knitted with ceramic-bearing fibres, and one was the control counterpart, identical in colour, knit structure, texture, thickness and weight but without ceramic-bearing fibres.

As no data were available in the literature regarding the effects of FIR-emitting garments on exercise capacity, we could not establish an adequate sample size a priori and the present research must be considered within the frame of a pilot study.

Twenty healthy recreationally active subjects, already familiarised to CPET, were enrolled in the

study and none of them withdrew from the study protocol. Ten volunteers were tested in an Italian research exercise laboratory and 10 were evaluated by ©NILIT[®] Ltd., who guarantee the quality of the tests as well as the accuracy and truthfulness of the collected data. Similar equipment and protocol were used in both laboratories.

The study adhered to the ethical standards of the Declaration of Helsinki and its later amendments. All subjects signed an informed consent for the exercise procedure and scientific use of data.

Assignment to either outfit was designed in a random order by ©NILIT[®] Ltd. and was concealed to researchers and volunteers. All subjects performed two maximal CPET¹⁸ on a cycle ergometer (Sensor Medics, Yorba Linda, CA, USA), in the same environmental conditions (laboratory temperature 22–23°C, $\leq 50\%$ relative humidity) and separated by one week, wearing either the functionalised or the non-functionalised outfit. Subjects were instructed not to modify their eating habits or training activity throughout the study protocol; in particular the day before the test, participants were asked not to ingest caffeine or alcohol and to refrain from strenuous exercise.

In particular, an individualised ramp protocol was applied, aimed at a test duration of 10 ± 2 minutes,¹⁹ with a progressive workload increase. Ventilation, expired and inspired gases were measured breath by breath²⁰ (V-max 229D Spectra metabolic cart; Sensor Medics, Yorba Linda, CA, USA) and collected data were analysed as a 20 seconds average. During the test, heart rate (HR), 12-lead ECG and pulse oxygen saturation (Radical 7, Masimo, Irvine, California, USA) were continuously monitored.²⁰ Blood pressure was measured every 2 minutes using a cuff sphygmomanometer.²⁰ Exercise was self-limited by the subjects after pushing themselves to exhaustion.

Among all data, oxygen uptake at peak of exercise (peak VO_2) was measured at presumed maximal effort as the highest VO_2 value, averaged over a 20 second period;²¹ it was considered correspondent to maximal VO_2 if the following criteria were achieved: attainment of a plateau in VO_2 graph in spite of incremental work rate, respiratory exchange ratio (RER) of 1.1 or greater and HR of 85% or greater of maximal predicted value. Peak VO_2 was expressed both in absolute value (ml/kg/min) and as a percentage of maximal predicted value ($\text{VO}_2\%$), estimated for each subject according to the Wasserman–Hansen formula.²²

Moreover, peak oxygen pulse (O_2 pulse) was automatically provided by the software. It is the VO_2/HR ratio at peak of exercise and reflects the amount of oxygen consumed per heart beat at the end of a maximal incremental exercise.²²

Furthermore, the anaerobic threshold (AT) was determined using the V-slope analysis from the plot of carbon dioxide production (VCO_2) versus VO_2 on an equal scale^{23,24} and confirmed by the consequent behaviour of carbon dioxide and oxygen end tidal pressures and ventilatory equivalents.²⁵⁻²⁷ O_2 pulse (AT O_2 pulse), time at the AT (AT time) and timing of AT with respect to total endurance time (AT/ET ratio) were reported, as well as VCO_2 (AT VCO_2), HR (AT HR) and oxygen uptake (AT VO_2) expressed both as absolute values (ml/kg/min) and as percentages of predicted maximal oxygen uptake (AT $VO_2\%$).

In 10 volunteers (tested in the Italian research exercise laboratory), a blood sample from an antecubital vein was also drawn for blood lactate concentration (BLC) measurement at rest, every 2 minutes of loaded exercise and at peak.

Finally, a wireless sensor was fixed on volunteers' chests by means of a plaster to monitor the temperature of the microclimate between the skin and the T-shirt.

Statistical analysis

Data are reported as mean \pm standard deviation. Differences between the FIR-emitting outfit and placebo were assessed with a paired Student's *t*-test. A *P* value of less than 0.05 is considered significant. All the statistical analyses were performed using SPSS computer software version 23 (IBM, Chicago, IL, USA).

Results

Twenty healthy subjects (9 women and 11 men) aged between 27 and 57 years (mean 38 ± 12) were enrolled in the study. Mean body mass index, weight and height were, respectively, 24.6 ± 2.8 kg/m², 74.4 ± 11.2 kg and 173.6 ± 9.5 cm. Non-significant differences were observed between placebo and the FIR-emitting outfit as regards CPET parameters at rest.

All subjects performed two maximal tests,¹⁸ both when wearing functionalised and placebo outfits (RER 1.14 ± 0.1 and 1.14 ± 0.1 , respectively; *P* = NS). On the FIR-emitting outfit, maximal exercise capacity was on average significantly higher than on placebo garments as shown by higher peak VO_2 and endurance time (ET) (Table 1 and Figure 1). In particular, peak VO_2 and ET increased in 16 and 12 cases, respectively. In spite of the limitations imposed by the exiguity of the sample, however, neither peak VO_2 and ET obtained with the placebo outfit, nor volunteers' baseline characteristics could identify subjects unable to improve performance with FIR-emitting outfits. Mean VO_2 ^{12,28} increased from 5.3 ± 1.3 ml/kg/min at rest to 38.0 ± 8.9 ml/kg/min at peak of exercise, which

Table 1. Cardiopulmonary exercise test parameters during exercise.

	Functionalised outfit	Placebo outfit	<i>P</i> value
Peak VO_2 (ml/kg/min)	38.0 ± 8.9	36.2 ± 8.5	0.006
Peak VO_2 (%)	116.4 ± 24.5	111.0 ± 24.0	0.005
Peak VCO_2 (l/min)	3.3 ± 1.0	3.1 ± 1.0	0.006
Peak HR (bpm)	171 ± 11	169 ± 11	0.015
Peak O_2 pulse (ml/beat)	16.6 ± 4.7	16.0 ± 4.4	0.020
ET (s)	592 ± 85	570 ± 71	0.009
AT VO_2 (%)	72.8 ± 19.3	64.4 ± 13.9	0.003
AT VO_2 (ml/kg/min)	23.5 ± 6.4	20.9 ± 5.4	0.005
AT O_2 pulse (ml/beat)	13.3 ± 3.8	12.4 ± 3.3	0.030
AT time (s)	461 ± 93	417 ± 103	0.001
AT/ET ratio (%)	79 ± 16	73 ± 18	0.031
AT VCO_2 (l/min)	1.6 ± 0.6	1.4 ± 0.5	0.006
AT HR (bpm)	132 ± 16	126 ± 15	0.001

Peak VO_2 : oxygen uptake at peak of exercise; Peak VO_2 (%): oxygen uptake at peak of exercise, expressed as percentage of predicted maximal oxygen uptake; Peak VCO_2 : carbon dioxide production at peak of exercise; Peak HR: heart rate at peak of exercise; Peak O_2 pulse: oxygen pulse at peak of exercise; ET: endurance time; AT VO_2 : oxygen uptake at the anaerobic threshold; AT VO_2 (%): oxygen uptake at the anaerobic threshold, expressed as percentage of predicted maximal oxygen uptake; AT O_2 pulse: oxygen pulse at the anaerobic threshold; AT time: time of exercise at the anaerobic threshold; AT/ET ratio: ratio between time of exercise at the anaerobic threshold and endurance time; AT VCO_2 : carbon dioxide production at the anaerobic threshold; AT HR: heart rate at the anaerobic threshold.

corresponds to $116.4 \pm 24.5\%$ of predicted maximal VO_2 , with FIR-emitting outfits, and from 5.3 ± 1.4 ml/kg/min at rest to 36.2 ± 8.5 ml/kg/min at peak, which is $111.0 \pm 24.0\%$ of predicted maximal VO_2 with the placebo garments. Accordingly, peak VCO_2 , peak HR and peak O_2 pulse¹⁸ were significantly higher with functionalised outfits (Table 1).

The AT was significantly delayed with bioceramics, as demonstrated by longer AT time and AT/ET ratio with FIR-emitting garments in comparison to placebo; furthermore, AT VO_2 , AT O_2 pulse and consequently AT VCO_2 and AT HR were significantly higher in functionalised versus placebo outfits (Table 1).

No significant differences were observed for ventilation¹⁸ at peak of exercise (93.1 ± 26.11 /min with the FIR-emitting outfit vs. 88.5 ± 19.61 /min with placebo; *P* = 0.156).

Finally, BLC did not differ significantly between the two garments until the eighth minute of exercise, while afterwards a significantly higher lactate concentration was observed with the placebo outfit compared to functionalised garments (at 10 minutes, respectively, 4.4 ± 0.96 vs. 3.6 ± 0.83 mmol/L; *P* = 0.02; Figure 2). Such a significant difference of BLC between the two

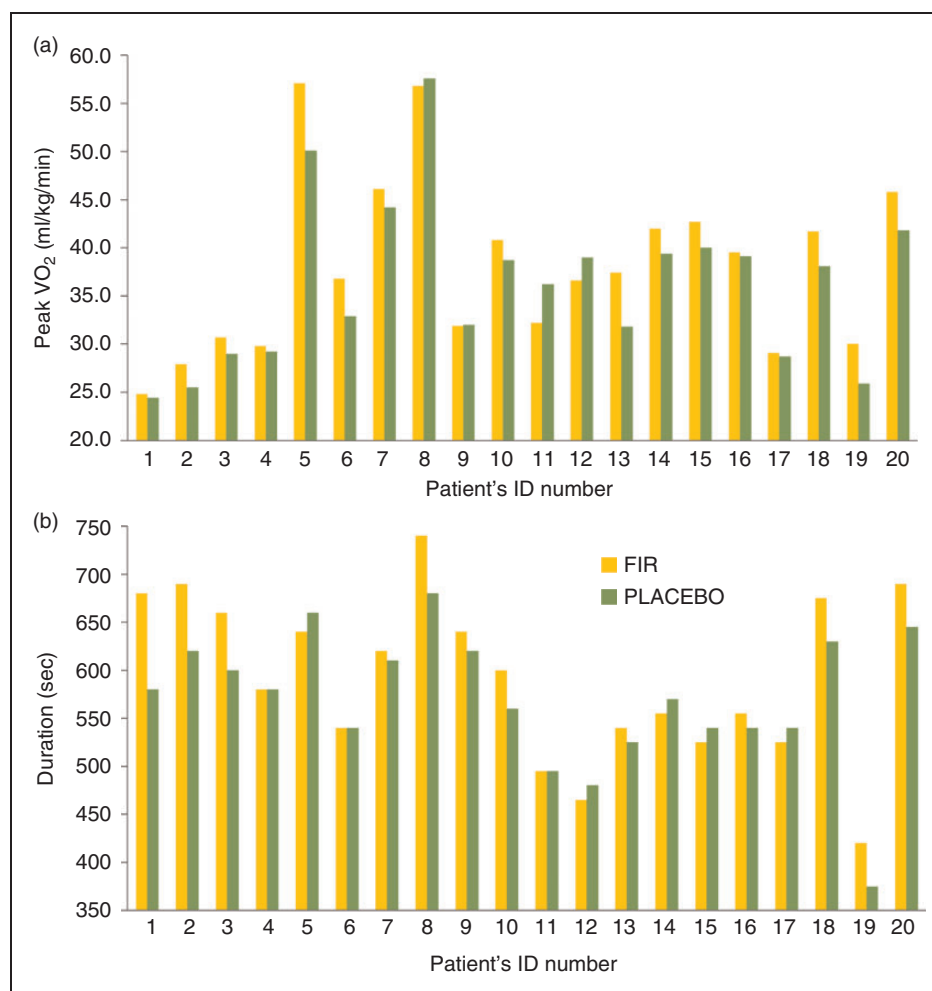


Figure 1. (a) Peak oxygen uptake of each subject performing a maximal cardiopulmonary exercise test, respectively wearing functionalised and placebo garments. (b) Endurance time of each subject performing a maximal cardiopulmonary exercise test, respectively wearing functionalised and placebo garments.

Peak VO_2 : oxygen uptake at peak of exercise; FIR: far-infrared radiation-emitting garments.

test conditions was correspondent to an average 20% lower BLC concentration with the FIR-emitting versus non-functionalised outfit.

From the analysis of microclimate mean temperatures during exercise, no significant differences emerged between functionalised and placebo garments (29.9 ± 1.5 vs. $30.0 \pm 0.7^\circ\text{C}$, respectively; $P = 0.66$).

Discussion

The main findings of the present study were as reported: active healthy subjects wearing fabrics impregnated with FIR-emitting nanoparticles (a) reached a significantly higher VO_2 at submaximal (AT) and maximal (peak) efforts; (b) exercised for a longer time during maximal incremental exercise test; (c) showed a significantly delayed AT, which means that recourse to anaerobic processes to produce

energy during physical activity²⁴ came later in comparison to the same subjects wearing garments without the same properties. This is in line with different trends of BLC observed with functionalised and placebo outfits, that diverged from the eighth minute (around the AT) and reached a significant difference at 10 minutes of exercise (Figure 2). These effects could be explained by an enhanced muscular oxygen delivery thanks to the non-thermic increase in muscular perfusion induced by FIR.

As lactates start accumulating in the working muscles beyond the AT, determining the emergence of muscular fatigue,^{29,30} the delay in AT is probably a determinant of longer exercise observed with the FIR-emitting outfit compared to placebo. Other studies on humans have demonstrated a correlation between the decline in intracellular skeletal muscle pH and the reduction of force production, due to the effect of

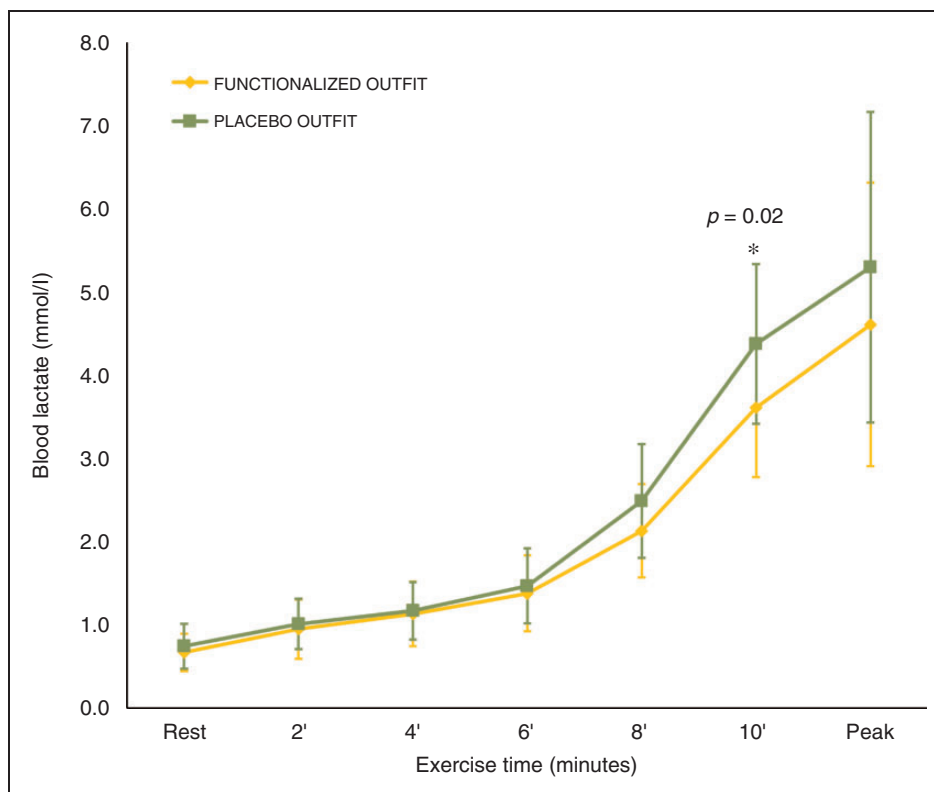


Figure 2. Mean blood lactate concentration during exercise with the two outfits, respectively. Rest: measurement at rest; Peak: measurement at peak of exercise.

acidification on myofibril proteins.² Leung and colleagues studied in vitro effects of FIR-emitting ceramic powders on isolated amphibian gastrocnemius muscle and demonstrated that bioceramics delayed the onset of fatigue induced by repeated activity of the muscle and higher muscular pH in the FIR group versus controls.²

However, the exact mechanisms by which FIR irradiation exerts its biological activities and effects on exercise performance are still not clear.

In the literature, two types of FIR are described.^{2,4,8} One is thermic FIR (FIR sauna and FIR generators powered by electricity) that transfers heat to the human body and increases the local temperature.^{4,9} This would induce muscular vasodilation and enhance muscular blood flow,^{4,8} that could be responsible for higher oxygen peripheral delivery,^{4,12,16,25} enhanced evacuation of oedema and facilitated removal of metabolic wastes.³¹ Interestingly, in Japan FIR dry sauna to warm the human body (Waon therapy) by 1.0–1.2°C has commonly been used to treat heart failure patients, even in an advanced state, and is indicated as class I for these patients in the Japanese heart failure guidelines.³² In fact, Waon therapy has been shown to reduce preload and afterload through peripheral vasodilation, to enhance nitric oxide synthase (NOS), to improve autonomic nervous activity^{32–34} and to reduce oxidative

stress. Vasodilation induced by the overexpression of NOS and reduced sympathetic nervous activity would increase cardiac output and reduce pulmonary congestion. All these biological effects have been demonstrated to improve heart failure symptoms, exercise tolerance and quality of life when Waon therapy is applied on top of optimal medical therapy.³²

However, garments furnished by ©NILIT[®] have exclusively non-thermic biological properties, as confirmed by the analysis of microclimate temperatures and in line with what the literature reports about fabrics enriched with bioceramics.⁴ This type of FIR emits such low irradiance that tissue is not heated when irradiated.^{1,3,4,7} However, similarly to heating FIR, non-thermic FIR is associated with increased skin blood flow, presumably secondary to a microvascular dilation induced by nitric oxide (NO).^{1,3,4,7} This would be produced in endothelial cells^{7,8} by NOS, both because of a FIR-induced upregulated expression of NOS⁸ and because of an increased level of calmodulin with secondary calcium/calmodulin-mediated stimulation of constitutive NOS.³ Pretreatment of FIR-irradiated rat models with inhibitors of NOS prevents the enhancing effect on microcirculation.⁷ Calbet and colleagues¹⁶ analysed the effects of vasodilation on haemodynamics by infusion of ATP during an incremental test in

healthy volunteers. Both systemic and leg peak VO_2 were not enhanced by augmented limb perfusion, nor were relevant differences observed in venous lactate concentration, because of a significant rise in venous oxygen content.¹⁶ However, the entity of vasodilation generated by the infusion of ATP may be different from that provoked by FIR. It could be that infused ATP induces an exaggerated response in active muscles, overriding their maximal vasodilatory capacity and deviating part of the blood flow from exercising muscles to less active tissues.¹⁶ This, in turn, would determine an increase in venous oxygen content, and reduce $\Delta a\text{-vO}_2$ with unchanged VO_2 . Moreover, some authors, in the setting of muscular vasodilation induced by local heating of the exercising muscle, found an increase in leg blood flow proportionally correlated with limb VO_2 during incremental exercise,^{14,15} consistent with the evidence of a significantly higher peripheral oxygen delivery¹⁵ and attenuated drop in venous pH.¹⁴

In addition, besides increased muscular perfusion, small amounts of energy reflected by non-heating FIR fabrics would cause small perturbations in cellular membrane structure where several ion channels are embedded, especially in mitochondrial membranes.⁴ FIR-induced opening of mitochondrial ion channels, especially calcium channels, would increase mitochondrial respiration and then oxygen consumption and ATP production.⁴ Finally, FIR is also supposed to reduce oxidative stress,^{1-3,7,8,11} thus inhibiting cytotoxicity¹ and probably contributing to delay metabolic acidosis and muscular fatigue.¹

Although inconclusive data reported in the literature seem to support our hypothesis that exercise in healthy subjects could be favourably influenced by non-thermic activities of garments knitted with bioceramics. In fact, functionalised sport clothes might induce local hyperaemia and enhance peripheral oxygen delivery (and removal of waste materials) in exercising limb muscles, which is the main limiting factor of maximal aerobic performance in healthy subjects after endurance training.³⁵ The increase in oxygen delivery would delay the emergence of anaerobic metabolism and muscular fatigue, on the one hand, and increase exercise capacity on the other hand. Amelioration of functional capacity at the AT is especially intriguing, considering that most daily activities are of moderate submaximal intensity.

Study limitations

Some study limitations need to be recognised. First, we studied a short-lasting (approximately 10 minutes) exercise test, therefore our results cannot be generalised to all effort durations, i.e. to very short or more prolonged efforts, in which a different metabolism or metabolic rate are present. Data in this regard are, to our

knowledge, not available and specific studies need to be done.

Second, we tested healthy fit subjects. Accordingly, our data cannot be extrapolated to patients with cardiac or pulmonary exercise limitation, to deconditioned subjects or to patients with limited vasodilating capacity, such as patients with diabetes and vascular diseases. The same applies to elite athletes.

Future perspectives

Although the efficacy and safety of FIR thermic saunas have already been demonstrated in patients with chronic heart failure,³² FIR garments have never been tested in patients. However, patients affected by chronic diseases, such as those with heart failure and pneumopathies, show a relevant compromise of exercise capacity due to an inadequate peripheral oxygen delivery and abnormal muscle function so that anaerobic sources for energy production are anticipated.^{36,37} Moreover, the effects of exercise training are a function of exercise intensity so that the higher the intensity, the better the results of any rehabilitation programme.^{37,38}

Consequently, it is intriguing to hypothesise that even fabrics enriched in bioceramics could increase muscular perfusion in chronic patients during exercise. It has been demonstrated that exercise training in heart failure patients induces a significant improvement in functional capacity by increasing exercise cardiac output;³⁷ FIR would contribute to an increase in oxygen delivery and a post-position of AT, thus enhancing the well-recognised benefits of physical rehabilitation. In addition, NO is involved in the regulation of sympathetic nervous activity in humans, therefore we could hypothesise that FIR-emitting garments could also modulate the hyperactivation of the sympathetic nervous system that typically occurs in chronic heart failure patients.

We believe that further studies are definitively needed as regards safety, efficacy, effects on symptoms and timing of FIR garments in chronic patients; investigations should also be encouraged on the possible effects of such rehabilitation programmes on exercise capacity (whether submaximal or maximal) and prognosis of chronic patients, as evaluated by CPET parameters.^{39,40}

Conclusions

In conclusion, the use of FIR-emitting garments generated by the incorporation of natural minerals is associated with an improvement in submaximal and maximal exercise capacity and a delay of AT in active healthy subjects, presumably by an increase in oxygen peripheral delivery. This might have implications for

patients; therefore, further testing of FIR-emitting garments in chronic patients engaged in rehabilitation programmes is justified.

Author contribution

AP, BM and BP contributed to the conception and/or design of the study. MV, CM, BM, FA, DF and AP contributed to the acquisition, analysis, or interpretation of data for the work. MV, CM and AP drafted the manuscript. All authors critically revised the manuscript, gave final approval and agree to be accountable for all aspects of the work ensuring integrity and accuracy.

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Declaration of conflicting interests

The authors declared the following potential conflicts of interest with respect to the research, authorship, and/or publication of this article: ©NILIT® Ltd. is the owner of far-infrared emitting garments. They are responsible for the results of the study tests performed on 10 volunteers and they provided the outfits for the tests performed in the exercise laboratory at Centro Cardiologico Monzino. Centro Cardiologico Monzino did not receive any financial support from ©NILIT®.

Valentina Mantegazza, Mauro Contini, Ada Ferri, Francesca Dotti and Piergiuseppe Agostoni declare that they have no conflicts of interest.

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