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A potential wearable solution for preventing heat strain in workplaces: The cooling effect and the total evaporative resistance of a ventilation jacket

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ABSTRACT

The increase in average seasonal temperatures has an impact in the occupational field, especially for those sectors whose work activities are performed outdoors (agricultural, road and construction sectors). Among the adaptation measures and solutions developed to counteract occupational heat strain, personal cooling garments represent a wearable technology designed to remove heat from the human body, enhancing human performance. This study aims to investigate the effectiveness and the cooling power of a specific cooling garment, i.e. a ventilation jacket, by quantifying the evaporative heat losses and the total evaporative resistance both when worn alone and in combination with a work ensemble, at three adjustments of air ventilation speed.

Standardised "wet" tests in a climatic chamber were performed on a sweating manikin in isothermal conditions considering three clothing ensembles (single jacket, work ensemble and a combination of both) and three adjustments of fan velocity.

Results showed a significant increase ($p < 0.001$) in evaporative heat loss values when the fan velocity increased, particularly within the trunk zones for all the considered clothing ensembles, showing that fans enhanced the dissipation by evaporation. The cooling power, quantified in terms of percent changes of evaporative heat loss, showed values exceeding 100% when fans were on, in respect to the condition of fans-off, for the trunk zones except for the Chest. A significant ($p < 0.01$) decrease (up to 42.3%) in the total evaporative resistance values of the jacket, coupled with the work ensemble, was found compared to the fans-off condition.

Results confirmed and quantified the cooling effect of the ventilation jacket which enhanced the evaporative heat losses of the trunk zones, helping the body to dissipate heat and showing the potential for a heat adaptation measure to be developed.

1. Introduction

Global warming appears more evident year by year registering the 2020 as Earth's second warmest year in the 140-year record (just behind 2016) and Europe's warmest year on record (NOAA, 2021). The situation has been aggravated by a significant increase in the frequency, the intensity and the duration of heatwave events (WHO, 2018), as well as a "deseasonalisation" of heatwaves, occurring outside of the typically

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considered hot period and above all with an increased earliness of heatwave (Morabito et al., 2017). These facts have had an impact in the occupational field particularly for those sectors where work activities are performed outdoors, especially in the agricultural, road and building construction sectors. In these cases, outdoor environmental parameters can represent a constraint because they cannot be regulated or adjusted.

Epidemiological studies provided evidences of the association between heat exposure and the risk of occupational injuries (Fatima et al., 2021; Marinaccio et al., 2019; Binazzi et al., 2019; Bonafede et al., 2016). Prolonged exposure to heat may, in fact, produce important impact on the health of workers (dehydration, heat cramps, heat exhaustion and heat stroke) as well as on their productivity (Flouris et al., 2018). From a physiological point of view, heat exposure can result in the need of the human body to dissipate both the heat stored when the air temperature is higher than the skin temperature and that internally produced by the performed activity. In these conditions, the human thermoregulatory system activates the appropriate mechanisms (vasodilatation and sweating) to try to keep the core temperature (CT) within a safe range. When these mechanisms are insufficient, the CT begins to increase progressively, heat strain can occur increasing the probability of occupational injuries. Therefore, there is a need to suggest mitigation and adaptation solutions to counteract occupational heat strain.

In the era of Industry 4.0 (Ajoudani et al., 2020), wearable solutions are being developed to improve work conditions and reduce risks within the workplaces (Del Ferraro et al., 2020b). Within the field of the Ergonomics of Thermal Environments, technological innovations are geared towards the development of wearable solutions with the scope of preventing heat strain (global warming is accelerating this process), creating innovative and smart systems for continuously monitoring worker's physiological parameters during heat exposure (Sergi et al., 2021; Falcone et al., 2021) or personal cooling garments (PCGs). PCGs were conceived with the intention of removing heat from the human body in order to cool it and alleviate physiological strain caused by heat exposure, enhancing human performance (Morris et al., 2020; Golbabaei et al., 2020; Chan et al., 2015). Nowadays, different types of PCGs exist, designed using different principles such as air-cooled garments (ACG), subdivided into natural air-cooled garments (ACG-Ns) which use evaporative cooling and cold air-cooled garments (ACG-Cs) that use conductive, convective and evaporative cooling; liquid cooling garments (LCGs) based on conductive cooling of a circulating liquid and phase change materials (PCMs) mainly based on conductive cooling by using the latent heat storage of phase change materials. In practice, the selection of the most appropriate PCG to counteract the effects of heat should take into account different factors: the technical characteristics, the effectiveness also in relation to thermal environment where the PCG should be used (for example, in general, PCGs based on evaporative cooling are less effective in very humid environments while those using conductive cooling can be effective regardless the environmental conditions) and the duration of the cooling power; any interferences with the working activity or with possible personal protective equipment and the acceptance by the worker. Innovations are continuously being developed in cooling garments such as the use of fans embedded in the clothing creating an air ventilation garment (AVG), as well as hybrid cooling garments (HCGs), which combine two of the above-mentioned cooling systems, for example PCMs and fans.

AVGs have attracted interest in the last years and also encouraged investigations by researchers due to their high portability, requiring no external connection to a compressor or a coolant supplier, guaranteeing a user's autonomy and mobility and being feasible for applications in occupational field. Studies were focused on the evaluation of the AVG cooling power and of their thermal properties (Zhao et al., 2013; Yi et al., 2017a; Yang et al., 2020; Del Ferraro et al., 2021), on the effects of AVGs on the human thermal response (Zhao et al., 2015a, 2015b, 2021) and on the cooling effect, when AVGs were combined with other cooling systems (HCGs) (Zhao et al., 2015a; Zhao et al., 2015b; Wang et al., 2020; Xu et al., 2020; Wan et al., 2018; Zhao et al., 2017; Yi et al., 2017b; Chan et al., 2017; Song et al., 2016). This type of investigation is generally performed by carrying out simulations in a climatic chamber on a sweating manikin (Del Ferraro et al., 2017, 2018, 2020a; Wang et al., 2012, 2014). In fact, Zhao et al. (2013) studied the effect of fans and openings placed at different parts of the torso and results suggested that the ventilation fans should be located along the spine area and in the lower back zone where the most evaporative cooling is required. Yi et al. (2017) compared the airflow rate and the work duration of two ventilation units powered by different types of batteries, finding that the unit powered by the rechargeable lithium-polymer battery not only reached a higher flow rate but had a longer work duration than the alkaline battery. Yang et al. (2020) investigated the effect of air ventilation, clothing size and air ventilation rate on the upper body heat loss and of the clothing size on thermophysiological responses by carrying out tests on a sweating manikin. They found that the effects of clothing size on the upper body heat loss varied with the ventilation rate and that this can reduce the upper body heat loss and the apparent evaporative resistance. Del Ferraro et al. (2021) investigated the effectiveness of a ventilation jacket focused on the dry heat exchanges, by quantifying the dry heat loss and the total thermal insulation of the single jacket also combined with a work ensemble at three different adjustments of the air ventilation speed and finding significant increase in the dry heat loss of the trunk zones and significant decreases in total thermal insulation as the air ventilation speed increased.

This study, as a part of the Italian project WORKLIMATE (project details available at https://www.worklimate.it), focused on the evaporative properties of a ventilation jacket, which are crucial to ensure heat dissipation from the human body through evaporation during heat exposure, by investigating and quantifying the evaporative heat loss (H_E) and the total evaporative resistance ($R_{e,T}$), both when worn alone and in combination with a work ensemble, at three different adjustments of air ventilation speed. Standardised tests ("wet" tests) in a climatic chamber on a sweating manikin were performed to investigate the effectiveness of the tested ventilation jacket on the evaporative heat exchanges.

2. Materials and methods

The cooling effect of a ventilation jacket was investigated by performing standardised "wet" tests in a climatic chamber (INAIL, Monte Porzio Catone, Italy) using a sweating thermal manikin. During this type of test, heat exchanges between the manikin and the environment only occurred through evaporation. H_E values were quantified and their values were used in the calculation of the total evaporative resistance $R_{e,T}$ values, as shown in paragraph 2.4.

2.1. *The tested cooling garment*

The ventilation garment tested was represented by a short-sleeve cotton jacket with two embedded fans located at the lateral lower back sites with a total weight of 0,75 Kg (Fig. 1).

The jacket was composed of two layers: an outer layer made of cotton and an inner layer of polyester with a net lining placed only at the trunk back side. Ventilation was assured by two fans, with a diameter of 8 cm, powered by a rechargeable Li-ION battery pack with an autonomy of 8 h, a voltage of 7.4 V and an energy capacity of 4400 mAh, embedded in a pocket placed inside the jacket. Air velocity could be adjusted at four different levels, reaching the maximum value of the flow rate of about 12 l/s for each fan. The jacket had six additional circular air – openings, placed vertically in the middle - upper part of the back, each of them with a diameter of 1 cm. The distance between two consecutive openings varied between 4.5 cm and 5 cm with a total of about 23.5 cm between the first and the last openings (from centre to centre). The bottom of the jacket fitted the buttocks tightly due to an elastic strap being sewn into the bottom hem of the jacket. Two external pockets in the upper front

Fig. 1. The ventilation jacket tested with six circular openings and two fans placed in the back site.

part and a long central zipper with a button at the beginning and at the end of the zipper completed the design of the tested ventilation jacket.

The pathway of the airflow is schematically illustrated in Fig. 1 where the natural air, entered from the fans, is channeled towards the upper part of the trunk (shoulders) coming out from six circular openings, as well as from the collar and sleeves.

2.2. *The sweating thermal manikin*

The evaluation of H_E and $R_{e,T}$ values derived from “wet” tests performed on a sweating manikin, i.e. on a manikin able to simulate the human sweating and the evaporative heat exchange. A twenty-six zone “Newton” sweating manikin (Thermetrics LLC, Seattle, WA) meeting the requirements of ASTM F2370 (2016) was used in this study, with surface discretization shown in Fig. 2.

The manikin was constructed using a thermally conductive carbon-epoxy composite shell with embedded heaters and wire sensors. It corresponded to the 50th percentile of Western Males and had a body surface area of 1.8 m^2 and a height of 1.78 m. A total of 139 pores were distributed on the manikin’s surface through which the system delivered the water punctually to the surface. The fabric skin, worn by the manikin during the tests, distributed the water uniformly, allowing the simulation of the human sweating.

The manikin was controlled by the Software ThermDac v8.4.4.0 (Thermetrics LLC, Seattle, WA).

2.3. *The experimental protocol*

Tests were carried out on a standing manikin placed in the central part of the climatic chamber where the air entered by flowing through a mesh wall in front of the manikin and exited through the back wall.

Standardised tests were performed in isothermal conditions (IC), with the manikin’s surface temperature (T_s) and the air temperature (t_a) set at 35 °C ($T_s = t_a = 35$ °C) according to ASTM F2370 (2016), which also required that:

- the air velocity (v_a) value should be set at 0.4 ± 0.1 m/s;
- the relative humidity (*RH*) value should be set at 40 ± 5 %;

With these requirements, the mean value ± standard deviation (SD) of the environmental parameters obtained in the climatic chamber by the performed tests were: $t_a = 35.0 \pm 0.3$ °C; $v_a = 0.37 \pm 0.01$ m/s; $RH = 40.0 \pm 0.65$ %.

Tests were exclusively run in a “wet test” mode which implied also a constant skin temperature mode. The manikin was firstly dressed with a pre-wetted fabric “skin” (as shown in Fig. 2) and then with the garments

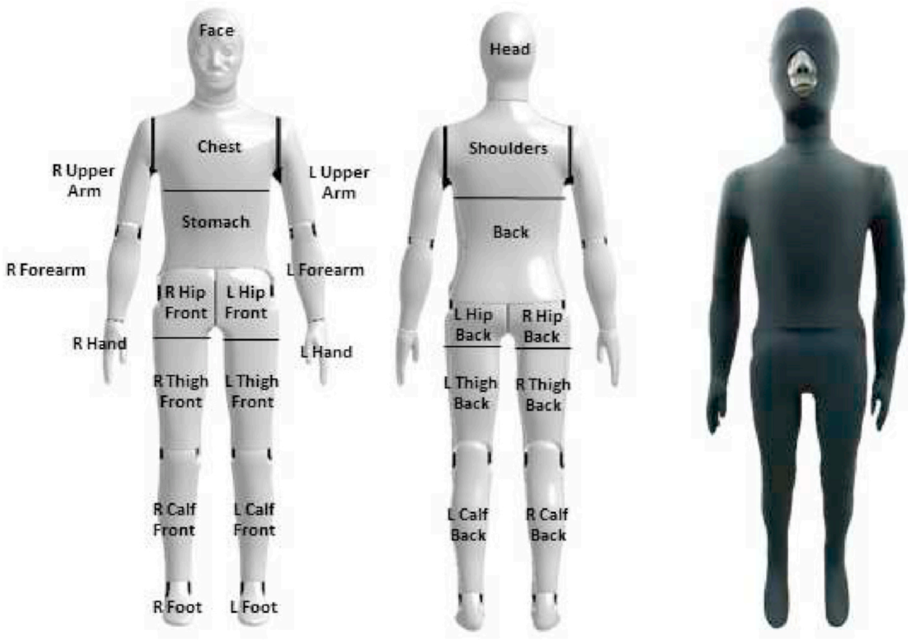

Fig. 2. The twenty-six thermal zones of Newton manikin and the fabric skin used in the “wet” tests.

to be tested. All the manikin’s zones were heated at 35 °C ($T_s = t_a$) and maintained at this temperature by the system. At the same time, the system started to deliver water to the manikin’s surface, through the pores distributed on the surface, in order to maintain the fabric skin saturation. Once the steady-state was reached (which was needed to be maintained for 30 min), the surface temperatures of the twenty-six thermal zones and the power to the manikin’s body segments ($H_{E,i}$, with $i = 1\ldots26$) were recorded every minute and averaged to calculate the $R_{e,T}$ value of the tested ensemble, as explained in paragraph 2.4.

Three clothing ensembles were tested:

1. The single ventilation jacket (JACK) with three different adjustments of the fan velocity (v_f): $v_f = 0$ (fans-off), $v_f = 2$ (fans-on at an intermediate value, with a flow rate of about 6 l/s for each fan) and $v_f = 4$ (fans-on at the maximum value, with a flow rate of about 12 l/s for each fan);
2. The work ensemble (ENS) consisting of a cotton short-sleeve T-shirt, a pair of cotton work pants (long straight pants), cotton briefs, ankle-length athletic socks and athletic shoes;
3. The ventilation jacket (zipper closed) worn over the work ensemble (ENS + JACK) with three adjustments of the fan velocity: $v_f = 0$, $v_f = 2$ and $v_f = 4$.

“Wet” tests on the nude sweating manikin were performed as a general reference condition before starting the tests on the garments.

For each clothing ensemble and fan adjustment, three independent replications were performed on the same day. For each garment, three identical sets were available and were tested randomly.

A total of twenty-four tests were run in IC (comprising of the “wet” tests on the nude sweating manikin).

2.4. The calculation of $R_{e,T}$ value

The parallel method formula (1) reported in ASTM F2370 (2016) and in Annex D of ISO 9920 (2007) allows the calculation of $R_{e,T}$ values from tests performed on a sweating manikin:

$$R_{e,T} = \frac{(P_s - P_a)A}{H_E - \frac{(T_s - t_a)A}{I_T}} \tag{1}$$

where:

P_s is the water vapour pressure at the manikin’s sweating surface (kPa);

P_a is water vapour pressure of the air (kPa);

A is the manikin’s surface area (m^2);

H_E is the power required to heat the manikin (W).

T_s is the manikin’s surface temperature (°C);

t_a is the air temperature (°C);

I_T is the total insulation of the clothing ensemble, including the surface air layer (m^2K/W) derived from the dry test on the thermal manikin.

In IC ($T_s = t_a$), the general formulation (1) is simplified into equation (2), as follows:

$$R_{e,T} = \frac{(P_s - P_a)A}{H_E} \tag{2}$$

For each investigated clothing ensemble, three values of $R_{e,T}$ were calculated (one for each replication performed) and averaged to determine the mean total evaporative resistance value ($\overline{R}_{e,T}$).ASTM F2370 (2016) required that any of the three replications did not vary more than ± 10 % from $\overline{R}_{e,T}$.

2.5. Statistical analysis

Descriptive data and statistical analyses were performed using the IBM SPSS Statistics version 26.0.

The observed H_E values calculated for different combinations of garments (JACK and ENS + JACK with three different adjustments of the fan velocity) and for each considered thermal zone of the manikin and $\overline{R}_{e,T}$ values were analysed by one-way analysis of variance (ANOVA). The Bonferroni test was applied to evaluate the paired differences (the significance level was set at $p < 0.05$).

3. Results

Results reported in this study are refer to the sixteen thermal zones selected among those assumed to be the most influenced by the effect of the fans, covered by the ventilation jacket or proximal to it, such as: Face, Head, Right Upper Arm (R Upper Arm), Left Upper Arm (L Upper

Arm), Right Forearm (R Forearm), Left Forearm (L Forearm), Right Hand (R Hand), Left Hand (L Hand), Chest, Shoulders, Stomach, Back, Right Hip Front (R Hip Front), Right Hip Back (R Hip Back), Left Hip Front (L Hip Front), Left Hip Back (L Hip Back). Among them, the four thermal zones belonging to the trunk are: Chest, Shoulders, Stomach and Back.

For all the considered ensembles and for each adjustment of the fan velocity, H_E mean values of each thermal zones and $\overline{R}_{e,T}$ values were quantified.

3.1. Evaluation of the evaporative heat loss H_E

H_E mean values of the selected sixteen thermal zones and their percent change in values both for JACK and JACK + ENS, at the three

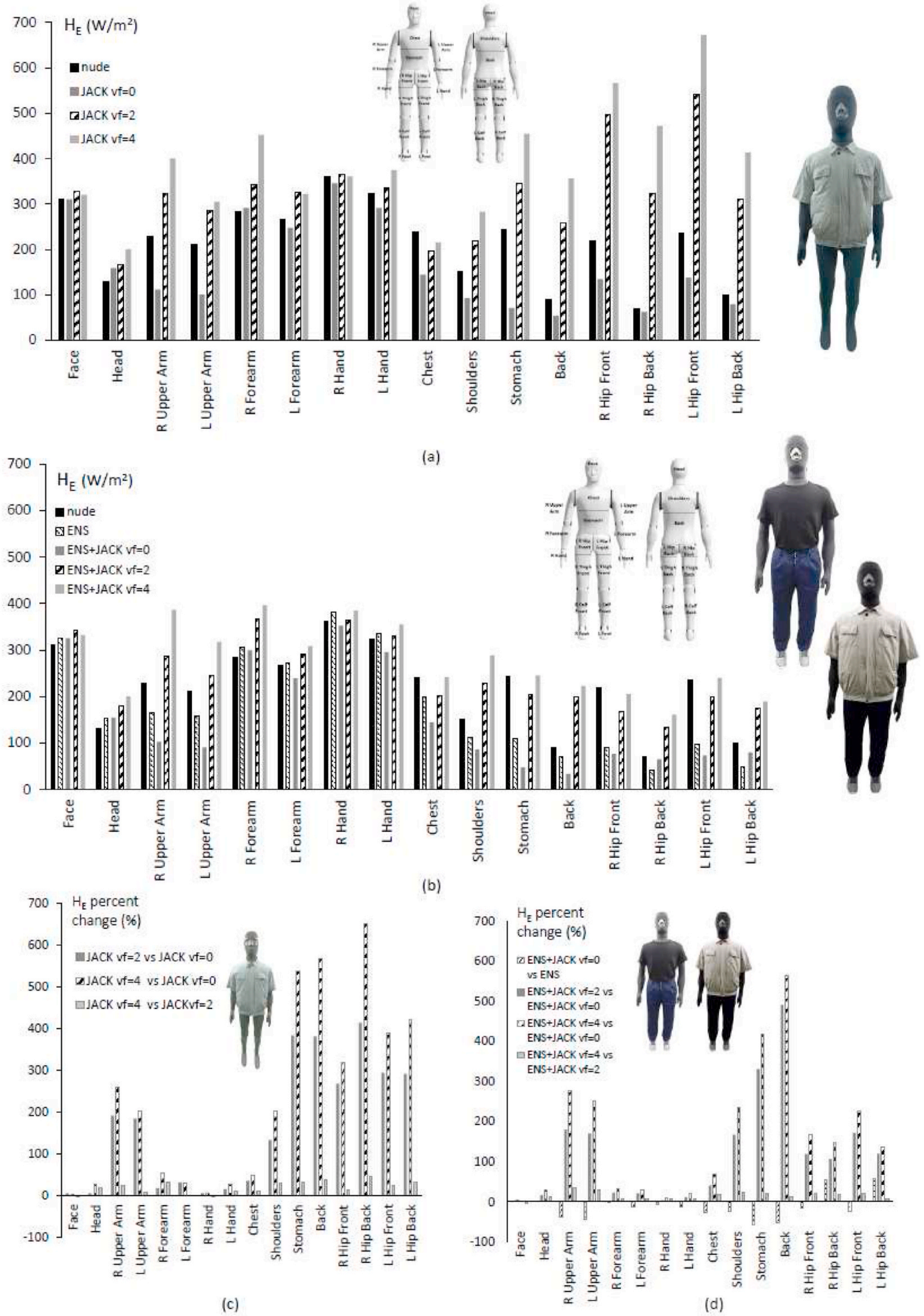

Fig. 3. H_E values of the selected thermal zones: (a) manikin dressed with only JACK; (b) manikin dressed with ENS and ENS + JACK. H_E percent changes:(c) manikin dressed with only JACK; (d) manikin dressed with ENS and ENS + JACK.

different adjustments of v_f, were reported in Fig. 3.

In the investigated conditions related to JACK, results revealed that, at $v_f = 0$ and among the sixteen thermal zones, the Back is the zone showing the lowest H_E value ($H_E = 53.48\ W/m^2$), the R Hand the highest H_E value ($H_E = 360.64\ W/m^2$) and, looking at only the zones of the trunk, the highest value was reached by the Chest ($H_E = 144.72\ W/\ m^2$). Considering the other two adjustments of v_f, the lowest H_E values at $v_f = 2$ and $v_f = 4$ were achieved by the Head (respectively $H_E = 167.32\ W/\ m^2$ and $H_E = 200.53\ W/m^2$) while the highest values by the L Hip Front (respectively $H_E = 541.69\ W/m^2$ and $H_E = 672.25\ W/\ m^2$). Among the trunk zones, the Chest showed the lowest H_E values ($H_E = 196.07\ W/\ m^2$at $v_f = 2$, $H_E = 215.56\ W/m^2$ at $v_f = 4$) while the Stomach the highest ($H_E = 345.57\ W/m^2$at $v_f = 2$, $H_E = 454.73\ W/m^2$ at $v_f = 4$).

In case of ENS and ENS + JACK conditions (panel (b) of Fig. 3), the lowest H_E values were reached in three conditions out of four by the R Hip Back ($H_E = 41.76\ W/m^2$ in ENS, $H_E = 134.82\ W/\ m^2$ in ENS + JACK at $v_f = 2$, $H_E = 160.78\ W/m^2$ in ENS + JACK at $v_f = 4$) while in ENS + JACK at $v_f = 0$ by the Back ($H_E = 33.53\ W/m^2$). The highest values were achieved by the R Hand for the two fans-off conditions ($H_E = 380.81\ W/\ m^2$ for ENS and $H_E = 352.26\ W/m^2$ for ENS + JACK at $v_f = 0$) and by the R Forearm for the other two fans-on conditions ($H_E = 367.03\ W/\ m^2$ for ENS + JACK at $v_f = 2$ and $H_E = 396.35\ W/m^2$ for ENS + JACK at $v_f = 4$). Among the four thermal zones of the trunk, results revealed that the Back reached the lowest H_E values for all the four conditions of ENS and ENS + JACK ($H_E = 71.77\ W/m^2$ in ENS, $H_E = 33.53\ W/\ m^2$ in ENS + JACKt at $v_f = 0$, $H_E = 198.47\ W/m^2$ in ENS + JACK at $v_f = 2$, $H_E = 222.33\ W/m^2$ in ENS + JACK at $v_f = 4$). Highest values were reached by the Chest in the two fans-off conditions ($H_E = 198.48\ W/\ m^2$ for ENS and $H_E = 144.03\ W/m^2$ for ENS + JACK at $v_f = 0$) and by the Shoulders in the two fans-on conditions ($H_E = 229.51\ W/m^2$ for ENS + JACK at $v_f = 2$ and $H_E = 288.12\ W/m^2$ for ENS + JACK at $v_f = 4$).

The cooling performance of the ventilation jacket was assessed in terms of H_E percent changes, as shown in Fig. 3, where the highest values were found when fans were turned on. In particular, panels (c) and (d) of Fig. 3 revealed that, among the zones of the trunk, the Back showed the highest H_E percent change values when the conditions of fans-on were compared with the condition of fans-off: in JACK, in fact, it reached the value of 381.8 % for $v_f = 2$ vs $v_f = 0$ (even if formally the Stomach reached the 384.1 %) and the value of 567.4 % for $v_f = 4$ vs $v_f = 0$; in ENS + JACK, it achieved the value of 491.9 % for $v_f = 2$ vs $v_f = 0$ and of 563.1 % for $v_f = 4$ vs $v_f = 0$. The Chest showed the lowest H_E percent change values in comparisons with the condition fans-on vs fans-off: in JACK, with a value of about 35.5 % for $v_f = 2$ vs $v_f = 0$ and about 48.9 % for $v_f = 4$ vs $v_f = 0$; in ENS + JACK about 40.2 % for $v_f = 2$ vs $v_f = 0$ and about 67.5 % for $v_f = 4$ vs $v_f = 0$.

The comparison between ENS and ENS + JACK at $v_f = 0$ revealed negative H_E percent change values for most of the selected thermal zones (twelve out of sixteen). The highest decrease was found in the Stomach (−56.5 %).

Tables 1 and 2 report results of the statistical analysis applied to H_E values with the indication of H_E mean values, their confidence intervals (CIs) and the significance of the tests.

In the case of JACK, results of the ANOVA revealed statistically significant differences for the most part of the selected zones except for the Head ($v_f = 0$ vs $v_f = 2$) and for the L Forearm ($v_f = 2$ vs $v_f = 4$) while for ENS + JACK, the differences are statistically significant for all the sixteen thermal zones considered.

3.2. Evaluation of the total evaporative resistance

Calculations of $\overline{R}_{e,T}$ values were performed according to Eq. (2) at the three adjustments of the fan velocity. $\overline{R}_{e,T}$ values and their percent changes were shown in Fig. 4, respectively in panels (a) and (b).

Table 1
Mean values and confidence intervals (CIs) of H_E for the sixteen thermal zones, for JACK with the three adjustments of v_f.

Manikin zone	Mean (CI) for $v_f = 0$ (W/m^2)	Mean (CI) for $v_f = 2$ (W/m^2)	Mean (CI) for $v_f = 4$ (W/m^2)	Sign.
Face	311 (308–313) [a]	329 (328–331) [b]	320 (316–325) [c]	***
Head	159 (157–161) [a]	167 (162–172) [a]	201 (195–206) [b]	***
R Upper Arm	111 (110–112) [a]	324 (322–326) [b]	401 (399–403) [c]	***
L Upper Arm	100 (100–101) [a]	285 (284–287) [b]	305 (303–306) [c]	***
R Forearm	291 (289–294) [a]	343 (340–346) [b]	452 (449–455) [c]	***
L Forearm	248 (246–250) [a]	326 (324–328) [b]	322 (320–324) [b]	***
R Hand	346 (344–348) [a]	367 (364–369) [b]	361 (359–363) [c]	***
L Hand	292 (290–294) [a]	335 (333–337) [b]	375 (372–378) [c]	***
Chest	145 (144–146) [a]	196 (195–197) [b]	216 (214–217) [c]	***
Shoulders	93 (91–96) [a]	218 (216–219) [b]	283 (281–285) [c]	***
Stomach	71 (70–72) [a]	345 (342–347) [b]	455 (453–457) [c]	***
Back	53 (53–54) [a]	258 (255–260) [b]	357 (355–359) [c]	***
R Hip Front	135 (134–136) [a]	497 (495–500) [b]	567 (564–569) [c]	***
R Hip Back	63 (61–64) [a]	323 (321–325) [b]	472 (470–474) [c]	***
L Hip Front	137 (136–138) [a]	542 (539–544) [b]	672 (670–675) [c]	***
L Hip Back	79 (78–80) [a]	310 (308–313) [b]	414 (411–416) [c]	***

***$p<0.001$ according to ANOVA; different letters in [] indicate statistically significant differences between different adjustments of v_f (p-value<0.05) according to the Bonferroni test.

The highest $\overline{R}_{e,T}$ values were obtained in the fans-off condition ($v_f = 0$), both for JACK and for ENS + JACK. The fans produced a decrease in the $\overline{R}_{e,T}$ values which is highest when $v_f = 4$ is compared to $v_f = 0$ ($\overline{R}_{e,T}$ percent change = - 47.1 % for JACK and $\overline{R}_{e,T}$ percent change = - 42.3 % for ENS + JACK). A reduction in $\overline{R}_{e,T}$ values, even if slightly lower than that obtained for $v_f = 4$, was registered also for $v_f = 2$ with respect to the condition of fans-off ($\overline{R}_{e,T}$ percent change = - 35.3 % for JACK and $\overline{R}_{e,T}$ percent change = - 34.6 % for ENS + JACK).

The $\overline{R}_{e,T}$ percent change revealed a positive value only for ENS + JACK at $v_f = 0$ vs ENS (+13 %).

The statistical analysis applied to $\overline{R_{eT}}$ values and reported in Table 3 with the indication of $\overline{R_{eT}}$ mean values, their CIs and the significance of the tests for the conditions tested, showed statistically significant differences obtained by ANOVA test both for JACK and for JACK + ENS.

4. Discussion

PCGs are hypothesized to be a promising wearable solution against heat stress, conceived with the scope to remove heat from the human body in order to cool it and to enhance human performance. Technological innovations are continuously introduced in this field, for example, through the use of fans embedded in a garment, creating an AVG. In this study, the effectiveness of a specific AVG is investigated, i.e. a ventilation jacket, focusing and quantifying its evaporative properties in terms of H_E and $\overline{R}_{e,T}$ values at three different adjustments of the fan velocity, through standardised "wet" tests in a climatic chamber on a sweating manikin. The choice of considering a scenario with the

Table 2

Mean values and confidence intervals (CIs) of H_E for the sixteen thermal zones, for ENS + JACK with the three adjustments of v_f.

Manikin zone	Mean (CI) for $v_f = 0$ (W/m^2)	Mean (CI) for $v_f = 2$ (W/m^2)	Mean (CI) for $v_f = 4$ (W/m^2)	Sign.
Face	325 (324–327) [a]	342 (340–344) [b]	332 (331–333) [c]	***
Head	155 (153–156) [a]	180 (177–183) [b]	200 (199–202) [c]	***
R Upper Arm	102 (102–103) [a]	286 (285–288) [b]	387 (386–388) [c]	***
L Upper Arm	90 (90–91) [a]	244 (243–246) [b]	317 (317–318) [c]	***
R Forearm	299 (296–302) [a]	367 (364–370) [b]	396 (394–398) [c]	***
L Forearm	239 (237–241) [a]	291 (288–293) [b]	308 (307–309) [c]	***
R Hand	352 (350–354) [a]	365 (362–367) [b]	385 (383–387) [c]	***
L Hand	295 (292–298) [a]	330 (327–334) [b]	355 (352–357) [c]	***
Chest	144 (143–145) [a]	202 (201–203) [b]	241 (240–242) [c]	***
Shoulders	86 (84–87) [a]	230 (227–232) [b]	288 (287–289) [c]	***
Stomach	47 (47–48) [a]	204 (203–206) [b]	245 (245–246) [c]	***
Back	34 (33–34) [a]	198 (197–200) [b]	222 (222–223) [c]	***
R Hip Front	77 (76–77) [a]	168 (167–169) [b]	205 (204–206) [c]	***
R Hip Back	65 (65-65) [a]	135 (134–135) [b]	161 (160–161) [c]	***
L Hip Front	73 (73–74) [a]	200 (198–201) [b]	239 (239–240) [c]	***
L Hip Back	80 (79–80) [a]	175 (174–176) [b]	189 (189-189) [c]	***

***p<0.001 according to ANOVA; different letters in [] indicate statistically significant differences between different adjustments of v_f (p-value<0.05) according to the Bonferroni test.

ventilation jacket coupled with a work ensemble allowed the cooling effects of the jacket to be observed with the presence of other clothes, simulating a condition of "real" use of the jacket and quantifying the cooling performance for the possible use of the jacket in specific occupational fields.

Results presented in this study derived from "wet" tests, where the heat exchanges between the manikin and the environment occurred only by evaporation. "Wet" tests were performed according to ASTM F 2370 (2016) which represents the only standard detailed requirements of the sweating manikin and the test procedures in order to measure the Re_T value of a clothing ensemble using a sweating manikin. While there are ASTM F 1291 (2016) and ISO 15831 (2004) for evaluating I_T value, the latter being the ISO specific reference for performing dry tests on a thermal manikin, there is no ISO standard for evaluating Re_T value (Lei, 2019). The European Standard EN 17528 was not published and it was a draft when the study was carried out.

There are some open issues relating to the measurement of the evaporative resistance of clothing raised from the literature. One refers to the isothermal condition required to perform the "wet" tests. Wang (2017) observed that there is a difference in temperature between the surface of the fabric skin ($T_{sk,f}$) used in the "wet" tests and the manikin surface and that the evaporation occurs from the fabric skin surface. According to study of Wang (2017), the isothermal condition should be established between the fabric skin surface temperature and the air temperature ($T_{sk,f} = t_a$) and not between the manikin surface temperature and the air temperature ($T_s = t_a$). He suggested a correction that should be made when "wet tests" are performed in the "so-called" isothermal condition ($T_s = t_a$) and the heat loss method (Eqs. (1) and (2)) is applied to calculate the total evaporative resistance. In this study, values of the total evaporative resistance are shown without the correction.

The local behaviour of the selected sixteen thermal zones showed that generally the zones with a direct contact with the air (R Hand, L Hand, R Forearm) showed the highest H_E values, while the zones more covered (such Back or Hip Back) showed the lowest values. The action of the fans showed an increase in H_E values, with respect to the condition of fans-off, for most of the considered thermal zones. The H_E increases, passing from the condition of fans-off to the condition of fans-on, appeared significant and more evident for the ten zones covered by the ventilation jacket (R Upper Arm, L Upper Arm, Chest, Shoulders, Stomach, Back, R Hip Front, R Hip Back, L Hip Front, L Hip Back), both for JACK and for ENS + JACK as expected and they increased with the increase of the fan velocity. This represented the first positive result which revealed that the fans enhanced the dissipation of the heat by evaporation compared to the condition of fans-off. Evaporation, in fact, represents the main way of dissipating the heat during exposure to a hot environment, especially when the "dry" heat losses are reduced due to the small temperature gradient between the skin and the environment ($t_a < T_s$) or when the body tends to "gain" heat because $t_a > T_s$. In these cases, enhancing evaporative heat losses from the body can be an effective way to help the body to dissipate heat and to try to keep the core temperature in a safe range.

The trend observed for H_E values is in line with the results found by Del Ferraro et al. (2021) who observed significant increases in the dry heat losses and decreases in the thermal insulation values due to fans for the same ventilation jacket and in combination with a work ensemble and by Yang et al. (2020) who found an increase in the total heat loss of the upper body region with the increase in the ventilation rate, for a long-sleeve ventilation jacket in non – isothermal conditions, for different sizes and levels of air ventilation rate.

The cooling power quantified in this study in terms of H_E percent change ((panels c) and d) of Fig. 3) showed values exceeding 100 % when fans were on (both in JACK and ENS + JACK) with respect to the fans-off condition, for all the ten thermal zones except for the Chest and, among the zones of the trunk, the Back is the one which revealed the highest H_E percent change values. This is an important finding because the upper back is one of the areas with the highest sweating rate.

An increase higher than 100 % was found also by Yang et al. (2020) in their study where an increase of 168 % in the upper body heat loss, for the clothing size L in the presence of high ventilation, was observed and by Zhao et al. (2013) who detected percent increases in heat losses of the whole torso ranging from 137 to 251 % compared to the fans-off conditions.

The second result that emerged from this study and that was strictly connected to the first one, was the significant reduction found in the $\overline{R}_{e,T}$ values when the fans were on (both for JACK and ENS + JACK) compared to the condition of fans-off. Calculations performed to quantify the percent change of $\overline{R}_{e,T}$ showed that the reduction in $\overline{R}_{e,T}$ values increases with the increase in the fan velocity and the cooling effect of the ventilation jacket (i.e. reduction in $\overline{R}_{e,T}$ values) was found not only when the manikin worn the single ventilation jacket but also when the jacket was worn over a work ensemble. A reduction in the thermal properties was also detected by Yang et al. (2020) who found a decrease in the apparent evaporative resistance in the upper body part due to the effect of a long-sleeve ventilation jacket in their test performed in non - isothermal conditions and by Yi et al. (2017b) who quantified the thermal insulation and the evaporative resistance of the torso in their study on the effectiveness of a newly designed hybrid cooling vest. The value of $\overline{R}_{e,T} = 0.017\ KPa{\cdot}m^2/W$ calculated in this study for JACK at $v_f = 0$ is very similar to the value of $0.0173\ KPa{\cdot}m^2/W$ reported by Zhao et al. (2013) in their study for the total evaporative resistance of their ventilation jacket.

Future human subject studies investigating the cooling effect of the

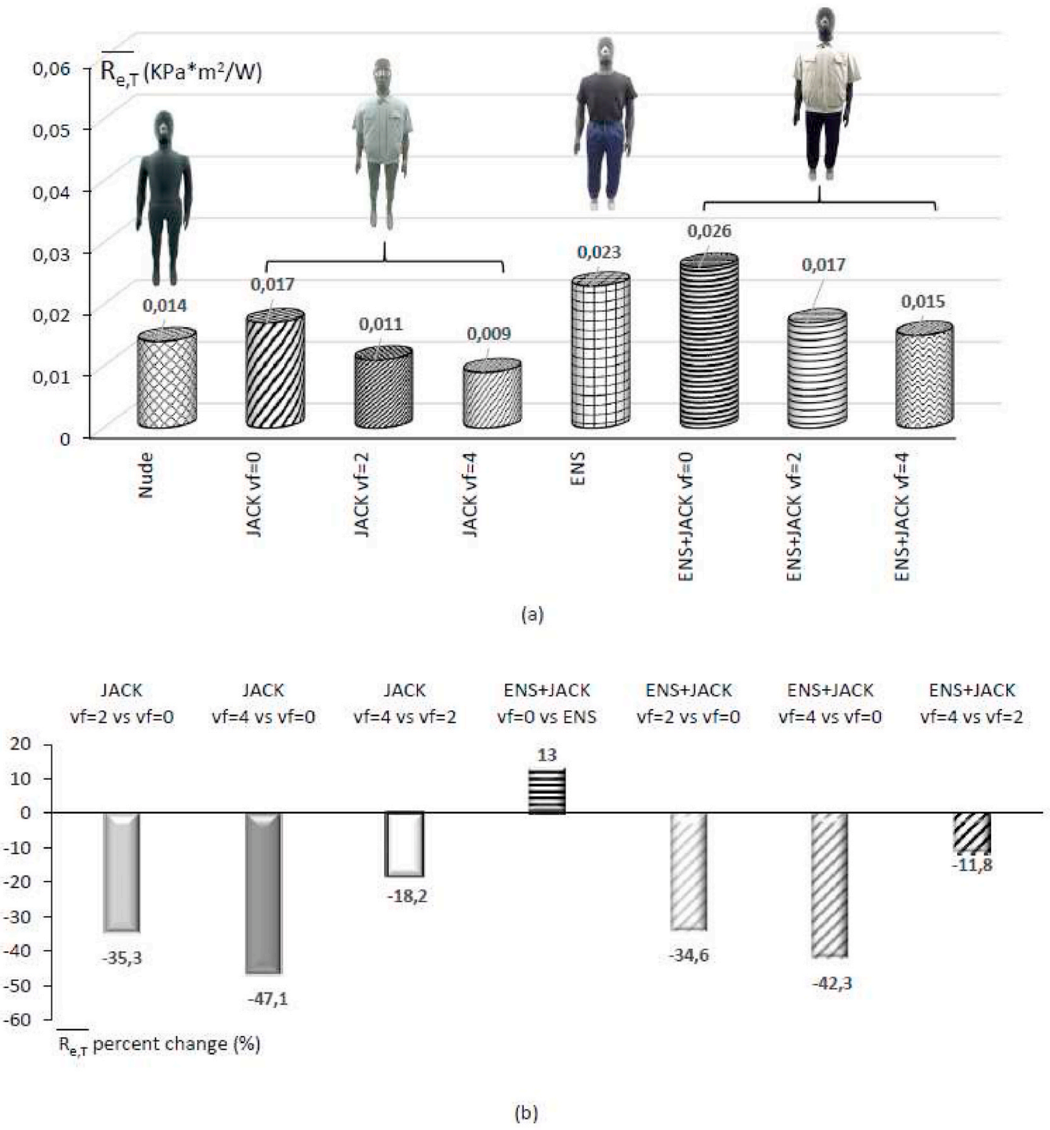

Fig. 4. (a) $\overline{R}_{e,T}$ values for the nude manikin and all the considered ensembles. (b) $\overline{R}_{e,T}$ percent change values.

Table 3
Mean values and confidence intervals (CIs) of $\overline{R_{eT}}$.

Condition	Mean (CI) for $v_f = 0$ ($KPa\cdot m^2/W$)	Mean (CI) for $v_f = 2$ ($KPa\cdot m^2/W$)	Mean (CI) for $v_f = 4$ ($KPa\cdot m^2/W$)	Sign.
JACK	0.017 (0.015–0.018) [a]	0.011 (0.009–0.012) [b]	0.009 (0.009–0.009) [c]	***
ENS + JACK	0.026 (0.025–0.028) [a]	0.017 (0.016–0.019) [b]	0.015 (0.015–0.015) [c]	***

***p<0.001 according to ANOVA; different letters in [] indicate statistically significant differences between different adjustments of v_f (p value < 0.01) according to the Bonferroni test.

tested ventilation jacket on the human thermophysiological response could be useful to complete the thermal analysis and to validate the effectiveness of this technology as a sustainable solution to reduce the impact of heat stress on health.

Results obtained in this paper should be interpreted with caution and need to be confirmed by human trials in order to verify the real effectiveness of the tested ventilation jacket and to better understand how (how often, for how long, etc.) it should be used. Furthermore, the impact of this technology on the user's acceptability should be evaluated, accounting for potential discomfort related to the use of the ventilation jacket during the execution of work activity in the heat.

5. Conclusions

This study investigated the cooling effect of a ventilation jacket performing "wet" tests in a climatic chamber on a sweating manikin in isothermal condition ($T_s = t_a = 35\ ^\circ C$) considering three clothing ensembles (the single jacket, a work ensemble and a combination of both) and three different adjustments of the fan velocity ($v_f = 0$, $v_f = 2$, $v_f = 4$). Results obtained showed:

1. Significant increases in evaporative heat loss, i.e. cooling effect with the increase of the fan velocity for all the thermal zones of the trunk and for all the considered ensembles;

2. Significant decreases of the total evaporative resistance values with the increase of the fan velocity (up to 42.3 % when the jacket is coupled with the work ensemble).

Results revealed that the action of the fans enhanced the evaporative heat losses of the trunk zones helping the body to dissipate heat.

Future investigations on the human thermal response will be useful to complete the analysis of this cooling garment and to understand if the ventilation jacket can represent an effective solution to be used as an adaptation strategy to counteract the heat stress for workers exposed to warm and hot environments. According to future climate projections, concrete actions are needed to prevent the potential impact of heatwaves and occupational heat exposure and to reduce the risk of injuries and productivity losses.

Credit author statement

Simona Del Ferraro: Conceptualization, Methodology, Validation, Formal Analysis, Investigation, Resources, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization. **Tiziana Falcone:** Methodology, Validation, Investigation, Writing - Review & Editing, Visualization. **Marco Morabito:** Conceptualization, Formal Analysis, Resources, Data Curation, Writing - Review & Editing, Supervision, Project administration, Funding acquisition. **Alessandro Messeri:** Conceptualization, Resources, Writing - Review & Editing, Supervision, Project administration, Funding acquisition. **Michela Bonafede:** Writing - Review & Editing, Supervision, Project administration, Funding acquisition. **Alessandro Marinaccio:** Writing - Review & Editing, Supervision, Project administration, Funding acquisition. **Chuansi Gao**: Resources, Writing - Review & Editing**. Vincenzo Molinaro:** Conceptualization, Methodology, Resources, Writing - Review & Editing.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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