

Effect of sportswear on performance and physiological heat strain during prolonged running in moderately hot conditions

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Abstract

Introduction: This study examined the impact of different upper-torso sportswear technologies on the performance and physiological heat strain of well-trained and national-level athletes during prolonged running in moderately hot conditions.

Methods: A randomized crossover design was employed in which 20 well-trained ($n=16$) and national-level ($n=4$) athletes completed four experimental trials in moderately hot conditions (35°C, 30% relative humidity). In each trial, participants ran at 70% of their peak oxygen uptake (70% $\dot{V}O_{2peak}$) for 60 min, while wearing a different upper-body garment: cotton t-shirt, t-shirt with sweat-wicking fabric, compression t-shirt, and t-shirt with aluminum dots lining the inside of the upper back of the garment. Running speed was adjusted to elicit the predetermined oxygen consumption associated with 70% $\dot{V}O_{2peak}$. Physiological (core and skin temperatures, total body water loss, and urine specific gravity) and perceptual (thermal comfort and sensation, ratings of perceived exertion, and garment cooling functionality) parameters along with running speed at 70% $\dot{V}O_{2peak}$ were continuously recorded.

Results: No significant differences were observed between the four garments for running speed at 70% $\dot{V}O_{2peak}$, physiological heat strain, and perceptual responses (all $p>0.05$). The tested athletes reported larger areas of perceived suboptimal cooling functionality in the cotton t-shirt and the t-shirt with aluminum dots relative to the sweat-wicking and compression t-shirts (d: 0.43–0.52).

Conclusion: There were not differences among the tested garments regarding running speed at 70% $\dot{V}O_{2peak}$, physiological heat strain, and perceptual responses in well-trained and national-level endurance athletes exercising in moderate heat.

KEYWORDS

athletic shirt, core temperature, garment, heart rate, hot, running speed, skin temperature, warm

1 | INTRODUCTION

Competing in the heat is becoming more and more frequent for international sporting events as in the recent cases of the Football World Cup, the World Athletics Championship, and the Olympic Games.^{1,2} Competing in such extreme thermal environments can negatively impact an athlete's health,^{3,4} physical performance,^{1,5} and cognition.⁶ With numerous major sporting events taking place in hot locations^{1,2,7,8} and with climate change fueling an increase in the occurrence of hot weather conditions, heat has become a critical issue for athletes during training and competitions. This concern is heightened by the fact that elevated body temperatures correlate with fatigue and diminished athletic performance.⁹

Thermal physiologists and sport scientists have increasingly worked on the development of evidence-based heat-alleviation measures to prevent physiological heat strain that include interventions such as heat-acclimation,^{10,11} as well as pre-¹² and per-¹³ cooling strategies. Another important factor in mitigating heat during exercise is proper clothing. This is especially true considering that accumulated sweat in fabric can heighten discomfort.¹⁴ For many years, textiles have been developed to facilitate heat dissipation and reduce or eliminate the hazards of heat stress, not just for athletes but also for workers.¹⁵ Today, there is an ongoing opportunity for the clothing industry to explore new and innovative ways to develop textiles that facilitate heat dissipation and reduce the hazards of heat stress and injuries in exercising individuals.¹⁶ Sportswear technologies with properties that enhance heat transfer from the body to the surrounding environment could provide a performance advantage for athletes who must perform in the heat. However, there is controversy regarding the effectiveness of such sportswear technology,^{17–19} particularly as some previous research has shown no significant physiological differences between exercising shirtless and clothed in warm environments.^{20–22} Nevertheless, it's important to note that the significance of clothing extends beyond its heat dissipation properties. Clothing also acts as a shield, reflecting radiant heat back to the environment.²³ However, this aspect is largely mitigated in endurance running events, since the majority of endurance races take place either early in the morning or late in the afternoon to avoid the adverse impacts of sun exposure on athletes.¹ Yet, it is important to recognize that not all athletic events, sports, or training sessions occur during these low-sunlight hours of the day, and therefore potential sun-mitigating properties of the clothing, such as its color,²³ might play a significant role in reducing the physiological heat strain experienced by athletes.

The potential for increased heat dissipation during exercise in warm/hot environments has led to lucrative sales

in sports clothing and apparel.¹⁶ However, it is important to note that while marketing campaigns have promoted the benefits of sportswear technology for improving heat dissipation,^{17,18,24} the relevant scientific evidence comes primarily from thermal manikin research.²⁵ Currently, there is no robust physiological evidence that makes these findings applicable to humans.²⁵ Previous research on sportswear technology has primarily focused on recreational athletes during low-intensity exercise [30%–50% peak rate of oxygen consumption ($\dot{V}O_{2peak}$)].¹⁹ Some studies incorporated moderate exercise intensity (70% $\dot{V}O_{2peak}$)^{20,26–28} but of short duration (25–30 min) and exposure to relatively mild heat conditions [average: ~23°C Wet-Bulb Globe Temperature (WBGT)].

Despite the rapid advancements in sportswear technology, there remains a lack of information on the impact of recent commercial garments, such as compression t-shirts and t-shirts with aluminum dots lining the inside of the upper back of the garment, as well as their effects on the physiology and performance of national-level athletes. Unlike traditional sweat-wicking technology that employs synthetic fibers specifically engineered to move sweat away from the skin towards the fabric's surface to a larger diffusion area and enhance evaporative heat dissipation from the body,²⁹ recent innovations in sportswear technologies may utilize different heat transfer pathways. For instance, the snug fit of compression garments has been proposed to potentially enhance the dissipation of heat away from the body,¹⁹ and has led to claims of thermoregulatory benefits as a result of improved sweat efficiency.³⁰ The latest advancement in sportswear design is the incorporation of aluminum dots lining the inside of the upper back of the garment. Although we were unable to find a scientific reference explaining the rationale behind this sportswear technology, we assume that it was developed to utilize aluminum's high thermal conductivity to dissipate body heat. These tiny dots may function as mini heat sinks, drawing heat from the body and dissipating it into the surrounding environment, thereby providing a cooling effect that may aid in body heat regulation during exercise.

In an effort to broaden our understanding of the impacts of sportswear technologies, the present study seeks to assess the effectiveness of commercially available athletic garments in facilitating heat dissipation and reducing heat stress during exercise in hot environments. Specifically, this study aimed to investigate the impact of different upper-body sportswear technologies (sweat-wicking t-shirts, compression t-shirts, and t-shirts with aluminum dots) on the performance and physiological heat strain experienced by well-trained and national-level athletes during prolonged moderate-intensity exercise in moderately hot conditions. In doing so, the study hopes to bridge the knowledge gap in

the literature concerning the impacts of new sportswear technologies on heat management during endurance exercise and maintain health and performance outcomes for athletes competing in hot environments.

2 | MATERIALS AND METHODS

2.1 | Participants

The minimum required sample size for investigating potential differences among four garments was calculated using information³¹ on whole body sweat loss in individuals exercising in the heat with cotton (1284.6 ± 120.1 mL) and synthetic (1182.6 ± 89.4 mL) sportswear. Using these data, an effect size (f) of 0.48 for the differences between the two textiles was computed. Assuming an α of 0.05 and β of 0.95, twenty participants would provide enough power to detect statistically significant differences of a similar magnitude (G*Power Version 3.1.9.2). Based on these calculations, a total of twenty healthy, non-smoking male athletes participated in the study (15 runners, 3 cyclists, and 2 triathletes). Four of them were members of the Greek National Team in endurance disciplines (3000 m steeplechase, 5000 m, marathon, and endurance cycling) and thus were considered national-level athletes [age: 25.5 ± 4.9 years; body mass: 67.4 ± 3.7 kg; stature: 1.76 ± 0.05 m; body mass index: 21.7 ± 0.7 ; body surface area: 1.8 ± 0.1 m²; $\dot{V}O_{2\text{peak}}$: 73.8 ± 2.2 mL/kg/min]. The remaining 16 participants (age: 29.1 ± 3.7 years; body mass: 74.0 ± 5.5 kg; stature: 1.75 ± 0.06 m; body mass index: 24.2 ± 1.6 kg/m²; body surface area: 1.9 ± 0.1 m²; $\dot{V}O_{2\text{peak}}$: 51.7 ± 5.6 mL/kg/min) were well-trained athletes running more than 80 km per week and/or exercising more than five times per week (self-reported information) at the time of the study. Although comparable $\dot{V}O_{2\text{peak}}$ values have been previously reported for male³² and female³³ runners with similar weekly running mileage, it is important to note that we did not have qualitative information regarding the training characteristics of our participants. Therefore, their training sessions could vary from slow, continuous running to high-intensity interval training. Nevertheless, to streamline our analysis, the categorization of athletes into well-trained (Tier 2: ~12%–19% of the global population) and national-level (Tier 3: ~0.014% of the global population) groups was done following previous methodology.³⁴ All participants had not undergone heat acclimation prior to experimentation and were not engaged in jobs and/or activities that involved frequent heat exposure. To avoid seasonal acclimatization effects,³⁵ testing of all groups was conducted in early spring, which was characterized by temperate (WBGT: $16.1 \pm 2.8^\circ\text{C}$) midday (10:00–14:00) environmental conditions (air temperature:

$14.8 \pm 3.4^\circ\text{C}$; relative humidity: $61.2 \pm 15.2\%$; wind speed: 1.5 ± 0.8 m/s; and solar radiation: 664.3 ± 113.7 W/m²; mean $\pm$ SD). Written informed consent was obtained from all volunteers after detailed explanation of all the procedures involved.

2.2 | Research design

This randomized controlled trial was approved by the Bioethics Committee of the Department of Physical Education and Sport Science of the University of Thessaly (protocol no. 469) in accordance with the Declaration of Helsinki, except for registration in a database.

All participants were asked to visit the laboratory on five separate occasions. During the first visit, which took place a week prior to the experimental phase, anthropometric (body mass and body stature) and demographic (age and health status) data were obtained, and all participants underwent an incremental treadmill test to exhaustion to determine $\dot{V}O_{2\text{peak}}$. Following this first visit, participants were asked to visit the laboratory for four separate experimental sessions over a 10-day period (experimental phase), each interspersed by ~72 h to allow sufficient recovery between sessions. Prior to each session, participants were instructed to refrain from alcohol, caffeine, and strenuous activity for a minimum of 24 h.

Upon arriving for each experimental trial, participants entered a thermally neutral room with ambient temperature and relative humidity at approximately 23°C and 55%, respectively. In this controlled environment, they were instrumented for data collection (see subsection “2.3. Data collection”). After instrumentation, participants proceeded to wear one of four distinct t-shirts: (i) 100% cotton shirt, (ii) sweat-wicking shirt, (iii) synthetic compression shirt, and (iv) shirt with aluminum dots lining the inside of the upper back of the garment (Table 1). The random order of t-shirts was determined using a pseudorandom number generator in Excel spreadsheets (Microsoft Office, Microsoft Corp.). All t-shirts were of similar color and shade (light blue), covering ~34% (short-sleeved shirts; ~0.18 clo) of the participants' body surface area. The manufacturers' specifications had been meticulously adhered to during this process, ensuring a uniform fit for all participants. This approach ensured consistency in the way the t-shirts covered and conformed to each participant's body. Similarly, to ensure that the clothing's cooling properties remained at the highest standard throughout the study, all t-shirts were carefully washed as per manufacturer's instructions. In addition to the tested t-shirts, to ensure uniformity in clothing across participants during the study, we provided the same running

Shirt Type	Material (% of t-shirt)			Other information	
	Polyester	Elastane	Cotton	Color (R, G, B)	Weight (gr)
Cotton	0	0	100	23, 50, 71	162
Sweat-wicking	87	13	0	15, 100, 190	158
Compression	77	23	0	8, 120, 196	128
Aluminum dots	100	0	0	55, 100, 125	122

Note: RGB refers to a color model in which red (R), green (G), and blue (B) colors are combined in various ways to make a different color; "gr" corresponds to gram.

TABLE 1 Characteristics of the studied athletic shirts.

shorts (~0.09 clo) and calf-length socks (~0.04 clo) to our participants during experimentation. However, they wore their own underwear (~0.04 clo) and athletic shoes (~0.04 clo) across all trials (total clothing insulation: ~0.39 clo). Standard values from the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) were used to estimate the insulation of individual clothing items.^{36,37}

During the experimental sessions, the treadmill was set so that each subject exercised for 60 min at 70% $\dot{V}O_{2peak}$. The treadmill was set at 1% incline to reflect the energetic cost of outdoor running³⁸ and the display was covered so participants were not aware of the running speed. No water consumption was allowed during running. Indirect calorimetry (CareFusion Germany, 234 GmbH) was used to maintain running speed at 70% of $\dot{V}O_{2peak}$ throughout the protocol. This was done to examine any potential drift in running speed. All experiments took place in an environmental chamber (2.85 m × 2.85 m × 4 m) maintained at 35 ± 0.5°C air temperature, 30% ± 3% relative humidity, with 0 W/m² solar radiation, and a very low air flow of 0.3 m/s. The air flow level in the heat chamber was maintained at 0.3 m/s using ceiling fans designed to distribute the air multi-directionally and equally in the chamber. This air flow level follows previous literature that investigated the impact of different garments on physiological heat strain.^{27,39,40} The corresponding WBGT for this environment is 26.3°C.⁴¹ The aforementioned environmental conditions were chosen because they are representative of the heat stress often experienced by endurance athletes who compete in international sporting events,¹ and professional football players.⁴²

2.3 | Data collection

One hour prior to each experimental session, participants arrived at the laboratory. During this hour, urine samples were taken, and urine specific gravity (USG) was measured using a refractometer (PAL-10S, Atago Co.). Participants were deemed euhydrated (USG ≤ 1.02) or dehydrated (USG > 1.02) based on published literature.⁴³ If

found to be dehydrated, participants were provided with water ad libitum for the next hour, and a second urine sample was obtained and tested to ensure euhydration prior to entering the environmental chamber. A second urine sample was collected at the end of each session and used to calculate changes in USG from baseline. Dry nude body mass was measured at the beginning (0 min) and immediately after each session (60 min) using a scale with a precision of 1 g (KernDE 150K2D, KERN & Sohn GmbH). Body stature was measured using a stadiometer (Seca 213, Seca GmbH & Co. KG). Changes in body mass were used to calculate the total body water loss (pre- and post-nude body mass), as well as height and body mass were used to calculate body surface area using the Du Bois' formula.⁴⁴

During experimentation, continuous physiological data, as well as heat flux from four sites were measured. Specifically, heart rate was collected using a wireless heart rate monitor (Polar RS800CX, Polar Electro) and expressed as a percent of the maximum heart rate (HR_{max}) recorded during the $\dot{V}O_{2peak}$ test. Core temperature (T_{core}) was indexed using ingestible telemetric capsules (CoreTemp, HQInc.). Skin temperatures were continuously measured from four sites (chest, arm, thigh, and leg) using wired thermistors (SmartReader 8 Plus, ACR) and were expressed as weighted mean skin temperature (T_{sk}) according to Ramanathan⁴⁵: $0.3 \times (\text{chest} + \text{arm}) + 0.2 \times (\text{thigh} + \text{leg})$. Heat flow on the skin surface under the shirt was measured using calibrated heat flux transducers with embedded thermistors (FR-025-TH44033-F6, Concept Engineering) which were placed on the center of the pectoralis major, rectus abdominis, trapezius, and the latissimus dorsi on the non-dominant side of the body. Heat flow data were recorded every 8 sec and expressed as average heat flow (HF_{avg}) using the arithmetic mean. All sensors were fixed in place using surgical tape (Fixomull stretch, BSN Medical). The average running pace of each participant during each session was collected from the treadmill velocity. These data were used to calculate the reduction in running speed compared to the running speed at 70% $\dot{V}O_{2peak}$ recorded during the $\dot{V}O_{2peak}$ assessment which was performed during the familiarization session. Subjective data including thermal comfort (1 = comfortable; 10 = extremely uncomfortable),⁴⁶ thermal sensation

(−4=very cold; +4=very hot),⁴⁷ and perceived exertion (0=not fatigued at all; 10=total fatigue & exhaustion – nothing left)⁴⁸ were assessed at baseline and every 10 min during the experimental protocol until completion.

Upon completion of each experimental trial, participants were provided with a tablet equipped with a custom-made software application. This software included a series of four questions that were used to characterize the subjective moisture management and cooling functionality of each of the four t-shirts tested: (i) “The way the garment manages moisture is...”, 1: very uncomfortable to 5: very comfortable; (ii) “The moisture management keeps the garment...”, 1: very wet to 5: very dry; (iii) “While wearing the garment to keep cool in warm conditions, I feel...”, 1: very uncomfortable to 5: very comfortable; and (iv) “The capacity of the garment to keep me cool in warm conditions is ...”, 1: very low to 5: very significant. The same software also allowed the participants to identify and highlight particular areas on each shirt where they felt that heat dissipation was not optimal. To accomplish this, participants were instructed to respond to the following prompt: “If applicable, please circle specific areas where the cooling capacity was not optimal.” Finally, sweat accumulation (pre- and post-clothing mass) in each t-shirt was determined by weighing it at the end of each trial using a scale with a precision of 1 g (KernDE 150K2D, KERN & Sohn GmbH). Sweat accumulation reflects the total amount of sweat gathered in the clothing and does not indicate regional sweat absorption, as previously shown.⁴⁹

2.4 | Data analysis

Average values for the collected variables were calculated for each participant during each experimental session. The majority (68%) of the tested variables were normally distributed, while six (32%) variables (HF_{avg} , delta USG, and the four questions related to subjective moisture management and cooling functionality) were not normally distributed, as determined by the Shapiro–Wilk test of normality. To clearly present the thermophysiological and perceptual responses of the monitored participants throughout the study, a descriptive analysis was performed in all recorded variables. Pearson's correlation coefficient was used to examine potential associations among all the variables measured during each trial. For normally distributed variables, a one-way ANOVA with a Bonferroni multiple comparison post hoc test was used to examine potential differences in running speed, physiological heat strain, and perceptual responses among the four t-shirt conditions. For non-normally distributed variables, the Kruskal–Wallis non-parametric test was employed to examine potential differences among the four

t-shirt conditions. In addition to the post hoc comparisons, Cohen's *d* effect sizes were computed among all t-shirts across all variables. To further investigate potential differences in T_{core} , T_{sk} , % of HR_{max} , and running speed across the tested t-shirt conditions at various time points (0, 15, 30, 45, and 60 min), a two-way ANOVA test was performed.

To accurately depict the specific regions on the shirt where heat dissipation was identified as suboptimal by the participants, a statistical analysis of their marked areas was conducted. Specifically, the percentages of the back and front areas of each t-shirt that were marked as having suboptimal cooling functionality during each trial were calculated by measuring the colored pixels and dividing them by the total number of pixels for the respective areas of the t-shirt (see Figure 4) using Adobe Photoshop 2022 (Adobe Systems Incorporated). Thereafter, a Kruskal–Wallis non-parametric test was utilized, along with Cohen's *d* effect sizes, to examine potential differences in perceived cooling functionality among the four t-shirt conditions. All statistical analyses were conducted using SPSS 28.0 for Windows (IBM) and Excel spreadsheets (Microsoft Office, Microsoft Corp.). The accepted level of significance was set at $p < 0.05$. The magnitude of effect sizes was determined as follows: *d* (0.01)=very small; *d* (0.2)=small; *d* (0.5)=medium; *d* (0.8)=large; *d* (1.2)=very large; and *d* (2.0)=huge.⁵⁰ All results are presented as mean $\pm$ standard deviation.

3 | RESULTS

During the experimental trials, the average running speed at 70% $\dot{V}O_{2peak}$ was 10.7 ± 1.6 km/h (6.6 ± 1.0 mi/h), with a range spanning from 7.0 km/h (4.3 mi/h) to 14.5 km/h (9.0 mi/h). Mean ($80 \pm 4\%$ of HR_{max}) and maximum ($89 \pm 5\%$ of HR_{max}) heart rate ranged from 71% to 90% of HR_{max} and from 79 to 99 of HR_{max} , respectively. Mean ($38.1 \pm 0.3^\circ\text{C}$) and maximum ($39.0 \pm 0.4^\circ\text{C}$) T_{core} varied from 37.1°C to 39.4°C and from 37.8°C to 40.2°C , respectively. Mean ($34.9 \pm 0.6^\circ\text{C}$) and maximum ($35.8 \pm 0.7^\circ\text{C}$) T_{sk} varied from 33.6°C to 36.3°C and from 34.4°C to 38.2°C , respectively. Mean ($-50.9 \pm 14.2 \text{ W/m}^2$) and maximum ($-85.9 \pm 18.9 \text{ W/m}^2$) HF_{avg} ranged from -3.2 W/m^2 to -78.6 W/m^2 and from -3.2 W/m^2 to -123.2 W/m^2 , respectively (negative heat flux indicates heat loss from the body to the environment). Body water loss ($1.9\% \pm 0.3\%$ body mass) ranged from 1.1% to 2.6% body mass. Mean thermal comfort (6.6 ± 0.8) and thermal sensation (2.3 ± 0.7) ranged from 4.4 to 7.9 (1 = comfortable; 10 = extremely uncomfortable) and from 1.0 to 3.8 (−4 = very cold; +4 = very hot), respectively. Mean perceived exertion (3.7 ± 1.4) ranged from 1.0 to 6.8 (0 = not fatigued at all; 10 = total

fatigue and exhaustion—nothing left). Average fluctuations of physiological heat strain and running speed over exercise duration are illustrated in Figure 1.

T_{core} was positively associated with T_{sk} ($r=0.385$), HR_{max} ($r=0.685$), running speed ($r=0.099$), running duration ($r=0.847$; Figure 1), thermal comfort ($r=0.255$), thermal sensation ($r=0.359$), and perceived fatigue ($r=0.400$), all at $p<0.001$. Conversely, there was a negative association between the T_{core} and HF_{avg} ($r=-0.620$, $p<0.001$), indicating that higher T_{core} led to increased heat dissipation. In terms of running speed, the only statistically significant association found with physiological or perceptual data was a negative one between mean thermal sensation and running speed ($r=-0.361$, $p=0.002$), as illustrated in Figure 2.

With respect to the primary aim of the study, no statistically significant differences (all $p>0.05$; for both normally and non-normally distributed variables) were detected among the four studied shirts in terms of running speed, physiological heat strain, and perceptual parameters of national-level and well-trained athletes (Figure 3). Similarly, there were no meaningful effect sizes among all t-shirts across all variables (average absolute $d=0.22$ and median absolute $d=0.18$). Additionally, no statistically significant

effects were observed for t-shirt condition (all $p>0.05$), while there was a significant effect of duration (all $p<0.001$) on T_{core} , T_{sk} , % of HR_{max} , and running speed at the examined time points (0, 15, 30, 45, and 60 min). However, it is worth noting that a marginally statistically insignificant difference was observed for the t-shirt condition on T_{core} , $F_{(3,354)}=2.625$, $p=0.0503$, with an average Cohen's d across all tested time points of 0.11. Despite the lack of statistically significant differences across all variables among the four investigated t-shirts, some of the participants in this study reported that a larger area in the cotton and aluminum dots shirts exhibited suboptimal cooling functionality in comparison to sweat-wicking and compression shirts (Figure 4). Specifically, six participants (30%) reported suboptimal cooling functionality in one or more sportswear as follows: cotton (4 participants: 20%), sweat-wicking (3 participants: 15%), compression (1 participant: 5%), and shirt with aluminum dots (4 participants: 20%). Although there were apparent visual distinctions in perceived cooling functionality (refer to Figure 4), statistical analyses revealed no significant differences ($p>0.05$) in perceived cooling functionality among the four t-shirts tested. Specifically, the average percentage of each t-shirt perceived to have suboptimal cooling functionality was: cotton $9.2\pm 22.7\%$,

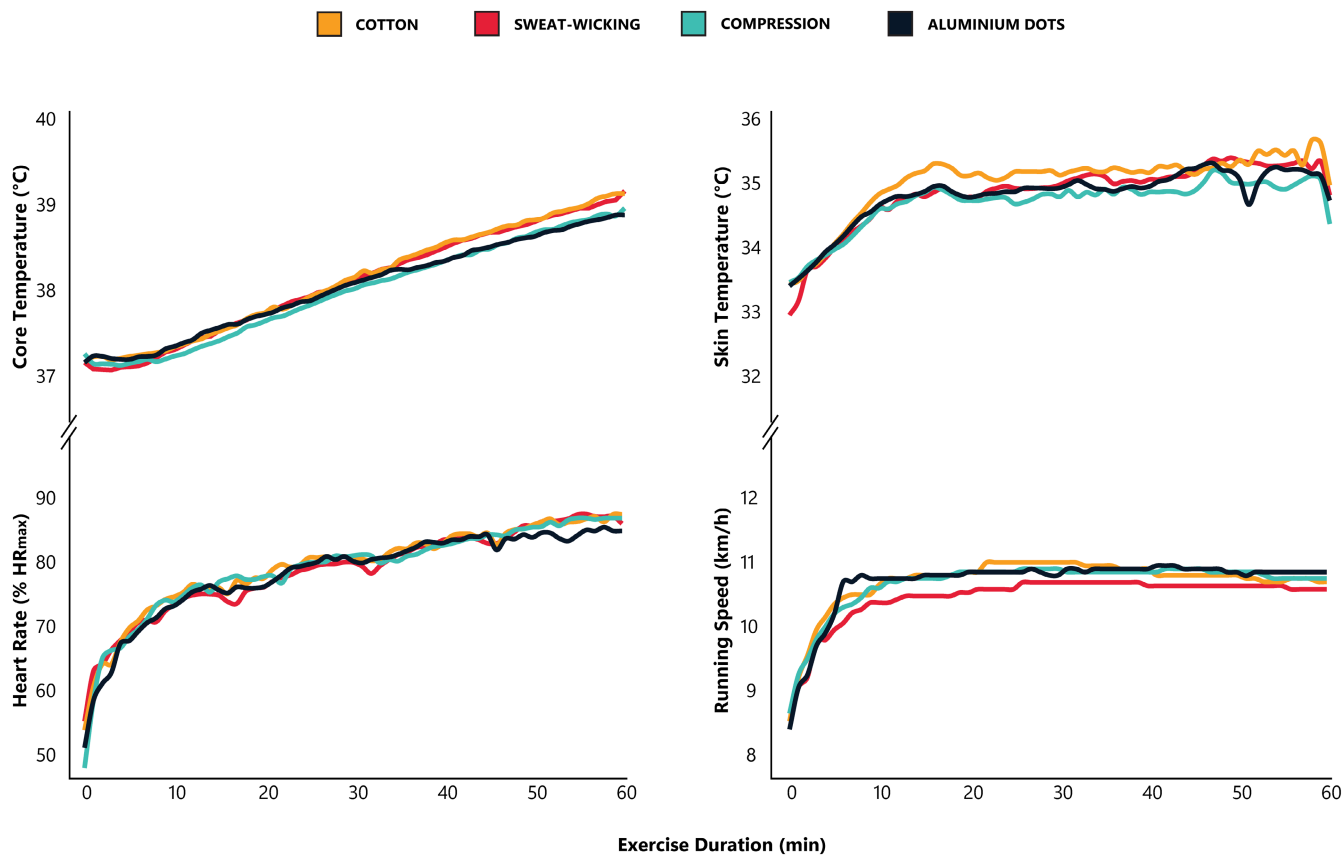
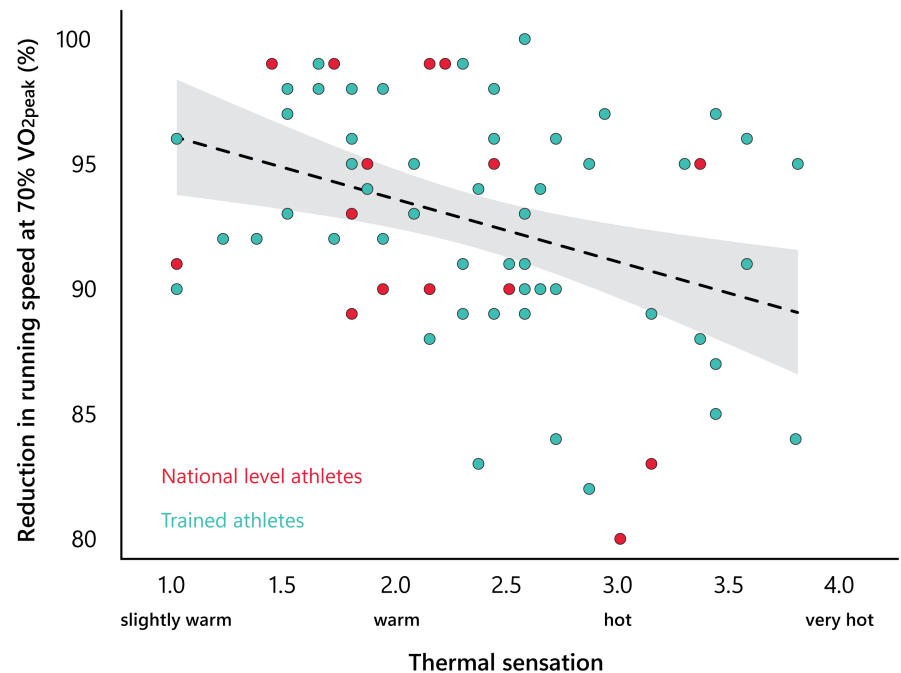


FIGURE 1 Average fluctuation of core and skin temperatures, as well as heart rate and running speed over the exercise duration. Orange, red, turquoise, and black lines represent the cotton shirt, sweat-wicking shirt, compression shirt, and shirt with aluminum dots on the upper back, respectively.

FIGURE 2 Relationship between the recorded running speed (calculated by comparing it to the running speed at 70% $\dot{V}O_{2peak}$ from the $\dot{V}O_{2peak}$ assessment during their first visit) and average thermal sensation during each running session. Red and turquoise colors represent national-level and well-trained athletes, respectively. Black dashed line and gray shaded area represent the linear trend and associated confidence band, respectively.



sweat-wicking $1.0\% \pm 3.2\%$, compression $0.6\% \pm 2.9\%$, and aluminum-dots $5.4\% \pm 13.8\%$. However, it should be emphasized that the cotton and aluminum-dots t-shirts exhibited lower perceived cooling functionality as compared to the sweat-wicking and compression t-shirts, with medium to large effect sizes ($d = 0.43$ – 0.52).

4 | DISCUSSION

The present study aimed to investigate the impact of different technologies embedded in sports t-shirts (sweat-wicking t-shirts, compression t-shirts, and t-shirts with aluminum dots) on the performance and physiological heat strain experienced by well-trained and national-level athletes during prolonged moderate-intensity exercise in moderately hot, dry conditions. Our results demonstrate no statistically significant differences in running speed, physiological heat strain, or perceptual responses among the tested technologies. Therefore, our findings in these controlled laboratory conditions suggest that the tested upper-body sportswear technologies did not confer substantially different advantages in terms of heat dissipation/gain and performance during endurance (one-hour run) exercise in moderate heat.

Over the past two decades, many studies have investigated the impact of commercial sportswear on exercise capacity, physiological heat strain, and perceptual responses.¹⁹ The majority of these studies primarily focused on the effects of sportswear technologies on physiological responses during very low-^{51,52} to low-^{31,53} intensity exercise, typically during fixed-rate

treadmill running or stationary cycling.¹⁹ Some studies^{20,26,27} used moderate- to high-intensity exercise; however, these studies featured short exercise durations, ranging from 25 to 30 min, and were performed in mildly hot conditions (22.1 – 24.6°C WBGT). For context purposes, the American College of Sports Medicine suggests that environmental conditions ranging from 23 to 28°C WBGT indicate a “red flag,” and all runners should be aware that heat injury is possible.⁵⁴ It is important to note that although this study was conducted at a higher exercise intensity than most previous studies, the observed perceived fatigue levels were lower than anticipated based on the recorded heart rate levels. We speculate that the unacclimated participants of the present study based their fatigue on past running paces, potentially overlooking the impact of heat on their bodies. This notion aligns with the understanding that perceived fatigue is inherently relative to an individual's usual daily experiences.⁵⁵ Nevertheless, despite being conducted in less thermally stressful conditions, two of those studies aligned with the findings of the present study, demonstrating no meaningful differences in physiological heat strain between commercially available sportswear technologies and standard cotton shirts.^{20,27} Only one study²⁶ found notable local skin temperature reductions (up to -3.8°C) when using a specific sportswear technology; however, these improvements in local skin temperature may be attributed to evaporative cooling from the experimental shirt being dampened with water rather than its cooling properties per se.

Much of the existing research on the impact of sportswear technologies on thermoregulation during exercise

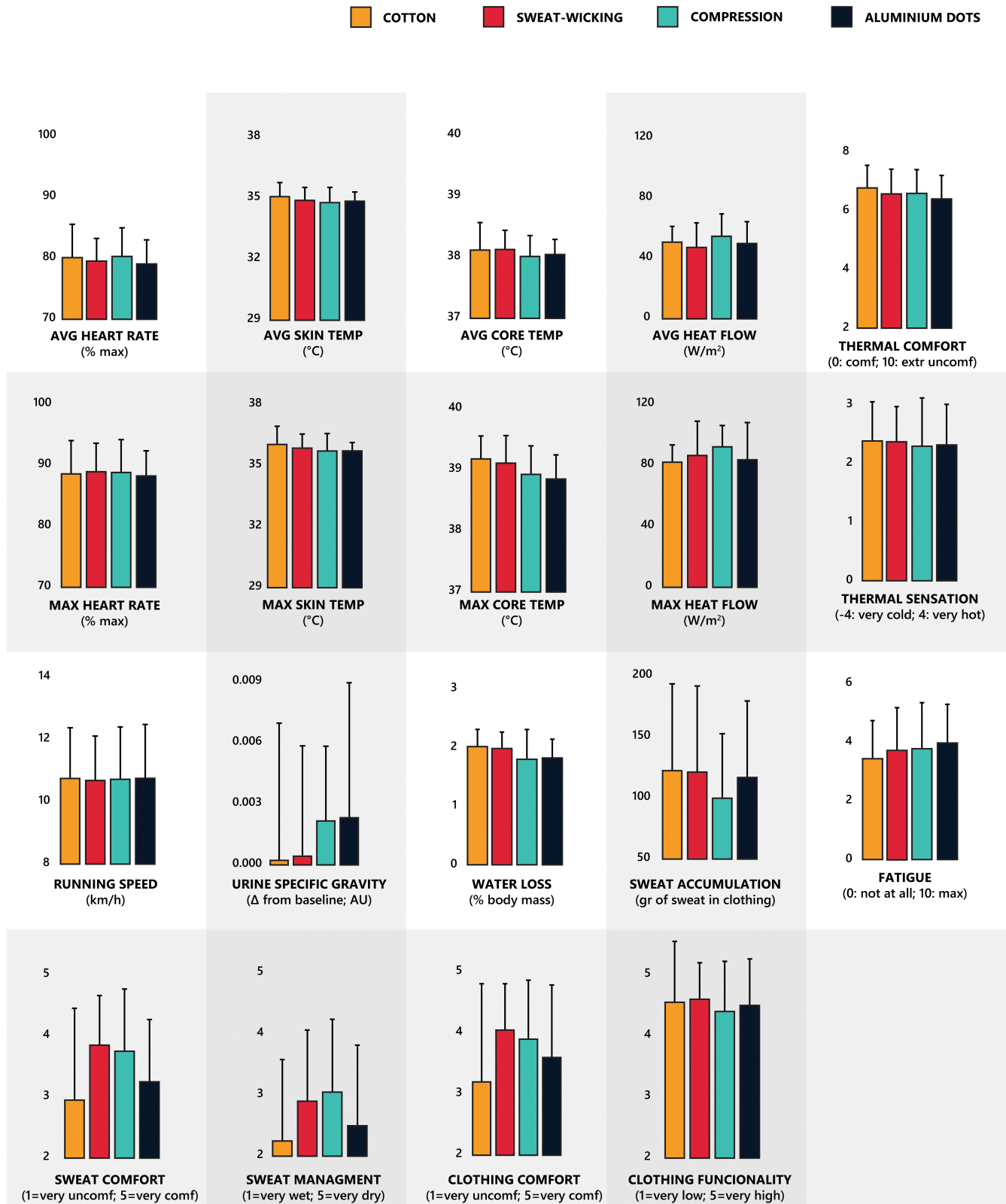


FIGURE 3 Physiological heat strain (average and maximum values), running speed, and perceptual parameters among the four clothing conditions (presented as means $\pm$ standard deviations). Orange, red, turquoise, and black bars represent the cotton shirt, sweat-wicking shirt, compression shirt, and shirt with aluminum dots on the upper back, respectively. No statistically significant differences were detected among the four clothing conditions in any of the presented parameters (all $p > 0.05$). The following abbreviations and acronyms were used: AU, arbitrary units; AVG, average; comf, comfortable; extr, extremely; gr, gram; MAX, maximum; Temp, temperature; uncomf, uncomfortable.

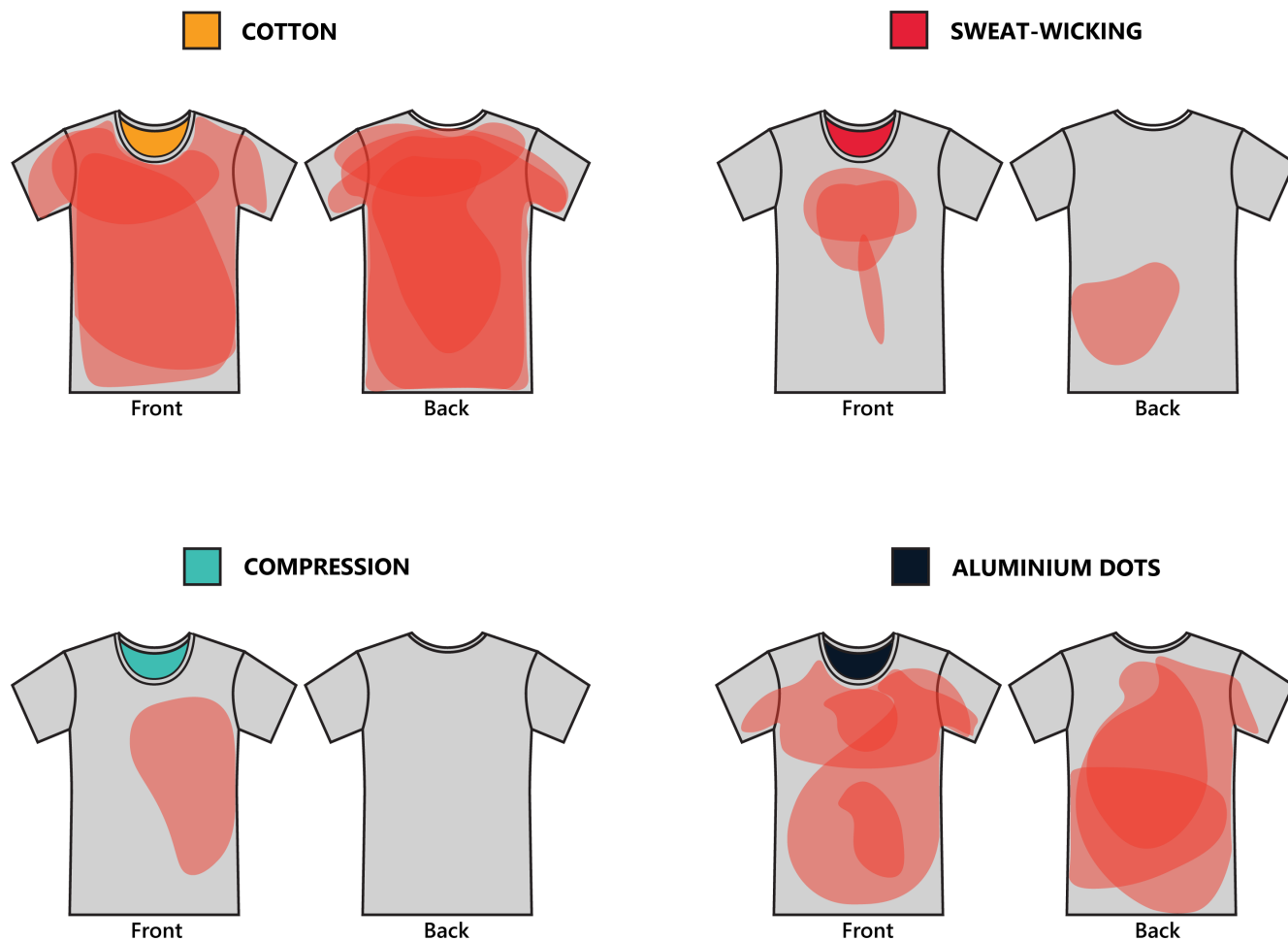


FIGURE 4 Red-shaded areas represent specific regions on the shirt where heat dissipation was deemed (self-reported using a custom software) suboptimal by participants in the present study. Absence of red shading indicates that no participants identified any areas with suboptimal cooling functionality. Conversely, darker shades of red signify regions reported as suboptimal by a larger number of participants.

in the heat has been primarily carried out using thermal manikins,²⁵ and there is a significant discrepancy between the data obtained from manikin studies and the corresponding data collected from human participants.¹⁸ The results from thermal manikin studies may not fully translate to physiological effects due to multiple factors. First, thermal manikins are inanimate objects lacking accurate thermophysiological responses, such as varying sweating and vasodilation, which play a crucial role in human thermoregulation during exercise in the heat. Second, the complexity of human body shapes, movements, and biomechanics is not adequately captured by thermal manikins, which may result in discrepancies in the efficacy of sportswear technology when applied to real-life scenarios.^{18,24} Nevertheless, it is crucial to recognize that while manikin studies have unveiled some differences among sportswear technologies, evaluating their relevance in humans is of great importance.²⁴ This is because these variations seem to be of little significance when it comes to influencing the physiological

heat strain and running speed of individuals exercising in the heat, as the human ability for thermoregulation appears to overshadow any minimal difference between sportswear technologies.

Despite the insights this study offers into the influence of sportswear technology on the physiological heat strain experienced by well-trained and national-level athletes during extended exercise in warm environments, it is essential to consider the study's limitations when interpreting its findings. First, the sample of the present study was focused on well-trained and national-level athletes, which may limit the generalizability of the results to other populations or sports disciplines. Second, we only examined the scenario of wearing the tested technologies during continuous exercise sessions, and it remains possible that intermittent exercise such as football, basketball, or racket sports, which are known to induce hyperthermia,⁵⁶ could lead to different outcomes. Third, this study was conducted in controlled laboratory conditions, which may not fully replicate the

complex and variable environmental conditions, including factors such as solar radiation and wind speed, which affect the physiological heat strain experienced by athletes during real-world competitions. For example, while many running events are scheduled early in the morning or in the late afternoon to reduce the adverse impacts of sun exposure on athletes, it is important to recognize that not all sports take place during these low-sunlight hours of the day. As such, future studies should consider accounting for sun exposure given its impacts on human physiology and cognition,^{23,57} as well as the potential for light-colored clothing to reduce skin temperature in sunny conditions.²³ An additional environmental factor that remained constant, yet was not specifically addressed in our study, is air velocity, set at a very low level of 0.3 m/s. Air velocity significantly influences both convective and evaporative heat loss from the body, playing a significant role in thermoregulation during exercise.⁵⁸ This factor is especially important for well-trained athletes, such as our study participants, who often have higher sweat rates.⁵⁹ As a result, these athletes might derive greater benefits from increased air velocities that facilitate evaporative heat loss.⁶⁰ We chose to maintain a multidirectional air flow of 0.3 m/s (comparable to the level of air flow in the majority of relevant studies in literature¹⁹) to minimize variability due to changes in body orientation in real-life scenarios and the fluctuating running speeds inherent in our study protocol. However, we acknowledge that this setting might not adequately represent the diverse wind conditions athletes face outdoors, such as in marathon races or cycling events, where conditions can range from calm to gusty. Such variability can affect the performance of sportswear technologies in mitigating physiological heat strain. Therefore, for a holistic understanding, future research should also examine the efficacy of sportswear technologies across various air velocity conditions.

The present study contributes to the growing body of literature examining the effectiveness of sportswear technologies in mitigating heat strain during endurance exercise in warm or hot environments. While our findings do not support a particular advantage of one of the tested technologies over the others, it is crucial for future research to continue exploring the potential benefits of sportswear technologies and their interactions with various environmental factors and individual characteristics. This is because the enhanced thermoregulatory capacity that typically characterizes well-trained individuals,⁶¹ such as the participants in the present study, could offset the impact of sportswear designed to increase heat dissipation. For example, healthy-fit individuals could counterbalance any sportswear-related

thermoregulatory restriction by sweating more for a given rise in body temperature. Conversely, clothing that facilitates heat loss could offer greater benefits to older or less fit adults, who often have diminished heat dissipation capabilities.^{61–64} Therefore, it is essential to consider how significantly clothing impacts individuals with reduced heat dissipation capabilities, an issue that may not apply as readily to young, well-trained athletes. This will allow for a more comprehensive understanding of the role of clothing in managing heat dissipation and ultimately contribute to the development of evidence-based recommendations for people exercising in thermally demanding conditions.

5 | PERSPECTIVE

In this study, we investigated the effect of different sportswear technologies on the running speed and physiology of well-trained and national-level athletes during one-hour exercise sessions at 70% $\dot{V}O_{2peak}$ in moderately hot conditions. Our results demonstrated that the tested upper body sportswear technologies had similar impacts on running speed at 70% $\dot{V}O_{2peak}$, physiological heat strain, and perceptual responses without offering any physiological and performance advantage. These findings cannot be attributed to a small study sample size and are in line with previous studies conducted in less thermally stressful conditions and/or at lower exercise intensities, which showed no significant impact of sportswear technologies on well-trained individuals.^{19,20,27} In addition to confirming previous findings on physiological heat strain, the present study tested new sportswear technologies such as compression t-shirts and t-shirts with aluminum dots lining the inside of the garment. We found no significant impact on physiological heat strain and running speed at 70% $\dot{V}O_{2peak}$ in well-trained and national-level athletes. Interestingly, although the present study revealed no significant differences among the tested sportswear, athletes in the study reported experiencing larger areas of suboptimal cooling functionality in some of the tested sportswear technologies.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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