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The impact of passive heat maintenance strategies between an active warm-up and performance: a systematic review and meta-analysis

Gavin Cowper* , Stuart Goodall, Kirsty Hicks, Louise Burnie and Marc Briggs

Abstract

Background: Prior to exercise, a warm-up routine has been suggested to be an imperative factor in task readiness with the anticipation that it will enhance performance. One of the key benefits of a warm-up is the increase in muscle and core temperature, which can be achieved in a variety of ways. An effective way to achieve improvements in core and muscle temperature is by performing an active warm-up. However, lengthy transition periods between an active warm-up and exercise performance are known to cause a decline in core and muscle temperature, thereby reducing performance capability. As such, methods are needed to assist athletes during transition periods, to maintain the benefits of a warm-up with the aim of optimising performance. Accordingly, the purpose of this review is to systematically analyse the evidence base that has investigated the use of passive heating to aide sporting performance when a transition period is experienced.

Methods: A systematic review and meta-analysis were undertaken following relevant studies being identified using PubMed, Web of Science, and EBSCO. Studies investigating the effects of passive heating strategies during the transition period between an active warm-up and exercise performance were included. The quality of the included studies were assessed by two independent reviewers using a modified version of the Physiotherapy Evidence Database scale.

Results: Seven studies, all high quality (mean = 7.6), reported sufficient data (quality score > 5) on the effects of passive heating strategies on exercise performance, these studies consisted of 85 well-trained athletes (78 male and 7 female). Passive heating strategies used between an active warm-up and exercise, significantly increased peak power output in all studies (ES = 0.54 [95% CI 0.17 to 0.91]). However, only a favourable trend was evident for exercise performance (ES = 1.07 [95% CI - 0.64 to 0.09]).

Conclusions: Based upon a limited number of well-conducted, randomised, controlled trials, it appears that passive heating strategies used between an active warm-up and exercise have a positive impact on peak power output. Although, additional research is necessary to determine the optimum procedure for passive warm-up strategies.

Keywords: Clothing, Core temperature, Muscle temperature, Passive heating, Peak power, Performance, Temperature

Introduction

Before exercise, a warm-up routine has been suggested to be an imperative factor in task readiness with the anticipation that it will enhance performance [1]. One of the key benefits of a warm-up is the increase in muscle and

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core temperature and this can be achieved in a variety of ways [2]. The most effective way to achieve improvements in core and muscle temperature is by performing an active warm-up, which involves a series of dynamic movements [3]. The subsequent increase in muscle temperature results in various physiological advantages, including an increased speed of contraction and relaxation of muscle fibres, increased anaerobic metabolic capacity and improved nerve conduction within the peripheral, and central, nervous systems [4]. Therefore, maximising the effectiveness of the active warm-up phase prior to sports performance is an integral part of preparation. After the active warm-up period, athletes can often wait between 10 and 30 min before the start of competition (transition period). Zochowski et al. found that a reduction in the length of the transition period yields performance benefits, whereas a lowering of core and muscle temperature occurs when transition periods are prolonged [5, 6]. However, it can be challenging to alter competition schedules by a substantial margin. As such, methods are needed to assist athletes through transition periods, to maintain elevated core and muscle temperatures gained from a warm-up with the aim of optimising performance.

Initially, hot showers or baths were used to combat the decline in muscle and core temperature in swimming [7, 8], however, logistical, and practical issues make these methods difficult to use in the majority of sporting scenarios. Therefore, recent investigations have developed methods to maintain an elevated muscle and core temperature during the transition phase between the warm-up, and subsequent exercise performance. Faulkner et al. were the first to implement a passive heating device following an active warm-up [9]. Specifically, these authors investigated the use of heated tracksuit pants in the marshalling period before a sprint cycling race, and the intervention significantly reduced the decline of muscle temperature whilst peak power output improved. Additionally, similar passive heating garments and blizzard survival jackets have been used to manipulate body temperature during the transition phase and have improved bobsled [10], rugby [11], swimming [12, 13], and rowing [14] performance.

Thus, passive heating seems to be a logical, practical intervention to maintain warm-up-induced elevations in core and muscle temperature throughout the long transition periods observed in sports competitions. The use of a heat maintenance device during the transition period following an active warm-up, and prior to competition, has the capacity to yield performance enhancing benefits akin to those of an active warm-up. Therefore, the purpose of this review is to systematically analyse the evidence base that has investigated the use of

passive heating in the transition period to aide sporting performance.

Methods

Search strategy

A systematic review was conducted according to Preferred Reporting Items for Systematic reviews and Meta Analyses guidelines (PRISMA) [15]. Relevant publications published prior to December, 2021 in three databases (PubMed, Web of Science & EBSCO) were identified. The search was performed using the Boolean search criteria, which limited the search results with operators including AND/OR to only those documents containing relevant key terms in the scope of this review (see Table 1).

Eligibility search

Research articles were included or excluded using criteria defined with the Population, Intervention, Comparison and Outcome criteria (PICO) [16], and the literature searches were limited to studies involving trained athletes, defined as an athlete who regularly competes in key regional or national tournaments in their specific sport. Grey literature such as thesis dissertations, and conference abstracts were excluded. Additionally, all included studies had to be written in the English language and had to be published in a peer-reviewed journal. The search strategy and eligibility criteria are shown in Table 1.

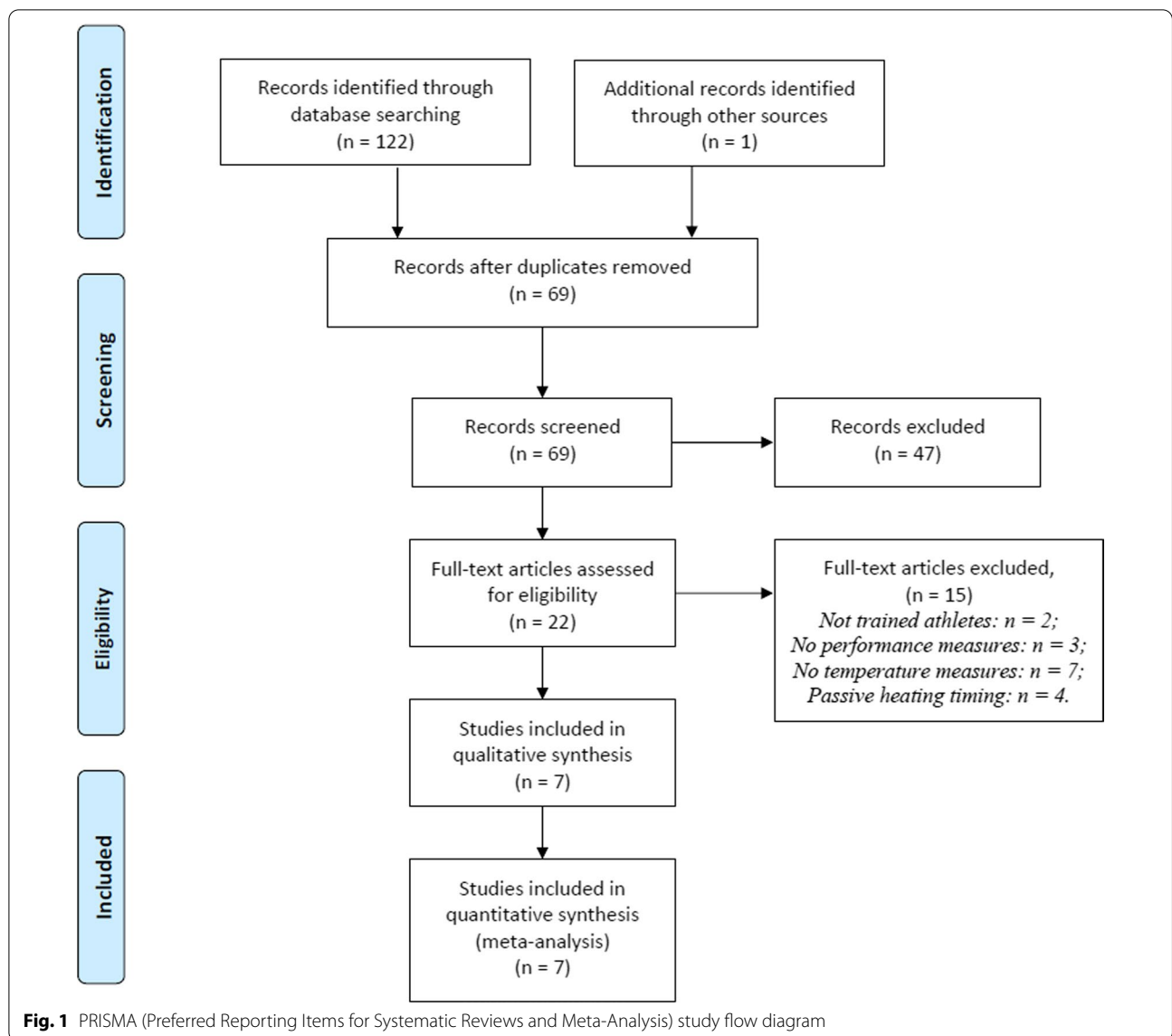
Study selection

The initial search identified 123 articles with potential relevance. After removing duplicates and studies that were not specific to passive warm-up strategies, a manual screening according to the abstract was performed, and those that were not relevant were excluded. Two authors (G.C., M.B.) independently assessed articles against the inclusion criteria. From these studies, 22 original full-text research articles were assessed for eligibility, and those that did not meet the inclusion criteria were excluded. For the quantitative analysis, seven articles were included (Fig. 1).

Once the articles were removed based on the exclusion criteria, the final papers underwent an assessment of quality, using a modified version of the Physiotherapy Evidence Database (PEDro) scale. Due to the specificity of the topic, the scale was altered and questions 3–6 were replaced with more pertinent related questions. The PEDro scale is an 11-item scale designed to measure the methodological quality of experimental studies, with the reliability of the database being previously established [17]. Each satisfied criterion (except item 1, which pertains to external validity) is graded one point to the overall score (possible range of 0–10 points). Eight items on

Table 1 Search strategy and inclusion/exclusion criteria based on PICO (population, intervention, comparison and outcome)

Databases	Search terms	PICO	Inclusion criteria	Exclusion criteria
PubMed, EBSCO, Web of Science	((sport* OR exercise* OR perform*) AND ("post-warm-up" OR "warm-up" OR "half-time" OR "rewarming" OR "re-warming" OR "passive warming" OR "interval" OR "quarter") AND ("passive heat*" OR "heat*" jacket" OR "heat*" pants" OR "blizzard survival jacket*" OR "heat*" garment"))	Population Intervention Comparison Outcome	Trained athletes An active warm-up combined with a passive heating intervention Passive heating strategies and control Core and/or muscle temperature variations during passive heating intervention Performance measures (time to competition, distance covered)	Non-trained athletes No passive heating intervention applied following an active warm up No comparison between a passive heating intervention and control No core and/or muscle temperature variations during passive heating intervention Performance measures not recorded



the scale assess the internal validity with the remaining two analysing the sufficiency of the statistical information. In agreement with previous reviews, studies with a score of 5 out of 10 or higher were included in the review to improve the credibility of the analysis [18, 19].

Data extraction

From the included articles, data on sample size and participant sex, passive heating strategy and the duration of the passive heating strategy, physiological temperature changes during the intervention, exercise protocol and the performance outcomes were extracted. In addition to the ambient temperature and humidity. Outcome data were presented using a Microsoft Excel 2016 spreadsheet (Microsoft, Redmond, WA, USA) (Table 2).

Meta-analysis

To analyse the impact of passive heating strategies on exercise performance, the mean and standard deviation of performance outcomes and physiological effects was inputted in a Microsoft Excel 2016 spreadsheet (Microsoft, Redmond, WA, USA). Cohen’s d was used to calculate effect sizes (ES), this was categorised as follows: <0.2 = trivial effect size, 0.2–0.5 = small effect size, 0.5–0.8 = medium effect size and >0.8 = large effect size [22]. Following this, the standard error of the effect size was calculated.

Meta-analyses and forest plots were produced using commercially available software (JASP Team, Amsterdam, Netherlands). The Cochran’s Q test was performed to test the null hypothesis of heterogeneity to identify

Table 2 Physiological and performance changes in exercise performance following a passive heating intervention

Study	Participants		Conditions		Intervention		Phys. changes (°C)		Performance task		Performance changes
	Temperature (°C)	Humidity (%)	Passive heating method	Duration (min)	Baseline—post rec	Post WU—post rec	Exercise protocol				
Cook et al. [10]	20	70–75	Tracksuit Top (CON) Blizzard Survival Garment (HEAT)	15	$T_{Tymp} = \downarrow 1.0$ $T_{Tymp} = \downarrow 0.1$		3 × 20 m Sledpull sprint (3 min recovery)	TTC ↓ 3.53% ± 0.61% for HEAT versus CON ($P < 0.05$)			
Cowper et al. [14]	8	50	Tracksuit Top (CON) Tracksuit Top with integrated electric heating elements (HEAT)	25	$T_{Tymp} = \downarrow 0.93$ $T_{Tymp} = \uparrow 0.54$		2000 M Rowing TT	TTC ↓ 1.1% for HEAT versus CON ($P < 0.01$)			
Falkner et al. [9]	15.9 ± 0.3	54.0 ± 4.0	Tracksuit (CON) External heated pants (HEAT) Insulated tracksuit pants (INS)	30	$T_{Rec} = \downarrow 0.2$ $T_{Rec} = \downarrow 0.3$ $T_{Rec} = \downarrow 0.1$		30 s maximal sprint cycle	PPO ↑ 9.1% HEAT versus CON ($P < 0.05$) PPO ↑ 4.1% HEAT versus INS Mean PO ↑ 7.8% HEAT versus CON Mean PO ↑ 8.4% HEAT versus INS			
Falkner et al. [20]	16.1 ± 0.2	53 ± 2.0	Tracksuit (CON) External heated pants during REC (HEAT) External heated pants during WU and REC (HEATHEAT)	30	$T_{Rec} = \downarrow 0.1$ $T_{Tmusc} = \downarrow 1.5$ $T_{Rec} = \downarrow 0.3$ $T_{Tmusc} = \downarrow 1.3$ $T_{Rec} = \downarrow 0.1$ $T_{Tmusc} = \downarrow 1.2$		30 s maximal sprint cycle	PPO ↑ 11.1% HEAT versus CON ($P < 0.005$) PPO ↑ 1.2% HEAT versus HEATHEAT Mean PO ↑ 4.3% HEAT versus CON ($P < 0.005$) Mean PO ↑ 0.7% HEAT versus HEATHEAT			
Killduff et al. [21]	19.5 ± 0.3	63.0 ± 3.0	Tracksuit (CON) Blizzard survival Garment (HEAT)	15	$T_{Pill} = \downarrow 0.56$ $T_{Pill} = \downarrow 0.19$		CMJ and 6 × 40 m (20+20 m) shuttle sprints separated by 20 s of passive recovery (RST)	CMJ PPO ↑ 3.5% HEAT versus CON ($P < 0.001$) RST Mean ↓ 0.7% HEAT versus CON ($P < 0.05$)			
West et al. [5]	21.4 ± 0.4	61.0 ± 2.0	Tracksuit (CON) Blizzard survival Garment (HEAT)	20	$T_{Pill} = \downarrow 0.64$ $T_{Pill} = \downarrow 0.2$		CMJ and 6 × 40 m (20+20 m) shuttle sprints separated by 20 s of passive recovery (RST)	CMJ PPO ↑ 3.2% HEAT versus CON ($P < 0.05$) RST Mean ↓ 4% HEAT versus CON ($P < 0.05$)			
Wilkins and Havenith [13]	23.4 ± 0.1	55.8 ± 1.4%	Tracksuit (CON) External heated jacket (HEAT)	30	$T_{Tymp} = \downarrow 0.8$ $T_{Tymp} = \downarrow 0.8$		Max plyometric presses (PPU) and 50 m freestyle swimming time trial	PPU Peak Force ↑ 10.1% HEAT versus CON ($P < 0.05$) TTC ↓ 0.83% for HEAT versus CON ($P = 0.06$)			

CON, Counter movement jump; REC, Recovery; RST, Repeated sprint time; PO, Power output; PPO, Peak power output; PPU, Plyometric press-up; T_{Tymp} , Tympanic temperature; T_{Rec} , Rectal thermometry; T_{Pill} , Ingestible core sensor; T_{musc} , Muscle temperature; TT, Time trial; TTC, Time to completion; WU, Warm-up; ↑, Increase; ↓, Decrease

whether studies had similar effect sizes. Statistical heterogeneity was defined as I^2 small (< 30%) and large (> 50%) respectively [23]. If specific data was not presented in the study, the corresponding author was contacted and given 30 days to respond. If no response was received, the data was excluded from the meta-analyses.

Results

Study identification and selection

Initially, a total of 123 studies were retrieved from the literature search. From these 123 articles, duplicates were removed ($n=54$). The titles and abstracts of each entry (69 articles) were then screened for their relevance, which resulted in the rejection of 47 articles from the analysis. Following this trimming, the full texts of the remaining 22 articles were reviewed. Of the 22 articles, 15 were excluded due to their irrelevance to the topic area. After one article was retrieved and accepted through other source, seven articles were accepted for the systematic review completing the full screening process. A summary of the process involved in retrieving suitable studies can be viewed in the flowchart presented based on the process developed for the quality of reporting of meta-analyses [15] (see Fig. 1).

Methodological quality

After the application of the pre-defined exclusion criteria, the remaining full-text articles were assessed for methodological quality via a Modified Physiotherapy Evidence Database (PEDro) scale. All seven of the remaining articles achieved a PEDro score of 5 or above and thus were included in the review commentary. The mean range of quality scores was 7.6 ± 1.1 (range, 6–9 out of 10) (Additional file 1: Table S1).

Study characteristics

A chronological analysis of the articles that comprised this review showed a recent interest in this area of research, with all the included studies published in the last eight years (2013–2021). In the seven eligible articles, outcomes were presented for 85 participants (individual study sample sizes ranging from six to 20 participants), which were well-trained athletes of whom 78 were male and seven were female. Exercise modalities included cycling, rowing, bobsleigh, repeated sprints, plyometrics and bodyweight exercises. Considerable methodological variations also existed with regards to the active warm-up and strategies of passive heating. The most prominent variations were in the passive heating duration and choice of garment (see Table 2).

Performance responses to passive heating

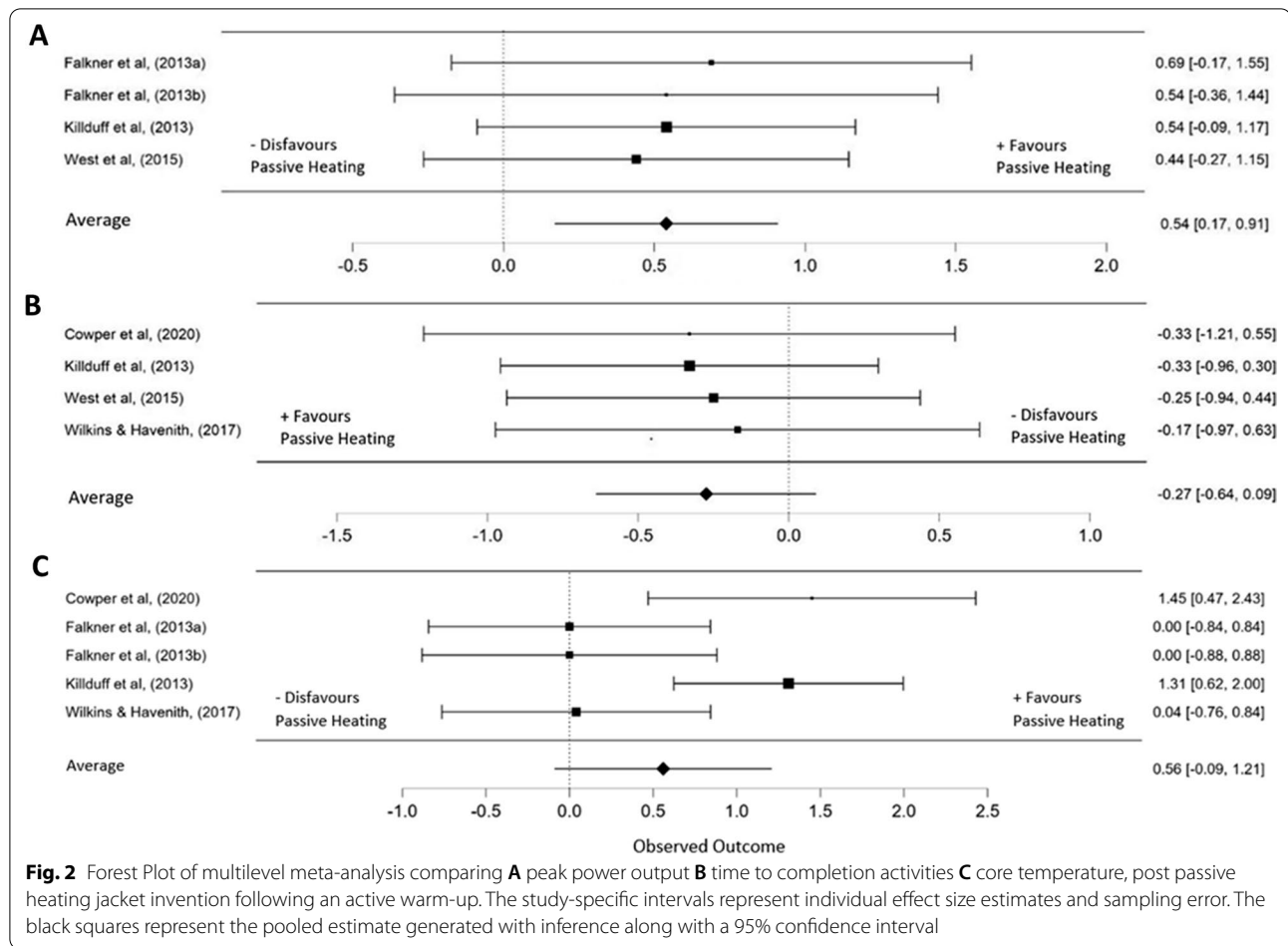
All seven studies found a significant improvement ($P < 0.05$) in one or more performance parameters following the passive heating intervention. Four out of the seven eligible studies assessed peak power output (PPO) which was measured in the form of cycling [9, 20], and countermovement jumps [5, 21]. The overall effect size suggests a significant improvement in PPO following a passive heating strategy (ES 0.54 [95% CI 0.17 to 0.91], $P = 0.005$, $I^2 = 0\%$). Additionally, four out of seven studies measured performance in a form of time trial, which included rowing [14], repeated sprints [5, 21] and swimming [13]. Interestingly, the improved PPO did not translate into an overall effect for time trial performance (ES = -0.27 [95% CI -0.64 to 0.09], $P = 0.141$, $I^2 = 0\%$) (Fig. 2).

Temperature responses to passive heating

Following the passive heating period between the active warm-up and performance, five out of the seven included studies reported core temperature readings. Three out of the five studies implemented aural tympanic thermometry [10, 13, 14], two implemented rectal thermometry [9, 20], and two implemented ingestible sensors to measure core temperature [5, 21]. Overall, no significant effect was found in core temperature following the application of a heated garment (ES = 0.56 [95% CI -0.09 to 1.21], $P = 0.09$, $I^2 = 68\%$) (Fig. 2). Two out of the seven studies implemented muscle temperature measurements from depths of 1, 2 and 3 cm in the vastus lateralis. Faulkner and colleagues found muscle temperature to be approximately 1 °C higher at a depth of 1 cm ($P < 0.001$) and 0.4 °C higher at 3 cm ($P < 0.01$) following the use of heated trousers against standardised tracksuit bottoms [9]. Furthermore, in a supplementary study, Faulkner and colleagues observed that following the passive rest period, muscle temperature declined in all conditions, however, remained higher during the use of heated trousers at all muscle depths compared to standardised tracksuit pants and insulated pants ($P < 0.001$) [20].

Discussion

This study has identified that completing a passive warming strategy with the use of heated garments between an active warm-up and competition can improve subsequent performance in the form of increased PPO (ES = 0.54 [95% CI 0.17 to 0.91]). From the studies included, improvements have been demonstrated in aerobic and anaerobic type sports such as rowing [14], cycling [9, 20] and swimming [13]. Improvements have also been shown in the activities of vertical jumping [5, 21] and repeated sprint performance [5, 10, 21]. The



included literature suggests that maintaining an elevated muscle temperature is only beneficial in the early stages of exercise, however, it should be noted that having a much greater start in a time trial, does not necessarily mean subsequent exercise performance will be improved due to elevated afferent feedback [24]. However, despite a consensus on the effect of heated garments, the degree of improvement varied widely, from less than 1 to over an 11% improvement, however, the studies included have exhibited sufficient quality as evidenced through extensive critique. The use of multiple variations of active and passive warm-up protocols, the wide variation in results may be attributable to the specifics of the warm-up practices employed, post-warm-up, transition period strategies and the exercise itself. This emphasises the need for continued research to determine which methods of warm-up are best for a given sport or activity.

Passive warm-up strategies and exercise performance

Asmussen and Boje [25] and Bergh and Ekblom [26] reported that the velocity-dependent effect of muscle temperature on maximum external power to be ~ 4%

higher in force and power per 1 °C rise in quadriceps muscle temperature. Furthermore, per 1 °C increase in muscle temperature, observed a 2–5% [27], and a 2–10% [28] increase in peak power during exercise performance.

A passive warming strategy, unlike a continuous active warm-up, during a transition period between an active warm-up and exercise performance allows a rise in muscle and/or core temperature without the reduction of energetic substrates [9, 20]. Initial studies emphasising passive warming strategies were solely laboratory based, with the method of increasing body temperature being accomplished by methods, such as hot baths/showers. Although impactful, these passive warm-up strategies are not often practical in a sporting scenario. Therefore, alternate methodologies of passive warming have been sought after, given that: (1) a lengthy period is expected (transition phase), between the end of the warm-up and the beginning of an event; (2) muscle temperature starts to fall immediately following exercise termination; and (3) substantial declines in body temperature occurs as early as ~ 15–25 min post-exercise [4, 5].

External heating garments and blizzard survival jackets and performance

All of the included studies in this review used either blizzard survival jackets or external heating garments, the majority of heated garments used across various sporting activities have heat filaments in the fabric. Faulkner et al. [9] reported an improvement in muscle temperature (1 °C rise in muscle temperature at a depth of 1 cm and a 0.4 °C rise at a 3 cm depth) and ~9% improvement in relative and PPO during a sprint cycling task when using an active warm-up and heated tracksuit pants in the 30-min transition period in comparison to standard tracksuit pants [9]. Additionally, further research by Faulkner and colleagues reported that muscle temperature remained increased when wearing heated tracksuit pants solely during the transition period (36.9 ± 0.3 °C) and when worn throughout the active warm-up and transition phase (37.0 ± 0.2 °C) in contrast to only an active warm-up (36.6 ± 0.3 °C) [20]. Although, an additional performance benefit was not found when wearing the heated tracksuit pants during an active warm-up as well as during the transition phase [20]. Supporting this, Cook et al. reported that wearing a blizzard survival jacket produces a rise in tympanic temperature and improved a 20 m sled sprint performance [10]. Additionally, Kilduff et al. reported an improved repeated sprint performance in elite rugby players when an active warm-up was followed by wearing a blizzard survival jacket throughout a 15-min transition period [21]. The decrease in core temperature during the transition phase was minimised when the blizzard survival jackets were worn (-0.19 ± 0.08 °C) compared to the standardised tracksuit top (-0.55 ± 0.10 °C). Therefore, participants began the tests with an elevated core temperature, suggesting that an increased core temperature prior to exercise can improve exercise performance [21].

The use of passive warming strategies are not common practice, however, the application of maintaining body and muscle temperature during a transition period is gaining recognition. Passive heat maintenance through the wearing of blizzard survival jackets and athletic heating garments appears to be an optimal technique in offsetting the reduction in core and/or muscle temperature and therefore improving exercise performance. However, athletic heating garments can have their limitations. Wired heated garments, do not provide uniform heat across the heating elements. Furthermore, for optimal heat transfer and increase in muscle temperature, the heating elements should be in direct contact with the skin, which involves the garment being tight to the skin [29]. Additionally, Faulkner et al. reported a significant decrease in muscle temperature during the inactivity period when the heated garments were worn, however,

the decline in muscle temperature was significantly less compared to the application of standard tracksuit bottoms [9]. Furthermore, Raccuglia and colleagues demonstrated by using water-perfused heated trousers, heated to a higher temperature, 43 °C, successfully maintained and even increased muscle temperature in the passive recovery period following an active warm-up [30]. However, water perfused trousers are not very practical for use in a competition setting as they need to be connected to a heating system, consisting of a temperature-controlled water bath and powered water pump. Alternatively, numerous studies have reported a significant improvement in exercise performance following the application of battery-powered athletic heating garments which use integrated flexible heating elements [9, 13, 14, 20]. This allows consumers to use the garments portably, however without multiple batteries, for a limited time period.

All the reviewed literature found a significant improvement in exercise performance ($P < 0.05$); particularly time trial performances, which have shown to display a wide variety of percentage increases. When examining these in more detail, the type of exercises might influence the overall percentage improvement. For example, Cowper et al. exhibited a performance increase of 1.1%, this slight increase in performance, might be because of the competition duration being long (>5 min) in comparison to the other studies which are all predominantly anaerobic and short-lasting in nature [14]. Limited studies have determined the physiological outcomes of passive warming for long-duration performances. This might be because a well-known limiting physiological factor for long-duration performances is excessive bodily heat [31, 32].

A rise in core temperature before exercise might be detrimental to long duration performance due to impaired thermoregulatory mechanisms [33, 34] and/or a decrease in heat storage capacity [35]. This increase in body temperature, may create a greater dependence on evaporative heat loss, thus an increase of sweating. Therefore, an individual may incur sub-optimal hydration over a prolonged period and subsequently hinder exercise performance [36]. Furthermore, González-Alonso et al. [33] found a detriment in time till exhaustion performance in hot environmental conditions (40 °C) when comparing 36 (CON), and 40 °C (HEAT) pre-exercise water immersions for 30 min. Observing that a reduction in performance was attributed to increases in heart rate and reductions in stroke volume paralleled the rise in core temperature [33].

When a heated jacket is utilised following an active warm-up in cool environments, body temperature would be comparatively lower than if the same protocol was applied in standard ambient temperatures (18–20 °C)

[37]. During colder environments, a delayed duration that the body takes to reach critical core temperature would occur and performance might improve. Alternatively, in standard ambient conditions, the use of a heated jacket may elevate the core temperature to critical levels and possibly decrease the capacity for exercise performance [14]. Due to the paucity of work in this area, the papers included in this systematic review have differing ambient temperatures. It is known that a change in ambient temperature can significantly alter the thermoregulatory profile at rest [38] and affect the ability to exercise [39]. As such, the ambient temperature is an important factor to consider when using interventions during the passive warming period. Therefore, further research is needed to determine the effect on performance following the use of passive heating garments in below ambient temperatures.

Limitations

Several methodological problems in the studies reviewed could have impacted the outcomes reported. Some of the studies did not measure temperature change post active warm-up, therefore it might be difficult to distinguish whether the change in bodily temperature was due to the active warm-up or the passive heating garment. Furthermore, chosen studies in this systematic review and meta-analysis displayed small sample sizes, this led to many of the confidence intervals crossing the “zero point”. While the conclusions from this review are based on mean data, it is important to state that even though none of the included studies displayed an absolute improvement in performance for passive heating when examining both the means and confidence intervals, no studies showed a mean or absolute decrease in performance. This demonstrates that passive heating during the period between active warm-up and performance has no effect on performance. There are certain weaknesses in this review, relatively small number of participants in some of the studies which increases the potential effects of chance. Furthermore, the limited number of studies included in the systematic review and meta-analysis and the studies that were included, some authors were unable to provide raw data to fully complete analyses.

The findings of this systematic review and meta-analysis offer a partial but best available evaluation of the influence of passive heating techniques prior to sport and exercise performance. This review aimed to eliminate possible sources of bias by employing a systematic review method, however, this does not ensure the absence of bias. Furthermore, a modified version of the PEDro scale was applied to distinguish between the quality of different studies. The modified PEDro scale has not likely to have biased our decisions since points are only granted to studies when the criteria are clearly fulfilled.

Furthermore, after a precise reading of the included research articles, if it was not evident that the criterion was reported, a point was not presented for that specific criterion.

Future considerations

Further research is necessary to determine the optimum procedure for passive warm-up strategies, including the length of time to wear the garments, garment temperature and the placement of the heating elements embodied into the garment. Furthermore, research on whether passive heating strategies could be applied to scenarios where it is difficult to maintain core temperature from metabolic heat production alone, such as repeated-sprint sports which are separated by low to moderate activity. Specifically, in below ambient conditions, where the decline in core and muscle temperature is excessive throughout a lengthy transition.

Conclusion

Passive heating devices have been shown to reduce the decline in muscle temperature, and therefore have been found to enhance PPO during exercise. Additionally, a favourable yet not significant reduction in the decline of core temperature was observed. Large heterogeneity, low participant numbers and a range of methodologies, shows a necessary scope of additional research to observe the effects of core and muscle temperature.

Abbreviations

CMJ: Countermovement jump; ES: Effect size; PEDro: Physiotherapy evidence database; PO: Power output; PPO: Peak power output; PPU: Plyometric press-up; REC: Recovery; RST: Repeated sprint time; T_{Pijj} : Ingestible core sensor; T_{Rec} : Rectal temperature; T_{Tym} : Tympanic temperature; TTC: Time to completion; WU: Warm-up.

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s13102-022-00546-7>.

Additional file 1. Table S1. Methodological quality scores of the included studies.

Additional file 2. Raw data of meta-analysis.

Author contributions

All authors contributed to the design of the review. GC wrote the main manuscript following the advice and revisions from MB, SG, KH and LB. Additionally, GC manually screened articles for the systematic review and GC and MB independently assessed the full-text articles for inclusion. All authors have approved the submitted version. All authors read and approved the final manuscript.

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Availability of data and materials

All data generated or analysed during this study are included in this published article (and its Additional files 1 and 2).

Declarations**Ethics approval and consent to participate**

This review has full ethical approval by Northumbria University, Newcastle Upon Tyne, UK (Reference Number: 45401).

Consent for publication

Not applicable.

Competing interests

I declare that the authors have no competing interests as defined by BMC, or other interests that might be perceived to influence the results and/or discussion reported in this paper.

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