Passive heating in sport: Context specific benefits, detriments, and considerations

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Abstract word count: 207
Manuscript word count: 13,148
Figures = 2
Tables = 0
Data availability: Not applicable
Competing interests: TC has received funding from Bestway International Ltd, the Society for Endocrinology, and the British Heart Foundation for projects relating to passive heating. All remaining authors declare no conflict of interest.

Abstract

Exercise and passive heating share some acute physiological responses. These include increases in body temperature, sweat rate, blood flow, heart rate, and redistribution of plasma and blood volume. These responses can vary depending on the heating modality or dose (e.g. temperature, duration, body coverage) and are beneficial to athletes in specific scenarios. These scenarios include being applied to increase muscle or force production, induce rapid weight loss, stimulate thermoregulatory or cardiovascular adaptation, or to accelerate recovery. The rationale being to tailor the specific passive heating protocol to target the desired physiological response. However, some acute responses to passive heating may also be detrimental to sporting outcomes, such as exercising in the heat, having unintended residual negative effects on performance or perceptions of fatigue, or even resulting in hospitalization if implemented inappropriately. Accordingly, the effects of passive heating should be carefully considered prior to implementation by athletes, coaches, and support staff. Therefore, the purpose of this review is to evaluate the physiological responses to different modes and doses of passive heating and explore the various sport contexts where these effects may either benefit or hinder athletes. Understanding these responses can aid the implementation of passive heating in sport and identify potential recommended heating protocols in each given scenario.

Key Words:

Passive heating, sports performance, recovery, training, dose

Take home message

When implementing passive heating in sport, effective protocol design should align the desired training or performance outcome to the physiological responses induced by the heating modality and dose.

Introduction

Athletes seeking performance advantages may implement novel interventions that manipulate factors such as environmental stimuli or diet, to improve performance, accelerate recovery, or augment the adaptive response to training (Hawley et al. 2018; Hyldahl and Peake 2020; Chaillou et al. 2022). The application of heat to the body at rest, termed passive heating, by methods such as hot water immersion, sauna-bathing or heated clothing have long been demonstrated to be beneficial when performed immediately before exercise (Asmussen and Bøje 1945), in recovery from exercise (Clarke 1963), or repeatedly to elicit adaptive responses (Fox et al. 1963). Accordingly, passive heating has been used and investigated in a number of contexts within sport with a view to improving the physiological processes that underpin sporting performance.

Passive heating can result in a wide range of physiological responses; this includes increases in skin, muscle, and/or core body temperature (e.g. González-Alonso et al. 1999; Pilch et al. 2013; Chiesa et al. 2016; Rodrigues et al. 2020), which can be accompanied by increased sweat rates (Kozlowski and Saltin 1964), and redistribution of blood to the periphery (Crandall and Wilson 2015) to dissipate heat. Indeed, passive heating leads to multiple acute cardiovascular responses, such as increases in arterial blood flow and shear stress with a concomitant increase in heart rate and reduction in blood pressure (Crandall and Wilson 2015; Thomas et al. 2016). Additionally, in response to these stressors, passive heating can induce an acute inflammatory and hormonal response (Kosunen et al. 1976; Gagnon et al. 2015; Hoekstra et al. 2018) and alter cellular signaling cascades within skeletal muscle (Ihsan et al. 2020). The extent and magnitude of these physiological responses is dependent on the specific passive heating protocol, with the potential beneficial effects being context specific to each sporting application. Therefore, it is vital that athletes and practitioners understand the underlying physiological effect they are seeking when implementing passive heating and appropriately design their passive heating protocol to match this.

Multiple excellent reviews to date have discussed the potential application of temperature manipulation (i.e. hot and cold) within sport but have largely focused on the application of cooling (Versey et al. 2013; Hyldahl and Peake 2020; Chaillou et al. 2022), or the specific ability of heat to elicit adaptive effects (Hawley et al. 2018; Kim et al. 2020a). Recent interest in the application of heating in multiple sporting contexts has added more knowledge to this specific area and as such this review will provide an overarching summary of the various scenarios in which passive heating can be used in sport. Although many effects of heating have been demonstrated using animal (e.g. Tamura et al. 2014) or cell-culture (e.g. Liu and Brooks 2011) models, this review will focus on evidence taken from human studies to allow for translation to practical application and to avoid discussion of effects that are a consequence of the higher tissue temperatures (e.g. > 42 °C) that can be achieved in these models but cannot be replicated in humans. A second focus of this review will be to demonstrate how the physiological effects of passive heating can be manipulated by factors such as mode or dose with different physiological effects desired in different sporting contexts. Accordingly, this review aims to discuss different protocols of passive heating and the associated physiological responses, critically appraise their efficacy in a range of sporting scenarios and provide recommendations for practice where there is sufficient evidence to do so.

Passive heating protocols; considerations of heating dose and mode

Heat transfer occurs between the passive heating source and an individual principally via conduction and convection. Heat transfer is dependent on the mode and dose of heat application and the ability of the individual to dissipate heat and prevent increases in body temperature. Accordingly, mode, dose, and individual characteristics should all be considered when designing a passive heating protocol to elicit the desired physiological effects.

The heating dose of a passive heating protocol is determined by the thermal energy load, which can be manipulated by the external heating temperature, the area of the body exposed to the stimulus, and the duration of the stimulus with the rate of energy transfer depending on the thermal gradient between the heating source and the individual. The relationship between the heating stimulus, core body, muscle, and skin temperature is specific to the heating protocol, with higher temperatures applied to a smaller area resulting in greater increases in skin and muscle temperature and a reduced effect on core body temperature. However, where the modality of heat transfer and area of the body exposed to the heating stimulus are held constant, increases in the heating temperature (Henderson et al. 2021; Cullen et al. 2024) or duration (Ježová et al. 1994; Steward et al. 2024) results in a greater effect on the body's temperature response and subsequently a larger acute physiological response.

The duration of passive heating used within the literature range from relatively short bouts (e.g. 15 minutes), to several hours. Due to the requirement to overcome the initial thermal inertia, core body temperature increases relatively slowly in the first 15 minutes of heating, increasing more rapidly later into the heating duration as the temperature of peripheral tissues are increased (Rodrigues et al. 2020; Larson et al. 2021; Campbell et al. 2022); this is an important consideration for scenarios such as heat acclimation, where a large increase in core body temperature is important for driving adaptation (as will be discussed in more detail later in this review) (Daanen et al. 2018; Ravanelli et al. 2021). In an uncompensable heat environment, where physiological mechanisms of thermoregulation are ineffective to maintain heat balance, body temperature progressively increases throughout the duration of the heating stimulus. However, many heating protocols apply an external stimulus that increases body temperature initially before plateauing once an equilibrium of heat transfer is reached. For example, 42 °C waist-deep water immersion can result in an initial steady increase in rectal and deep *vastus lateralis* temperature in the first 60 minutes of heating before plateauing at 38.8 and 39.0 °C, respectively after ~85 minutes (Rodrigues et al. 2020).

As passive heating applies heat to the skin, skin temperatures increase rapidly from the onset of heating before plateauing and differs according to the external environment or heating modality (Rodrigues et al. 2020; Campbell et al. 2022). This rapid increase in skin temperature has been linked to thermal discomfort and is suggested to initiate behavioural thermoregulation (Bulcao et al. 2000). Indeed, prolonged passive heating often results in thermal discomfort (Hoekstra et al. 2018; Mansfield et al. 2021; Campbell et al. 2022), which can result in a reduced duration of passive heating due to intolerance (Zurawlew et al. 2016, 2018; Campbell et al. 2022). Indeed, irrespective of efficacy, an individual's tolerance and potential adherence to a given intervention should be carefully considered. The total duration can be extended through short breaks to the heating stimulus that acutely improve thermal comfort (Heinonen and Laukkanen 2018; Steward et al. 2023), or implementing mitigation strategies such as fan cooling (Steward et al. 2023). It should be acknowledged that these mitigation strategies may impact the subsequent desired physiological response. Mansfield et al., (2021) demonstrated that the inflammatory response to lower limb passive heating was not altered by upper body cooling, however the same research group later demonstrated attenuated vascular responses with lower body compared to whole body heating (Hoekstra et al. 2021). In contrast, several studies from a different research group have maintained a core body temperature of ~38.5 °C for a prolonged period (~60 min) by altering immersion depth throughout the protocol (Brunt et al. 2016; Francisco et al. 2021). Francisco et al demonstrated that despite no further increases in core body temperature, there were continued physiological effects of an extended duration, such as decreases in diastolic blood pressure and increases in mean shear rate in the brachial artery (Francisco et al. 2021). This demonstrates that duration has physiological effects independent of progressive increases in body temperature and as discussed elsewhere in this review, there are many important physiological stimuli for adaptation beyond increases core body temperature.

Passive heating modalities commonly used in sport include hot water immersion, sauna-bathing, environmental (heat) chambers and heated clothing (Menzies et al. 2023). Selection of an appropriate heating modality may be a combination of a physiological rationale, as well as practical or logistical considerations. For example, the use of sauna-bathing may depend on the cost and proximity to appropriate facilities, with greater access in parts of the world such as Finland that have a greater sauna-bathing culture. In contrast, hot water immersion can be considered relatively cheap and accessible due to the use of bathtubs or portable, inflatable, hot tubs, however this modality may be logistically more challenging with large groups of athletes, or in situations where access to a power supply is not possible. Nevertheless, recent work from our group has indicated that hot water immersion may be the most common mode of passive heating used in sport (Menzies et al. 2023). Alternatively, despite the increasing prevalence in a laboratory setting, and appeal from an experimental design perspective, water-perfused suits are not available to most of the general public and therefore represents an impractical or inaccessible mode of passive heating for use in sport. In contrast, electrically heated clothing may be the most easily accessible method of passive heating, although as discussed later in this review, careful consideration should be given to the efficacy of this method.

Each mode of passive heating creates a different thermal environment, which impacts thermal energy transfer resulting in different temperatures used for each modality. For example, given that water has a higher thermal conductivity than air, water temperatures can be lower than air temperatures in the application of a heating protocol. Water immersion protocols typically use temperatures of > 38.5 °C. When submerged in hot water, the body has an inability to dissipate heat through evaporation or conduction, meaning thermoregulatory processes of sweating and increased skin blood flow are ineffective. Moreover, the heat transfer from the water to the skin makes increased blood flow counterproductive and further increases core and muscle temperatures

(Faulkner et al. 2017; Rodrigues et al. 2020; Steward et al. 2023; Cullen et al. 2024). Air temperatures of 40 °C and ~40% relative humidity in an environmental chamber can result in no observed increase in core body temperature, but ~3 °C increases in skin temperature (Hesketh et al. 2019). Increasing the relative humidity (and reducing the water vapour gradient) can reduce the capacity for evaporative heat loss resulting in increased thermoregulatory challenge (Alber-Wallerström and Holmér 1985). Accordingly, increasing the air temperature or relative humidity results in larger changes in thermo-physiological effects (Henderson et al. 2021). As a result, traditional saunas consist of an environment of 70 – 100 °C and 10 – 20% relative humidity but the adding of water to a sauna's heat source increases the humidity meaning that typically slightly hotter sauna temperatures are paired with lower relative humidity and vice versa. Unlike traditional saunas, infrared sauna or waon therapy generate infrared waves that can penetrate the skin meaning comparatively lower air temperatures (60 °C) are required to elicit increases in core body temperature (Tei et al. 1995). Although there are multiple whole body heating modalities that can be used to elicit thermo-physiological stressors, users should consider the overall effects of each mode rather than simply isolating the thermal effects. Independent of temperature, water immersion exerts hydrostatic pressure on the body, resulting in increases in mean arterial pressure, stroke volume, cardiac output, and peripheral artery diameter (Farhi and Linnarsson 1977; Ayme et al. 2014). Similarly, when compared to traditional sauna the relatively smaller increases in skin temperature and skin blood flow observed with infrared sauna or waon therapy may lead to differences in adaptations, however, these suggestions remain to be studied empirically (Brunt and Minson 2021). Additionally, more work is required to determine the distinct physiological responses to small changes in environmental temperature. For example, a ~1 °C greater reduction in water temperature during a 30-minute exposure when starting at 39 °C, can result in a blunting of the increase in superficial femoral artery blood flow of approximately 35% (Cullen et al. 2024).

Some heating modalities allow for heat to be applied to a specific region, increasing skin (John et al. 2024) or muscle temperature (Faulkner et al. 2013a) but not necessarily core body temperature. For example, heated trousers with a 40 – 42 °C electrical heating element used to heat the thigh muscles have been used to attenuate the reduction in muscle temperature by 0.5 – 1.0 °C following exercise (Faulkner et al. 2013a). Moreover, pulsed shortwave diathermy delivers high frequency electromagnetic energy to heat body tissue and two hours of 800 pulses per second, with a pulse duration of 400 microseconds applied to the quadriceps muscles increased deep *vastus lateralis* temperature by ~3.9 °C in the first 30 minutes before plateauing (Hafen et al. 2018). It should also be highlighted that water temperature and depth can also be manipulated during water immersion protocols to alter both local and whole-body thermo-physiological responses. For example, similar increases in rectal temperature can be achieved through different combinations of water temperature and depth with, 60 minutes of neck-deep immersion in 39 °C water being shown to increase rectal temperature by ~1.5 °C (Hoekstra et al. 2018) and a similar increase observed from the same duration of waist-deep immersion in 42 °C (Mansfield et al. 2021). However, it remains unclear whether these different protocols may have differing effects on muscle and skin temperature, potentially impacting subsequent localized or peripheral adaptations. Indeed, the optimal heating protocol is dependent on the desired physiological response. For example, localized heating methods may be advantageous in certain scenarios given that local temperature is suggested to be important for increases in blood flow (Chiesa et al. 2016), accelerating glycogen resynthesis (Cheng et al., 2017), or stimulating mitochondrial adaptation (Kim et al. 2020a), or angiogenesis (Hesketh et al. 2019). In contrast, core body temperature is a key stimulus in heat acclimation (Daanen et al. 2018; Ravanelli et al. 2021), and the acute neuro-endocrine or inflammatory response (Rhind et al. 2004; Hoekstra et al. 2021). The majority of these responses appear intuitive, with local stimuli inducing peripheral adaptations, however, there are some scenarios where this appears not to be the case. For example, when wanting to elevate signaling processes involved in skeletal muscle hypertrophy, experimental data in humans to date suggests that elevated muscle *and* core body temperature may also be required (Ihsan et al. 2020). Ihsan et al., reported that 60 minutes whole body heating in an environmental chamber (44–50 °C, 50% humidity) increases molecular signalling responses associated with hypertrophy of skeletal muscle with local heating of the lower limbs using a water suit (water temp 49 °C) (Ihsan et al. 2020). A strength of this study was that the elevation in muscle temperature was similar between local and whole-body heating (~3 °C increase from baseline), while core body temperature was only increased (by ~2 °C) in the whole-body heating condition, suggesting that increases in core body temperature may be favourable for enhancing anabolic responses within skeletal muscle.

Within sport, the individual characteristics and requirements of each athlete will differ both within and between sports, which should be taken into consideration when implementing a passive heating protocol. In an uncompensable environment, the rate of temperature rise is largely dependent on body mass, surface area to mass ratio, and body composition, with an individual of larger mass heating more slowly than someone of smaller mass (Havenith 2001; Petrofsky and Laymon 2009). This principle of heat transfer will apply to both whole body and localized heating meaning that even when applied to achieve the same sporting objective (e.g. increases in power), a different protocol may be required for a >150 kg judoka compared to a <50 kg gymnast. Moreover, in a compensable environment, physiological responses such as increased sweat rate, or skin blood flow enable individuals to dissipate heat more effectively resulting in a reduced effect of the external heating stimulus. Differences in these responses have been observed with acclimation status (Zurawlew et al. 2016), training status (Zurawlew et al. 2018), sex (Larson et al. 2021), and age (Inoue et al. 1998) meaning that these factors should also be considered in passive heating protocol design. Therefore, passive heating protocols should be designed and interpreted in the context of its intended population with progression applied as individuals adapt to the thermal stress.

Uses of passive heating in sport

Warm-up & breaks in competition

Athletes regularly complete a warm-up prior to competition, completing bouts of exercise that increase core body and muscle temperature (Saltin et al. 1968). Elevated muscle temperature increases muscle force and power production in isolated rat muscle *in vitro* (Ranatunga 1998), whilst in humans, power production during a vertical jump and sprint cycling increases by 2 – 10% per ˚C increase of muscle temperature between ~30 - 39 ˚C (Bergh and Ekblom 1979; Sargeant 1987). These improvements occur due to intramuscular increase in calcium influx and sensitivity along with increases in intracellular fluid that improves both voluntary and involuntary muscle force output in the heated muscle (Rodrigues et al. 2023). However, it is common for athletes to experience a gap following a warm-up prior to competition where decreases in temperature can reduce these effects and can negatively impact performance (West et al. 2013). Moreover, many intermittent team sports include a half time of 10-20 minutes, whilst the competition schedule in sports such as track cycling or judo often require athletes to compete multiple times with short (15 – 60 minutes) breaks between rounds, races, or fights. Therefore, the use of passive heating at competitions could benefit performance through increases or maintenance of body temperature during these periods of inactivity.

In sports with requirements for high power production, passive heating is beneficial in mitigating decreases in body temperature following an active warm up. This can result in improved peak power production and subsequently performance when performed under conditions that do not have large thermoregulatory demands (Faulkner et al. 2013a; Cowper et al. 2022). The use of insulated clothing maintains core body and muscle temperature following an active warm-up prior to a rugby match or bob-skeleton run (Cook et al., 2013; Kilduff et al., 2013; West et al., 2016), and during half time of a simulated rugby match performed in temperate conditions (Russell et al. 2015, 2018), resulting in improved sprint times, power production, and performance. Indeed, passive heating may also be useful in scenarios where there is minimal space or time for incoming substitutes to perform an effective warm-up (Cowper et al. 2024). Beyond mitigating decreases in body temperature, the application of heat can increase muscle temperature in similar scenarios following an active warm-up across numerous disciplines, including sprint swimming (McGowan et al. 2016; Wilkins and Havenith 2017), sprint cycling (Faulkner et al. 2013a, 2013b; Raccuglia et al. 2016), and alpine skiing (McGawley et al. 2021). However, there is a suggested plateau where increases in muscle temperature no longer increase power production (McRae and Esrick 1993), resulting in post warm-up passive heating having no benefit beyond an active warm-up when the time gap prior to performance is relatively short (<15 minutes) (Marshall et al. 2015; Cocking et al. 2020). Therefore, the potential benefit of passive heating to sports with demands for high power production, in maintaining or elevating body temperature prior to competition or during a break between rounds, is context dependent on the scheduling demands of the competition. However, more research may be required to investigate the efficacy of this intervention in other potentially applicable scenarios with different logistical or environmental constraints, such as gymnastics, high diving, or jumping and throwing events in athletics. Further research may also be needed to optimise protocols between athletes of vastly different body shape and limb size, which may also impact the speed and efficacy of local heating protocols.

In contrast, sports of longer durations with large thermoregulatory demands, due to sustained elevations in metabolic heat production, may see detrimental effects of using passive heating immediately prior to competition. Prior hot water immersion reduces time to exhaustion during constant load cycling in the heat (40 ˚C) and intermittent treadmill exercise in temperate conditions (22 ˚C) by ~40% (González-Alonso et al. 1999; Gregson et al. 2005). Similarly, simulated football sprint performance in the heat is impaired in the second half with the use of insulated clothing to increase heat maintenance at half time (Soo et al. 2019). These studies postulate that fatigue is accelerated due to hyperthermia-related mechanisms, such as a reduced cardiac output and increased competition for blood flow between the skin and muscle at elevated core body temperatures, which occur earlier in exercise as a consequence of elevating core body temperature prior to exercise. Not only can additional thermal strain accelerate fatigue, but it can also impair cognitive performance and decision making which are important factors in many sports (Donnan et al. 2022). Athletes competing in events that place demands on the thermoregulatory system should avoid the use of passive heating and its associated increases in core body temperature, and may in fact benefit from pre- (Ross et al. 2013) or per-cooling (Graham et al. 2021; Brown et al. 2024) strategies instead.

Recommendations for the use of passive heating as part of a warm-up or during breaks in competition depend on the physiological requirements of the competition, competition schedule, and environmental conditions. Athletes should aim to increase (or mitigate decreases) in muscle temperature to improve power production, whilst increases in core body temperature may be detrimental for prolonged sports with large thermoregulatory requirements. Therefore, local heating modalities, such as heated clothing, that focus on the active muscle groups, may be the most appropriate in this context and given the apparent plateau in beneficial increases in muscle temperature on power production (McRae and Esrick 1993), modest heating doses are likely sufficient. The beneficial effects of passive heating in these contexts are likely reduced with shorter durations between warm up and competition or gaps in competition, and when used in hotter environmental conditions. Finally, in sports with requirements for both high power production and aerobic capacity, such as soccer, basketball or rugby, athletes and practitioners should consider the potential pros and cons of engaging in passive heating on performance outcomes. Accordingly, the most appropriate strategy may differ depending on the context of the specific environmental conditions, the thermo-physiological demands of each athlete, and typical clothing worn during competition.

Rapid weight loss

Many sports, such as boxing, weightlifting, or rowing, involve separating athletes into weight divisions to ensure the safety and fairness of competition. Accordingly, it is common practice for athletes in these sports to engage in weight manipulation strategies, prior to competition, to transiently reduce their body mass at weigh in to gain a perceived competitive advantage (Franchini et al. 2012; Pettersson et al. 2013). Passive heating promotes high sweat rates that enables rapid reductions in body mass through reducing body water content (Burke et al. 2021). For example, 60 minutes in a 70 ˚C sauna decreases body mass by 1-2% amongst athletes weighing ~70 kg (Gutiérrez et al. 2003). In more extreme cases, passive heating has assisted in reductions of 5 kg in a single day, albeit with inducing rhabdomyolysis and fatal consequences (Murugappan et al. 2019). Indeed, about 75% of athletes in combat sports engage in passive heating in the lead up to competition to induce rapid weight loss (Giannini Artioli et al. 2010; Matthews and Nicholas 2017; Barley et al. 2018). Despite the perceived benefits of rapid weight loss followed by subsequent regaining of weight prior to competition, this strategy may still have some detrimental effects on competition. Many athletes have been identified as dehydrated on the day of competition following attempts at rehydration (Pettersson and Berg 2014), with acute hypohydration being associated with reductions in muscular endurance, strength and anaerobic power in non-body weight dependent muscle performance (Savoie et al. 2015). Moreover, detrimental effects of rapid weight loss on power production have been observed to persist following rehydration in women (Gutiérrez et al. 2003) suggesting more prolonged negative effects of rapid weight loss on performance.

Although passive heating is commonly used in the lead up to competition in combat sports, athletes and practitioners should be cautious of the dangerous and potentially detrimental consequences associated with this strategy and consider practical long-term approaches to body-weight management, which may be more favorable for health and performance (Burke et al. 2021). For those still wishing to engage in passive heating, relatively large heating doses are required to induce sweat losses, and modalities such as sauna-bathing and hot water immersion are likely the most effective in this regard and have been shown to induce similar sweat rates (Campbell et al. 2022). Combat sport athletes typically lose 1.4 – 3.4 kg of body mass in the 24 hours prior to weigh-in (Barley et al. 2018) and therefore 30 – 60 minutes of intermittent passive heating may be used to contribute ~0.4 – 1.4 kg of this (Gutiérrez et al. 2003; Steward et al. 2023). However, athletes and practitioners should be aware of the potential negative effects and symptoms imposed by these protocols prior to implementation, and it should be reiterated that other, healthier strategies should be implemented ahead of heat-induced weight loss (Burke et al. 2021).

Heat acclimation

Aerobic exercise performance is impaired in hot and humid environmental conditions (Galloway and Maughan 1997; Jenkins et al. 2023). However, repeated exposure, in the lead up to competition, to simulated heat (termed heat acclimation), results in thermoregulatory adaptations and subsequently improved endurance performance in the heat (Périard et al. 2015). Traditional heat acclimation protocols involve exercise in a hot (e.g. 40 ˚C) environmental chamber over a period of 5 – 21 days (Périard et al. 2015; Tyler et al. 2016). However, this approach may be inaccessible or impractical for some athletes without access to an environmental chamber. Therefore, passive heating may be a more accessible method of repeated exposures to elevated core body temperatures, and a systematic review of passive heating as a method of heat acclimation concluded it can be an effective method of inducing thermoregulatory adaptations (Heathcote et al. 2018). Comparisons between 40 ˚C hot water immersion and 55 – 70 ˚C sauna bathing have shown similar magnitudes of acclimation with after five days of 30-60 minutes of heat exposure per day (Kissling et al. 2022; Ashworth et al. 2023). Therefore, providing appropriate temperatures are used to account for the different thermal conductivity of water and air, either modality may be used by athletes. Athletes at risk of impaired aerobic exercise performance in the heat may benefit from engaging in passive heating in the lead up to a competition in a hot environment or during a tapering phase, with current recommendations suggesting a minimum of 6-7 days of consecutive exposure to heating with a minimum duration of 30 minutes per session (Heathcote et al. 2018). Passive heating can also be employed post-exercise when core temperature is already elevated to extend both the magnitude and duration of the heating stimulus (Zurawlew et al. 2016; Kirby et al. 2020). A particular strength of this work by Zurawlew and colleagues was that it isolated the effects of temperature (from those of hydrostatic pressure) by including a control condition which employed thermoneutral water (34°C) immersion post-exercise, wherein no improvements to thermoregulation or performance were observed.

When comparing passive and active heat acclimation, hot water immersion post-exercise has been shown to induce greater thermoregulatory adaptations, such as a decrease in resting rectal temperature (-0.38 vs -0.14 ˚C) and the rectal temperature at the onset of sweating (-0.43 vs -0.22 ˚C) than traditional heat acclimation protocols (McIntyre et al. 2021, 2022). This increased adaptive response may be due to the dual stimulus of acute elevations in both core and skin temperature that occurs with passive heating, that are key to inducing a more complete state of heat acclimation (Regan et al. 1996). Given that passive and active heat acclimation both appear effective, and through similar mechanisms, these strategies may also be used interchangeably during the same period (Ruddock et al. 2016; Fenemor et al. 2022). However, when engaging in heat acclimatization through training camp in hot environmental conditions, the addition of passive heating in the form of 40 °C hot water immersion has been shown to add no further adaptative responses (Stevens et al. 2020).

Training and/or acclimation status may alter the required passive heating protocol required to elicit an adaptive thermoregulatory response. Indeed, endurance athletes are considered partially heat acclimated (Piwonka et al. 1965; Strydom et al. 1966) and demonstrate increased heat tolerance before and after heat acclimation compared to less trained, age-matched individuals (Cheung and McLellan 1998). Accordingly, trained athletes can tolerate greater durations resulting in a larger overall stimulus than recreationally active individuals (Zurawlew et al. 2018). Moreover, during duration and temperature matched passive heating, trained athletes show a lower resting and end of exposure core temperature (Pilch et al. 2013), greater whole body sweat rates (Pilch et al. 2013), and a reduced expression of stress-related genes (Żychowska et al. 2017). Therefore, due to adaptations such as reduced resting rectal temperature and increased sweat rates, the magnitude of heating stimulus from post-exercise hot water immersion, as measured by area under the curve (AUC) for rectal temperatures above 38.5 °C, is only maintained across six consecutive days by increases in heating duration (Zurawlew et al. 2018). Additionally, despite generally longer immersion times and a greater AUC rectal temperature stimulus amongst trained athletes compared to recreationally active individuals, both groups demonstrated similar magnitudes of thermoregulatory adaptation suggesting a greater stimulus may be required for the same adaptative response amongst trained individuals (Zurawlew et al. 2018).

Maximizing adaptation & limiting deconditioning

The adaptive response to exercise training is a key response in determining the limits of athletic performance through enhancing key physiological characteristics that underpin the competition demands. Repeated exposure to passive heating alongside exercise training has been suggested to aid or augment the adaptive responses to enhance both endurance and resistance determinants of performance (Hyldahl and Peake 2020), making this strategy potentially applicable to many sporting disciplines. Additionally, these adaptive responses to passive heating may enable athletes to maintain conditioning through periods of injury and return to competition faster (Ihsan et al. 2019). Accordingly, athletes may seek to complement the adaptive responses to exercise training with passive heating out of competition during regular training or periods of injury. Indeed, athletes and practitioners should consider when passive heating may be most beneficial and compliment the effects of training without providing additional muscular load and potentially reducing the risk of injury, and when the time required to complete passive heating may be better used elsewhere (e.g. additional training load, tactical/technical session etc.).

The physiological determinants of endurance performance range from whole body characteristics, such as lactate threshold or maximal oxygen uptake ($\dot{V}O_{2max}$), to muscular components, including capillary density or mitochondrial enzyme activity (Joyner and Coyle 2008). Engaging in 30 – 50 minutes of passive heating three times per week for 6 – 8 weeks can increase $\dot{V}O_{2max}$ by ~5% in untrained individuals (Bailey et al. 2016; Hesketh et al. 2019). When implemented alongside training, three weeks of 30-minute sauna-bathing 3 – 4 times per week improves $\dot{V}O_{2max}$, lactate threshold, and time to exhaustion in trained endurance athletes by a mean of 8%, 4%, and 12 – 32%, respectively (Scoon et al. 2007; Kirby et al. 2020). Similarly, six weeks of 2 – 3 times per week of 15-30-minute 39.5 °C water immersion improves intermittent running performance in semi-professional Australian Rules Football players (Philp et al. 2022). These improvements in the determinants of endurance performance may be underpinned by increases in capillary density (Hesketh et al. 2019), mitochondrial biogenesis (Hafen et al. 2018), and red blood cell volume (Scoon et al. 2007), which have all shown to increase in response to different forms of passive heating. However, not all studies have reported positive findings; 90 – 120 minutes of post exercise lower limb heating using heated trousers five times per week for four weeks resulted in no greater improvements in $\dot{V}O_{2peak}$, or efficiency compared to exercise only in recreationally trained individuals (John et al. 2024). Whilst four weeks of post exercise water immersion for 20-minutes in 40 °C water four times per week was insufficient to induce increases in $\dot{V}O_{2max}$ or peak power output from an incremental exercise test in trained speed skaters (Méline et al. 2021). Notably, the heating stimulus appears modest in both of these studies, characterized by a short duration (Méline et al. 2021), while in the case of John et al., high skin temperatures were reported but with a more modest impact on core temperature. Taken together it appears that the heating dose required for beneficial effects on endurance performance may be moderate-high, such as >30 minutes of systemic heating using modalities such as hot water immersion or sauna-bathing.

Muscular strength and power are key performance determinants for a range of sporting events (Wisløff et al. 1998; Chaabène et al. 2015; Kordi et al. 2020, 2021). *In vitro* studies have shown hypertrophic responses in muscle cells at increased environmental temperatures (Yamashita-Goto et al. 2002; Guo et al. 2016), however, in humans, single leg immersion for 20 minutes in 46 °C water does not alter muscle protein synthesis responses in the immersed leg following resistance exercise (Fuchs et al. 2020). Similarly, research by Ihsan et al, suggests that whole body but not localized heating increases the molecular signaling responses associated with hypertrophy of skeletal muscle (Ihsan et al. 2020), although signaling responses have been augmented when localized heating is implemented in conjunction with resistance exercise (Kakigi et al. 2011). Findings with repeated heating exposures are similarly mixed. Ten weeks of eight hours per day, four times per week of heat exposure using heat and steam generating sheets increased thigh muscle cross-sectional area and maximum isometric knee extensor force (Goto et al. 2011). Similarly, isometric torque production in the knee extensors is improved relative to a control after four and eight weeks of water-perfused heating of the thigh for 90 minutes, five times per week (Kim et al. 2020b). In conjunction with low-intensity resistance exercise, application of a heat pack in the 20 minutes prior to training for six weeks increased muscle strength and thickness in the triceps brachii relative to an exercise-only group (Nakamura et al. 2019). However, a similar heating protocol implemented following resistance training with higher loads for 12 weeks showed no additional increases in muscle strength or size of the knee extensors compared to an exercise-only condition (Stadnyk et al. 2018). In a sporting context findings are also mixed, for example it has been reported that four weeks of post-exercise 40 °C water immersion in trained rugby players does not enhance lower body power or body composition compared to control (Horgan et al. 2023). While Méline et al. (2021), showed increases in knee extensor strength without any changes in muscle cross-sectional area following four weeks of post-exercise hot water immersion. This may suggest heating can influence neural pathways that influence strength that are separate to the hypertrophic response, but this theory remains to be investigated in detail. The discrepancies in the findings on the use of passive heating alongside resistance training may be due to the mode and intensity of the heating intervention or exercise intensity of the population studied with small increases in the adaptive response observed with lesser trained populations and in conjunction with lower exercise intensities. Accordingly, further studies are required to better understand the potential underlying mechanisms and determine combinations of passive heating and resistance exercise with greatest efficacy.

Given that passive heating appears to provide some beneficial adaptive responses without exercise, some researchers have theorised that passive heating may be used during periods of injury to minimise the deconditioning effects on both cardiorespiratory fitness and muscle atrophy (Ihsan et al. 2019). In these scenarios there could feasibly be more time available in an athlete's schedule to commit to these activities in comparison to the generally shorter periods of heating employed post training. For example, two hours of daily microwave diathermy attenuates muscle atrophy during 10 days of lower-limb immobilisation (Hafen et al. 2019). Similarly, passive heating can result in increases in cardiac function (Wilson et al., 2020), plasma volume (Beaudin et al. 2009), and VO_{2max} (Bailey et al. 2016; Hesketh et al. 2019) demonstrating a potential to provide a sufficient stimulus to minimise losses in cardiorespiratory fitness. However, research in injury rehabilitation is limited, meaning that although passive heating appears to be a promising tool to accelerate rehabilitation for an injured athlete, these benefits remain largely uninvestigated and theoretical, with recommendations for appropriate protocols, modalities, or heating dose currently lacking.

Recovery

The physiological stress caused by training and/or competition can compromise future exercise performance, with methods of accelerating recovery therefore enhancing future performance, enabling tolerance to a greater training load, and reducing the risk of injury or overtraining (Barnett 2006). The multifactorial nature of recovery means the context and outcome measures of interest can vary greatly (Kellmann et al. 2018), leading to divergent conclusions about the potential of passive heating to improve recovery. However, passive heating is considered an effective mode of recovery by athletes (Menzies et al. 2023), with sauna-bathing being commonly used and considered one of the most important recovery methods for athletes in Germany (Meyer et al. 2016). Indeed, sauna-bathing is used all over the world, with athletes considering it to induce relaxation, reduce stress, relieve aches and pains (Meyer et al. 2016; Hussain et al. 2019). Despite the apparent importance of relaxation and stress reduction in the context of highly stressful competitive sporting environments there can sometimes be a disconnect between athlete beliefs and the evidence base that supports efficacy. Nevertheless, its perceived importance may suggest passive heating can be an effective method for accelerating recovery and the following section will assess the evidence supporting the processes by which passive heating can enhance recovery from exercise.

Muscle glycogen – Muscle glycogen resynthesis is a key component of recovery of exercise capacity in prolonged sports (Alghannam et al. 2016). Increasing muscle temperature to ~37 ˚C without increasing core temperature through localised heating methods in the 2-4 hour period immediately post-exercise has been shown to accelerate glycogen resynthesis resulting in improved performance (Cheng et al., 2017; Slivka et al., 2012). This has been suggested to be due to increases in muscle temperature increasing blood flow, and glucose delivery (Slivka et al. 2012). In contrast, four hours of post-exercise whole body heating in a 33 °C environmental chamber resulting in increases in core body temperature to >38 ˚C impairs glycogen resynthesis (Naperalsky et al. 2010). This differential effect of whole body versus local heating methods may be explained by core body temperature increasing blood adrenaline concentration, which has an inhibitory effect on glycogen synthase (Hutson et al. 1976). Therefore, the mode of passive heating may result in differential effects on glycogen recovery, with favourable outcomes limited to local or peripheral heating. However, more research is required to investigate these differences and potential effects of different heating dose before robust recommendations about application can be made.

Delayed onset muscle soreness (DOMS) & muscular force production – Exercise-induced muscle damage is characterised by structural changes to the muscle and often results in decreased muscle function and DOMS which increases the risk of injury and reduces training or competition performance (Owens et al. 2019). Historically cold-water immersion has been prioritised by athletes seeking to enhance recovery of muscle function and soreness primarily based upon the theory that cooling the muscle reduced inflammation and oedema, however, recent research has shown that cold water immersion does not alter intramuscular inflammatory or cellular stress responses to resistance exercise (Peake et al. 2017). It has since been proposed that increased muscle blood flow exhibited with post exercise heating may facilitate a more rapid resolution of inflammatory processes associated with muscle damage and repair, thereby enhancing the overall recovery process (Wilcock et al. 2006) but until recently this theory had not been extensively tested. Two recent studies have shown that waist-deep 40 °C water immersion for 10 minutes

(Jackman et al. 2023), or 15 minutes in 39 °C water (Horgan et al. 2022) does not enhance the recovery of muscle function (as measured by maximal voluntary isometric contraction force) or muscle soreness following exercise induced muscle damage. However, subsequent work by Sautillet and colleagues has reported that waist-deep immersion in 41 °C, but not 40 °C, water enhanced the recovery of the rate of force development at 24 hrs and peak force at 48 hrs post exercise muscle soreness as measured by the pressure pain threshold (Sautillet et al. 2024b, 2024a). Importantly, the duration used by Sautillet and colleagues was fairly long (~47 minutes) in comparison to typical recovery interventions, and this could be considered impractical or at least interfere with other important post exercise activities in some scenarios. Nonetheless, the dose of heating appears important for benefits to be evident. Indeed, the authors suggest the mechanism that underpins these benefits could be related to the upregulation of heat shock proteins. This does seem reasonable given that other studies have shown that 60 minutes of whole-body heating in an environmental chamber (44–50 °C, 50% humidity), increased the skeletal muscle expression of selected heat shock proteins and signalling molecules in the Akt/mTOR signalling pathway in skeletal muscle (Ihsan et al. 2020). Aside from water immersion, there is also emerging evidence suggesting far infrared radiation lamps used for 30 minutes can enhance recovery from eccentric exercise in lab (Chen et al. 2023) and field studies (Tseng et al. 2024). Future studies investing these interventions should also endeavor to study the molecular signaling responses within skeletal muscle to confirm this hypothesis. While the recent results in this area appear promising there is still a considerable volume of research required to understand these processes and propose an optimal strategy.

In the absence of strong evidence for the intramuscular mechanisms underpinning the benefits of passive heating on muscle function and DOMS, researchers, athletes, and practitioners should also consider the potential role of psychological responses in mediating any effects. The placebo and/or expectation effect may be particularly important as blinding participants from the intervention is impossible in heating studies of this nature. Indeed, 85% of athletes engaging in passive heating for recovery believe it to be beneficial for recovery (Menzies et al. 2023). This belief in passive heating could itself have a positive effect on recovery as research into cold-water immersion has shown a large psychological or perceptual component to recovery, with an athlete's belief of recovery or the placebo effect relating to beneficial outcomes (Broatch et al., 2014; Cook & Beaven, 2013). Passive heating may also bring about psychological benefits to reduced stress and enhanced relaxation. Several studies from our laboratory have shown that multiple physiological aspects associated with 'psychological stress' such as blood pressure and cortisol are reduced following modest hot water immersion protocols (30 minutes neck deep immersion at 39 °C) which resulted in increases in core body temperature of ~0.5 °C (Cullen et al. 2024). However, when the duration is extended to 60 minutes and core body temperature increased, ~1 °C cortisol concentration is increased while thermal comfort is significantly decreased (Steward et al. 2024). Similarly, a short (15 minutes) but intense sauna (96 °C) has been shown to increase cortisol concentration (Pilch et al. 2013), suggesting that at higher doses of warm water immersion may no longer be beneficial to relaxation and stress reduction. Future studies are required to further understand the mechanisms and benefits of passive heat induced relaxation for athletes. Our current recommendation would be that athletes should avoiding excessively long or intense bouts of heating and prioritise their personal preferences when choosing an appropriate protocol.

Perceptions of fatigue and decrements in performance or training load – Reductions in self-selected training volume or intensities have been observed with periods of post-exercise sauna-bathing (Stanley et al. 2015). This may be artefact of the additional time commitments required to complete post exercise passive heating or a physiologically induced increase in perceptions of fatigue. Indeed, peak rectal temperature has previously been associated with subsequent perceptions of fatigue (Willmott et al. 2017). This is likely due to a number of inflammatory and hormonal factors, such as interleukin-6 (IL-6) and cortisol, that have been associated with fatigue (Vargas and Marino 2014; Cullen et al. 2017) and transiently increase in response to passive heating (Ježová et al. 1994; Faulkner et al. 2017; Steward et al. 2024). Skorski et al. (2019) demonstrated intense swimming intervals followed by 3 x 8 minutes of 80 – 85 °C sauna-bathing impairs next day sprint swimming performance and perception of recovery. Alternatively, no effect of passive heating on perception of effort or recovery has been observed with more moderate heating doses such as 14 minutes of 38 °C water immersion (Vaile et al. 2008), 30 minutes of arms out 40 °C water immersion (Menzies et al. 2024), 20 minutes of waist-deep 41 °C water immersion (Solsona et al. 2023), or in ~30 minutes of ~101 °C sauna (Kirby et al. 2020). Therefore, athletes engaging in passive heating protocols eliciting large acute increases in core body temperature should be aware of potential detrimental effects on future training sessions or competition, however these effects do not appear to be present with more moderate and/or localised heating doses.

Summary

Passive heating elicits a wide range of physiological responses, which can be used for enhancing training or performance outcomes in many different sporting scenarios. The physiological responses to passive heating are specific to the mode and dose of heating and should be carefully selected so that they are aligned to the determinants of the sporting performance or training process being targeted (Figure 1). Consequently, the use and efficacy of passive heating protocols will differ by individual, sport, situation, or environmental conditions. As such, where there is a sound understanding of the physiological mechanism that results in improved outcomes (e.g. increased muscle temperature increases power production), more research is required to expand the application of this knowledge to different individuals and settings. Additionally, there are many unanswered questions about the applications or mechanism of certain uses of passive heating (e.g. promoting muscle hypertrophy) that require more investigation before their efficacy can be determined. When implementing a passive heating protocol in sport, athletes and practitioners should aim to understand the physiological responses that should be targeted for the given use. To determine the appropriate heating mode and dose, key factors in its implementation should be considered, such as potential negative consequences, practical restrictions, or the specific requirements of the individual, sport, situation, or environmental conditions (Figure 2).

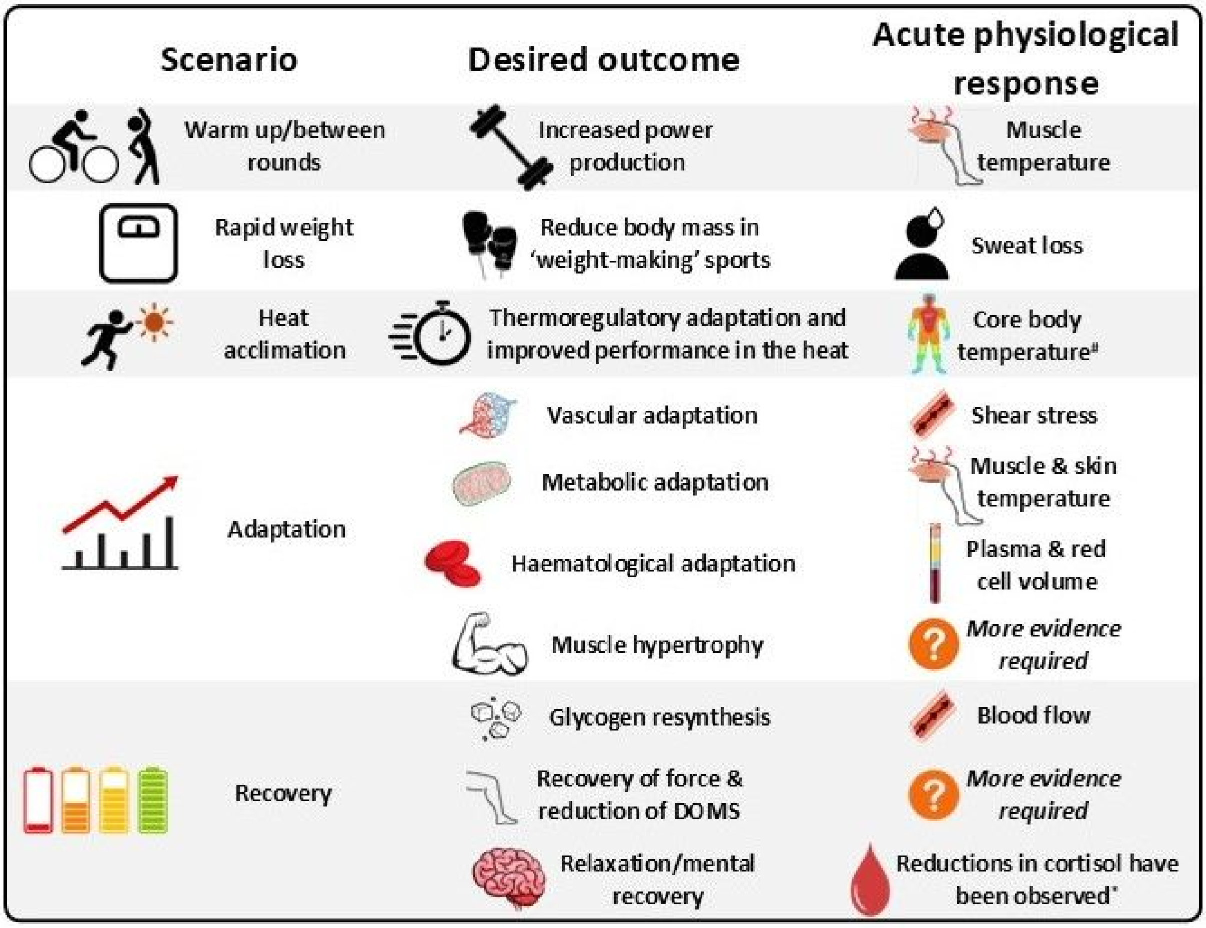

Figure 1 - Summary of the acute physiological responses that could be targeted in different scenarios of passive heating implementation.

#repeated exposures over >5 days.

*Psychophysiological mechanism not fully understood.

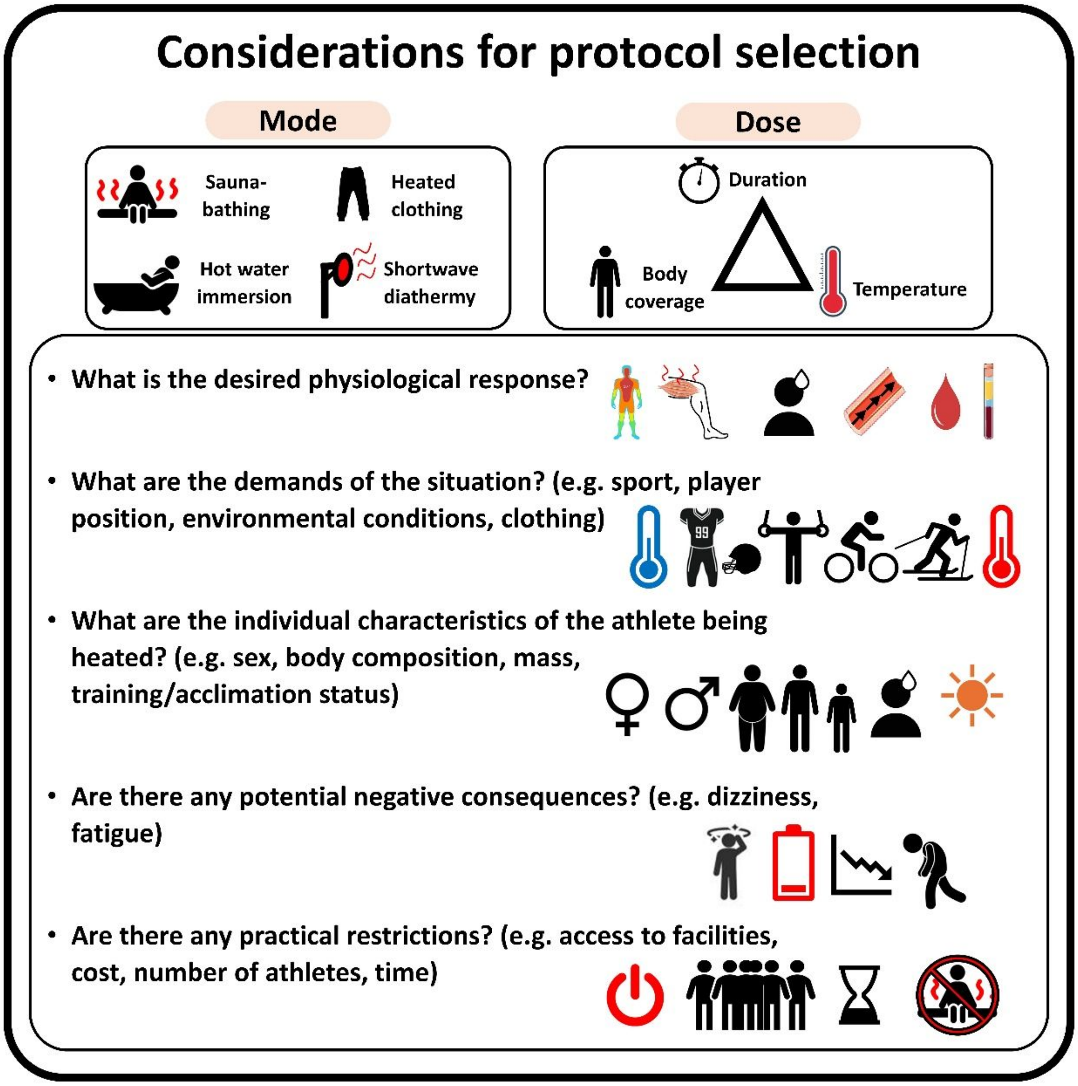

Figure 2 – Key factors for consideration in the implementation of a passive heating protocol within sport. Different modalities and doses of heating have different physiological effects with the desired effect and utility of passive heating being context specific based on a number of factors (e.g. demands of the situation, individual characteristics, potential negative effects, practical restrictions).

Funding

The authors declare no specific funding for this work.

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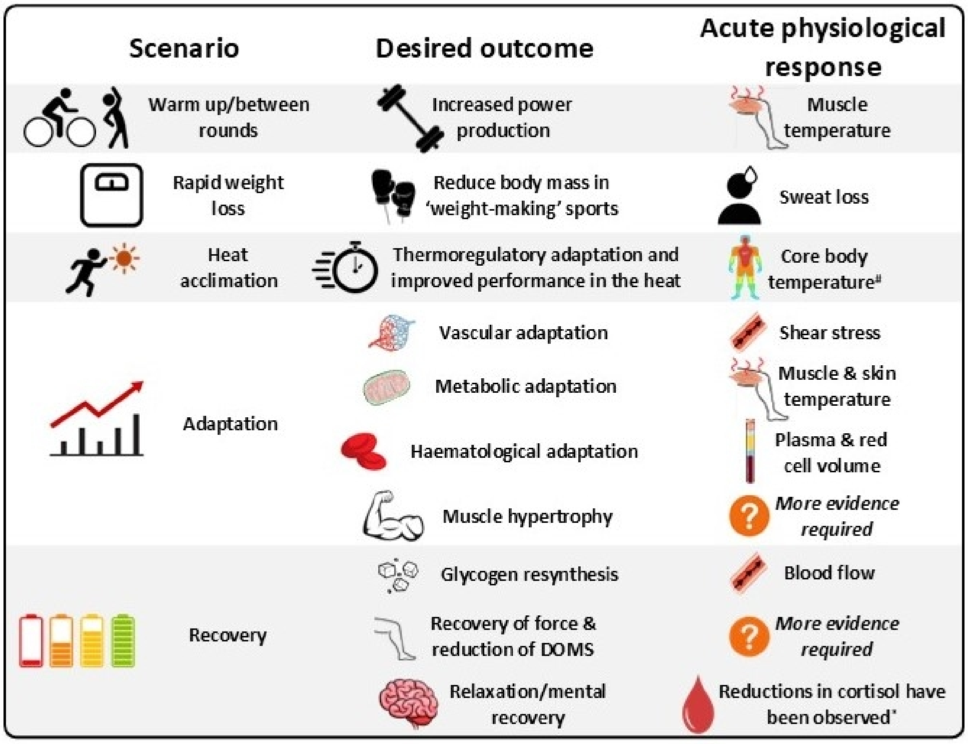

Figure 1 - Summary of the acute physiological responses that could be targeted in different scenarios of passive heating implementation.

#repeated exposures over >5 days.

*Psychophysiological mechanism not fully understood.

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Figure 2 – Key factors for consideration in the implementation of a passive heating protocol within sport. Different modalities and doses of heating have different physiological effects with the desired effect and utility of passive heating being context specific based on a number of factors (e.g. demands of the situation, individual characteristics, potential negative effects, practical restrictions).