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# The reliability of a portable steam sauna pod for the whole-body passive heating of humans

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ABSTRACT

*Introduction:* Passive heating is receiving increasing attention within human performance and health contexts. A low-cost, portable steam sauna pod may offer an additional tool for those seeking to manipulate physiological (cardiovascular, thermoregulatory and sudomotor) and perceptual responses for improving sporting or health profiles. This study aimed to 1) report the different levels of heat stress and determine the pods' inter-unit reliability, and 2) quantify the reliability of physiological and perceptual responses to passive heating.
*Method:* In part 1, five pods were assessed for temperature and relative humidity (RH) every 5 min across 70 min of heating for each of the 9 settings. In part 2, twelve males (age: 24 ± 4 years) completed two 60 min trials of passive heating (3 × 20 min at 44 °C/99% RH, separated by 1 week). Heart rate (HR), rectal ($T_{rectal}$) and tympanic temperature ($T_{tympanic}$) were recorded every 5 min, thermal comfort ($T_{comfort}$) and sensation ($T_{sensation}$) every 10 min, mean arterial pressure (MAP) at each break period and sweat rate (SR) after exiting the pod.
*Results:* In part 1, setting 9 provided the highest temperature (44.3 ± 0.2 °C) and longest time RH remained stable at 99% (51±7 min). Inter-unit reliability data demonstrated agreement between pods for settings 5–9 (intra-class correlation [ICC] >0.9), but not for settings 1–4 (ICC <0.9). In part 2, between-visits, high correlations, and low typical error of measurement (TEM) and coefficient of variation (CV) were found for $T_{rectal}$, HR, MAP, SR, and $T_{comfort}$, but not for $T_{tympanic}$ or $T_{sensation}$. A peak $T_{rectal}$ of 38.09 ± 0.30 °C, HR of 124 ± 15 b min$^{-1}$ and a sweat loss of 0.73 ± 0.33 L were reported. No between-visit differences ($p > 0.05$) were observed for $T_{rectal}$, $T_{tympanic}$, $T_{sensation}$ or $T_{comfort}$, however HR (+3 b.min$^{-1}$) and MAP (+4 mmHg) were greater in visit 1 *vs.* 2 ($p < 0.05$).
*Conclusion:* Portable steam sauna pods generate reliable heat stress between-units. The highest setting (44 °C/99% RH) also provides reliable but modest adjustments in physiological and perceptual responses.

## 1. Introduction

Passive heating is an area receiving increasing attention within human health (Brunt and Minson, 2021; Kim et al., 2020) and performance contexts (Heathcote et al., 2018), given the potential for hyperthermia to induce positive adaptations. There exists a range of passive heating modalities, including hot water immersion (HWI) (Brunt et al., 2016b; Zurawlew et al., 2016), sauna exposure (Ashworth et al., 2023; Kirby et al., 2021; Scoon et al., 2007), and water-perfused garments (Chiesa et al., 2016; Gibson et al., 2022). Such techniques may be used in isolation or in combination with exercise (Ruddock et al., 2016), to induce local or systemic responses. When repeated across multiple days, these responses stimulate thermally driven adaptations (Taylor, 2014).

Traditionally, to induce heat adaptation, individuals such as athletes or military personnel, were required to perform 'active' heat acclimation and/or acclimatisation (HA), i.e., undertake prolonged, low-to-moderate intensity exercise in hot conditions (Tyler et al., 2016). Whilst these protocols are effective at inducing physiological and perceptual adaptations leading to improved performance in the heat (James et al., 2017, 2018; Willmott et al., 2016, 2017, 2018), frequent and repeated exercise bouts are required to achieve the described physiological responses, notably often targeting a core temperature of 38.5 °C (Daanen et al., 2017; Taylor, 2014). Active HA approaches

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**Abbreviations**

| | |
|---|---|
| ANOVA | Analysis of variance |
| A.U | Arbitrary unit |
| CI | Confidence interval |
| CV | Coefficient of variation |
| ES | Effect size |
| HA | Heat acclimation/acclimatisation |
| HR | Heart rate |
| ICC | Intraclass correlation coefficient |
| IQR | Interquartile range |
| LoA | Limits of Agreement |
| MAP | Mean arterial pressure |
| RH | Relative humidity |
| $RH_{pod}$ | Relative humidity within portable steam sauna pod |
| RPE | Rating of perceived exertion |
| SD | Standard deviation |
| SR | Sweat rate |
| $T_{comfort}$ | Thermal comfort |
| $T_{pod}$ | Temperature within portable steam sauna pod |
| $T_{rectal}$ | Rectal temperature |
| $T_{sensation}$ | Thermal sensation |
| $T_{tympanic}$ | Tympanic temperature |
| TEM | Technical error of measurement |
| $VO_{2peak}$ | Peak oxygen uptake |
| $VO_{2max}$ | Maximal oxygen uptake |
| Δ | Change |

necessitate physical activity of differing intensities and volumes according to the specific nature of the HA protocol (Gibson et al., 2015a, 2015b). This creates an opportunity for individualisation of the intervention, however, this method can be logistically challenging to implement for multiple individuals simultaneously (Gibson et al., 2015b, 2020). In these situations, a more simplistic but less efficient protocol e.g., fixed intensity exercise, is often implemented. In contrast, passive HA minimises exercise requirements and complexities This subsequently reduces the interference with training programming by enabling routine training and adding the chosen heat stimulus afterwards (Gibson et al., 2020). Achieving heat adaptation through passive means is therefore appealing to populations who carefully manage volumes of physical activity (e.g. military, sporting populations). Previous research reports three weeks of post-training sauna bathing, can improve run time to exhaustion (+32% [Scoon et al., 2007],) and enhanced key determinants of endurance performance, e.g., increased maximal oxygen uptake ($VO_{2max}$: +0.3 L $min^{-1}$) and speed where blood lactate concentration ≥4 mmol.$L^{-1}$ (+0.6 km $h^{-1}$) (Kirby et al., 2021). The application of passive heating extends beyond preparing individuals for physical activity in a hot environment, as this construct, also termed "thermal or heat therapy", may promote positive health outcomes. For example, ameliorated metabolic profiles/status (Ely et al., 2019a, 2019b), improved cardiovascular risk factors (Brunt et al., 2016a, 2016c, 2019), and enhanced muscle function (Ely et al., 2019b; Racinais et al., 2017; Rodrigues et al., 2021). Epidemiological and experimental data also supports the efficacy of passive heating, via sauna use, as a tool to improve morbidity and mortality (Laukkanen et al., 2015, 2018a, b; Laukkanen and Laukkanen, 2018).

To achieve heat adaptation, the physiological stimulus evoked during passive heating may be characterised by core temperatures >38.5 °C, and an elevated heart rate (HR) and sweat rate (SR) above that expected during the same activity in a thermoneutral environment (Sawka et al., 2011). Typical responses to a single sauna bathing are apparently similar to the physiological stimuli 'required' for heat adaptation. Specifically, it has been reported that a 60 min sauna at 80 °C (Leppäluoto et al., 1986) elicited an increase in rectal temperature ($T_{rectal}$) of 0.8–1.1 °C, with a HR of ~110 b $min^{-1}$, and a sweat loss of +0.7–0.9 kg in young, healthy participants. Implementing intermittent sauna exposures at 90 °C, 5–16% relative humidity (RH) i.e., three 15 min exposures with 2 min normothermic intervals (Gryka et al., 2014), increased $T_{rectal}$ by 1.5 °C and induced a HR of ~130 b $min^{-1}$ in young males. Interestingly, a relatively shorter duration sauna (30 min) evoked comparable changes in $T_{rectal}$ (+2.0 °C) in older volunteers, even when the heat stress was lower (73 °C, 10–20% RH) (Laukkanen et al., 2018a, b). These data using sauna only exposures are similar to the physiological responses reporting during post-exercise heating, i.e., peak tympanic/rectal temperatures of 38.6–39.2 °C, HR of 110–130 b $min^{-1}$ and SR of +0.6–1.6 L $h^{-1}$ (Ashworth et al., 2023; Kirby et al., 2021; Stanley et al., 2015). Taken together, these data support passive heating via sauna as an appropriate methodology for manipulating core temperature and associated physiological responses contributing to heat adaptation.

Given the potential performance and health benefits of passive heating interventions, to increase opportunity for their use there is a need to seek simple and cost-effective equipment that can be used across a number of settings. In particular those that permit home-based usage, e.g., outside of Scandinavia, access to sauna facilities may be limited to specialist facilities. Recently portable steam sauna pods have become commercially available and therefore individuals seeking to undertake sauna exposure for health or performance reasons may now be in a position to remove some barriers preventing use. Accordingly, the aims of this study were to: 1) investigate the different levels of heat stress and determine the inter-unit reliability of a commercially available portable steam sauna pod; 2) quantify the acute physiological and perceptual responses to 60 min of seated rest within the portable steam sauna pod, and 3) quantify between-day reliability in physiological and perceptual responses during 60 min of seated rest within the portable steam sauna pod. It was hypothesised that the devices would demonstrate intra-unit reliability and would reproducibly elicit desirable physiological responses including core temperature >38.5 °C, HR > 100 b $min^{-1}$ and SR of >1 L $h^{-1}$.

## 2. Methods

### 2.1. Experimental design and ethical approval

This two-part study was approved by the lead institution's Research Ethics and Governance Committee and conducted in accordance with the principles of the World Medical Association (2013). Part 1 investigated the stability of five commercially available portable steam sauna pods across pre-programmed heat stress settings. Human participants were not involved in these assessments. Part 2 investigated the between-day reliability of human physiological and perceptual responses to 60 min of passive heating within two sauna exposures (separated by 1 week [test-retest]) using setting 9 only. Each exposure was divided into three 20 min periods, separated by 5 min rest in temperate conditions.

#### 2.1.1. Part 1: the stability of heat stress within the portable steam sauna pod systems

The full-body, portable 2 L steam sauna pod ([SKU: BA7426] Costway, UK) examined in this study are manufactured from multi-layered cotton (for insulation) and polyester (for waterproofing), around a polyvinyl chloride frame (width: 72 cm, depth: 99 cm, height: 85 cm, volume 0.6 $m^3$). A folding chair was located inside given prospective users will be seated with their head protruding through the open neckline. For safety, the water steamer container and associated digital control panel were located outside of the sauna, remaining connected through plastic tubing (Fig. 1).

To assess the stability of heat stress within the portable steam sauna pods, each heat stress setting (i.e., 1 to 9) was tested for a period of 70 min, with testing repeated in a random counterbalanced order, with at least 24 h between tests. The five portable steam sauna pods were set up in accordance with the manufacturer guidelines within temperate laboratory conditions (18.7 ± 0.3 °C, 44.6 ± 0.6% RH). Sauna pods were placed in line, with ~100 cm between pods, and zipped up before the water steamer container were filled with 2 L of water (~16–18 °C). The pods were then turned on, adjusted to the pre-determined setting, and followed the fixed heat stress test protocol (70 min at a single setting for the entire duration). A thermistor probe (PROACT, UK [accuracy to ± 0.1 °C]) and humidity sensor (Eidyer, UK) were suspended centrally inside the portable steam sauna pods and located above the interior steam output container, which was ~10 cm above the centre of the inserted chair. The thermistor probe and humidity sensor interfaces were located outside of the systems to allow for continuous monitoring of the pod temperature ($T_{pod}$) and relative humidity ($RH_{pod}$).

#### 2.1.2. Part 2: investigating the between-day reliability of human physiological and perceptual responses to 60 min of passive heating within the portable steam sauna pod system

*2.1.2.1. Participants.* For part 2, twelve recreationally trained, young healthy males (age: 24 ± 4 years, body mass: 77.0 ± 12.1 kg, stature: 1.77 ± 0.07 m, body mass index: 24.5 ± 3.1 kg $m^2$, body surface area: 1.94 ± 0.18 $m^2$, $VO_{2peak}$: 3.85 ± 0.42 L $min^{-1}$) volunteered, having provided written informed consent. All participants completed an incremental cycle test in temperate conditions (19.9 ± 0.6 °C, 46.6 ± 3.5% RH) to determine $VO_{2peak}$, prior to undertaking the two separate visits, 1 week apart, which involved 60 min (3 × 20 min periods) of passive heating within the portable steam sauna pod.

*2.1.2.2. $VO_{2peak}$ test.* The first visit comprised of baseline physiological assessments including stature (SECA 217 mobile stadiometer, UK) and body mass (electronic weighing scales Adam Equipment Co Ltd., UK). Participants completed a cycling $VO_{2peak}$ test on a static ergometer (Monark 874 E, Vansbro, Sweden), starting at 70 W for 5 min, then increasing 21 W $min^{-1}$ until volitional exhaustion. HR and rating of perceived exertion (RPE: 6–20 scale [Borg, 1982]) were recorded in the final 15 s of each stage. Upon reaching an RPE of 16, expired air was collected in Douglas bags for ~45 s per stage until the end of the test (i.e., cadence <60 RPM or volitional exhaustion). Expired air was sampled using a MiniMP 5200 analyzer (Servomex, UK) and a dry gas meter (Harvard Apparatus, UK).

*2.1.2.3. Experimental protocol.* Prior to arrival, participants were informed of all the experimental procedures and advised to arrive rested (e.g. no high-intensity exercise 24 h prior) and in a hydrated state (e.g. ingest ~500 mL 60 min prior). Upon arrival, participants' urine was analysed to assess hydration status via osmolality (<700 mOsmol.$kg^{-1}$ [Osmocheck, Vitech Scientific Ltd., Japan]), specific gravity (<1.020 [handheld refractometer, Atago, Japan]) and colour <3. Nude body mass was then measured, before participants self-inserted a disposable rectal probe (PROACT, UK) 10 cm past the rectal sphincter. Participants then rested in a temperate environment (19.8 ± 1.1 °C, 42.7 ± 3.2% RH) for 15 min where baseline physiological and perceptual measures were recorded. $T_{rectal}$ was measured to the nearest 0.10 °C using a 4600 Series Precision™ thermometer (Yellow Springs Instruments [YSI], USA) and tympanic temperature ($T_{tympanic}$) was measured using a digital ear thermometer (Braun ThermoScan® [IRT 4520] GmbH, Germany). Both methods were utilised to examine for differences in temperature given the participants' heads were located outside of the sauna system and that $T_{tympanic}$ monitoring is more likely to be implemented outside of research settings. This information was used to identify important health and safety considerations for users. HR was measured using a watch and chest strap (Polar T31, Finland), and systolic and diastolic blood pressure recorded using an automated cuff (Omron M3 Intellisense) with mean arterial pressure (MAP) calculated later. Perceptual measurements of thermal comfort ($T_{comfort}$: 4 = '*very uncomfortable*' to +4 = '*very comfortable*' [Zhang et al., 2004)]) and thermal sensation were also assessed ($T_{sensation}$: 0 = '*unbearably cold*' to 8 = '*unbearably hot*' [Toner et al., 1986]). Following the resting period, participants sat in the portable sauna pod, which were set to setting 9 for a total 60 min (three 20 min periods), with 5 min rest outside of the sauna system every 20 min. All participants wore underwear and shorts throughout both trials. No fluid ingestion was permitted during.

### 2.2. Data and statistical analyses

Data are reported as mean ± standard deviation (SD) unless otherwise stated. Data were assessed and conformed to normality and sphericity prior to analyses. Analyses were conducted using reliability spreadsheets (Hopkins, 2017) and SPSS software (v28.0, IBM, USA). Statistical significance was set at $p < 0.05$.

For part 1, two-way repeated measures ANOVA were used to examine the main effect of time points (0–70 min) and sauna settings (1–9) for mean $T_{pod}$ and $RH_{pod}$ data, and the time*setting interaction. Mean ± SD stability data for $T_{pod}$ and $RH_{pod}$ were estimated from 5 min interval data across the 70 min test and calculated from baseline where;

**Fig. 1.** The portable steam sauna pod system (left: image of open portable sauna with seat inside and water steam container outside, right: image with participant inside the sealed system).

$T_{pod}$ increased and remained stable with <1.0 °C change (Δ), and RH reached 99.0% and remained stable with <1.0% Δ, both for the remainder of the test. For part 2, two-way repeated measures ANOVA were used to examine the main effect of time and visit, and the time*visit interaction. Data were collected every 5 min for $T_{rectal}$, $T_{tympanic}$ and HR, and every 10 min for $T_{comfort}$ and $T_{sensation}$. MAP data were collected at the end of each period of heating (i.e. between 20 and 25, 45–50, and 70–75 min). Following a significant F-value, Bonferroni-corrected post-hoc comparisons were used. To estimate whole-body sweat loss, changes in pre-to-post body mass were calculated and analysed using a paired sample *t*-test.

To determine reliability, Pearson's correlation coefficients (*r*: between the two visits, and for the relationship between $T_{tympanic}$ and $T_{rectal}$) and intraclass correlation coefficients (ICC: between the two visits) were used to present test-retest correlations, with agreement categorised as: '*Negligible*' = 0.0–0.3, '*Low*' = 0.3–0.5, '*Moderate*' = 0.5–0.7, '*High*' = 0.7–0.9, and, '*Very high*' = 0.9–1.0 (Altman and Bland, 1983). Typical error of measurement (TEM) and coefficient of variation (CV) were used to measure absolute and relative levels of reliability, respectively. CV results were categorised as: '*Poor*' = >10%, '*Moderate*' = 5–10%, and, '*Good*' = <5%. Effect size (Hedge's *g* mean bias and 95% limits of agreement [LoA] with upper, lower confidence intervals [CIs]) were also calculated (Lakens, 2013). Effect size data were categorised as: '*Trivial*' = <0.19, '*Small*' = 0.20–0.49, '*Medium*' = 0.50–0.79, and, '*Large*' = ≥0.80. Data for peak and Δ (e.g., $\Delta T_{rectal}$) were calculated post-visit retrospectively.

## 3. Results

### 3.1. Part 1: the stability of heat stress within the portable steam sauna pod systems

A main effect of time was observed for $T_{pod}$ ($f = 6765.2$, $p < 0.001$) and $RH_{pod}$ ($f = 1031.1$, $p < 0.001$). $T_{pod}$ ($f = 5158.4$, $p < 0.001$) and $RH_{pod}$ ($f = 5928.7$, $p < 0.001$) also demonstrated main effects for setting and the time*setting interaction ($T_{pod}$: $f = 1603.6$, $p < 0.001$; $RH_{pod}$: $f = 205.5$, $p < 0.001$). For clarity, full post-hoc comparisons, and $T_{pod}$ and $RH_{pod}$ data are presented in Fig. 2. In summary, for within-setting

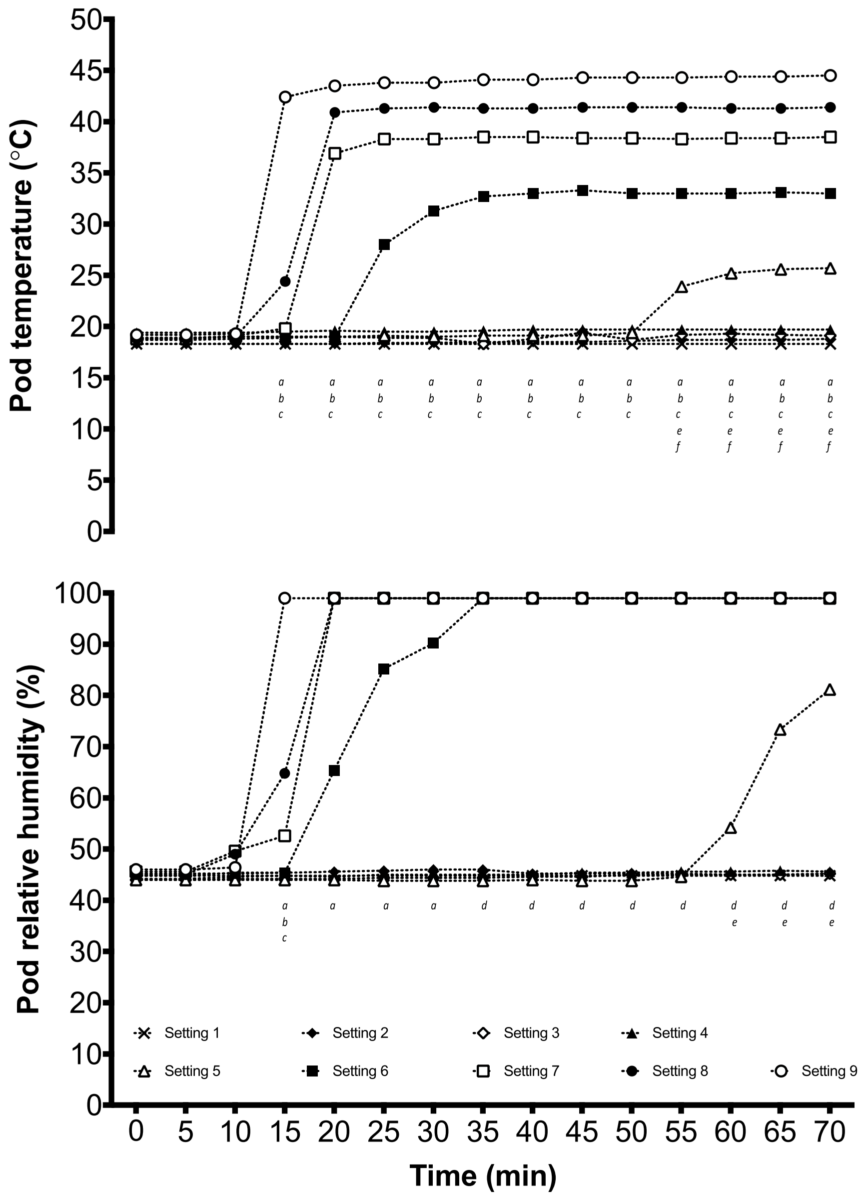


**Fig. 2.** Mean pod temperature ($T_{pod}$; top) and relative humidity ($RH_{pod}$; bottom) across settings 1–9 (note: standard deviation data removed for clarity). Note: significant differences ($p < 0.05$) between sauna pod levels are indicated by: *a* = 1–6 *vs.* 7–9, *b* = 7–8 *vs.* 9, *c* = 7 *vs.* 8, *d* = 1–5 *vs.* 6–9, *e* = 1–4 *vs.* 5, and *f* = 5 *vs.* 6.

analysis over the 70 min trial duration, a linear increase and a higher $T_{pod}$ ($p < 0.05$) were observed from; 55 min for setting 5, 20–35 min before stabilising for setting 6, 20–25 min before stabilising for setting 7, and, 15–20 min before stabilising for setting 8 and 9. For $RH_{pod}$, a linear increase and higher humidity ($p < 0.05$) were also observed from; 60 min for setting 5, 20–35 min before stabilising for setting 6, 10–20 min before stabilising for setting 7 and 8, and, 10–15 min before stabilising for 9. No changes in $T_{pod}$ nor $RH_{pod}$ were found over time for settings 1–4 ($p > 0.05$). Inter-unit reliability data are presented in Table 1, where high correlations, low TEM and good CV were found for $T_{pod}$ and RH across settings 5–9.

### 3.2. Part 2: investigating the between-day reliability of human physiological and perceptual responses to 60 min of passive heating within the portable steam sauna pod system

#### 3.2.1. Baseline measures

There were no between-visit differences ($p > 0.05$) in the participants' physiological (body mass: 76.9 ± 12.0 *vs.* 76.8 ± 12.0 kg, urine colour: 2 ± 1 *vs.* 2 ± 1 A.U, urine specific gravity: 1.011 ± 0.008 *vs.* 1.013 ± 0.006 A.U, urine osmolality: 256 ± 184 *vs.* 294 ± 148 mOsm. $kg^{-1}$, resting HR: 70 ± 8 *vs.* 68 ± 8 b $min^{-1}$, resting $T_{rectal}$: 37.34 ± 0.15 *vs.* 37.38 ± 0.22 °C and resting $T_{tympanic}$: 36.5 ± 0.2 *vs.* 36.2 ± 0.5 °C) and perceptual state ($T_{sensation}$: 3.6 ± 0.6 *vs.* 3.7 ± 0.4 A.U and $T_{comfort}$: 0.5 ± 1.0 *vs.* 0.5 ± 1.2 A.U). The $T_{pod}$ (40.5 ± 0.6 °C *vs.* 40.6 ± 0.7 °C) and $RH_{pod}$ (99 ± 0% *vs.* 99 ± 0%) were also not difference between visits ($p > 0.05$).

#### 3.2.2. Between-visit differences

A main effect of time was observed for all variables including: $T_{rectal}$ ($f = 28.7$, $p < 0.001$), $T_{Tympanic}$ ($f = 42.6$, $p < 0.001$), HR ($f = 125.6$, $p < 0.001$), MAP ($f = 12.6$, $p < 0.001$), $T_{sensation}$ ($f = 188.0$, $p < 0.001$), and $T_{comfort}$ ($f = 26.5$, $p < 0.001$). $T_{rectal}$ and $T_{tympanic}$ increased from baseline after 55 min and 65 min respectively, HR increased from baseline after 20 min, MAP was different from baseline at 25 min and 75 min, and, $T_{sensation}$ and $T_{comfort}$ differed from baseline after 20 min and 45 min respectively (Fig. 3).

There were no between-visit main effects for $T_{rectal}$ ($f = 0.0$, $p = 0.896$), $T_{tympanic}$ ($f = 3.0$, $p = 0.110$), $T_{sensation}$ ($f = 3.3$, $p = 0.098$), and $T_{comfort}$ ($f = 0.1$, $p = 0.756$). A between-visit main effect was observed for HR ($f = 6.1$, $p = 0.031$) and MAP ($f = 9.8$, $p = 0.010$), whereby both were higher (HR +3 ± 3 b $min^{-1}$ and MAP +5 ± 4 mmHg) in visit 1 *vs.* visit 2. SR did not differ between visits ($t = 0.3$, $p = 0.754$).

Only HR demonstrated a significant interaction effect ($f = 2.0$, $p = 0.033$), whereby it was observed that an increase from baseline occurred after 20 min in visit 1, and after 30 min in visit 2. HR was also higher in visit 1 *vs.* visit 2 at 10, 20, 35 and 55 min (Fig. 3).

#### 3.2.3. Reliability outcomes

Between-visits, high correlations, low TEM and good CV were found for $T_{rectal}$, HR, MAP, SR and $T_{comfort}$ measures, but not for $T_{tympanic}$ or $T_{sensation}$ (Table 2). Significant differences were found between $T_{rectal}$ and $T_{tympanic}$ for mean, peak and Δ data (all $p < 0.05$) within visit 1 (mean bias ± SD: 1.1 ± 0.3 °C, 0.5 ± 0.3 °C, and 0.3 ± 0.3 °C, respectively) and visit 2 (1.2 ± 0.3 °C, 0.6 ± 0.3 °C, and 0.6 ± 0.7 °C, respectively).

### 3.3. Relationship between tympanic and rectal temperature data

Non-significant correlations were observed between $T_{rectal}$ and $T_{tympanic}$ when examined as mean (visit 1: $r = 0.094$, $p = 0.770$; visit 2: $r = 0.553$, $p = 0.062$), peak (visit: 1 $r = 0.319$, $p = 0.312$; visit: 2 $r = 0.562$, $p = 0.057$), and the change (visit: 1 $r = 0.362$, $p = 0.248$; visit: 2 $r = 0.110$, $p = 0.734$).

## 4. Discussion

This two-part study quantified the different magnitudes of temperature and relative humidity elicited by each setting of the portable steam sauna pods and determined the intra-unit reliability. Subsequently, the physiological and perceptual responses to 60 min of passive heating during seated rest within the portable steam sauna pod and their inter-day reliability were quantified. The sauna pods provided a range of temperature and humidity conditions across the 9 available heating settings. Setting 9 provided the highest $T_{pod}$ (44.3 ± 0.2 °C) and longest duration where RH remained stable at 99% (51 ± 7 min). Inter-unit reliability data demonstrated agreement of temperature and humidity between pods when used for settings 5–9. Participant's physiological and perceptual responses between-visits also demonstrated agreement, with low variations observed, although HR demonstrated differences between trials. At the end of the passive heating period, a peak $T_{rectal}$ of 38.09 ± 0.30 °C (+0.72 ± 0.38 °C), a HR of 124 ± 15 b $min^{-1}$ (+53 ± 14 b $min^{-1}$) and a SR of 0.73 ± 0.33 L $h^{-1}$ (−0.9% of body mass) were induced. The time course of change in physiological and perceptual responses differed between variables, whereby differences from baseline were observed in HR and $T_{sensation}$ after 20 min, MAP at 25 min, $T_{comfort}$

**Table 1**
Mean ± SD inter-unit reliability data for $T_{pod}$ and $RH_{pod}$ data across the five sauna pods for settings 1–9.

| Setting | Conditions | Sauna pods | | | | | Mean Bias ± SD | ICC | TEM (CV %) |
|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | | | |
| **1** | **$T_{pod}$ (°C)** | 18.3 ± 0.0 | 18.4 ± 0.0 | 18.3 ± 0.0 | 18.2 ± 0.0 | 18.2 ± 0.0 | 0.0 ± 0.0 | 0.71 | 0.0 (0.1%) |
| | **$RH_{pod}$ (%)** | 44 ± 0 | 46 ± 0 | 44 ± 0 | 46 ± 0 | 44 ± 0 | 0 ± 0 | – | 0 (0.0%) |
| **2** | **$T_{pod}$ (°C)** | 18.6 ± 0.2 | 18.3 ± 0.1 | 18.6 ± 0.2 | 18.5 ± 0.2 | 18.6 ± 0.2 | 0.0 ± 0.1 | 0.86 | 0.1 (0.4%) |
| | **$RH_{pod}$ (%)** | 46 ± 1 | 45 ± 0 | 46 ± 0 | 45 ± 1 | 45 ± 1 | 0 ± 1 | 0.46 | 0 (0.9%) |
| **3** | **$T_{pod}$ (°C)** | 18.9 ± 0.5 | 19.2 ± 0.1 | 18.9 ± 0.1 | 18.7 ± 0.4 | 19.3 ± 0.3 | 0.1 ± 0.3 | 0.56 | 0.2 (1.1%) |
| | **$RH_{pod}$ (%)** | 44 ± 0 | 45 ± 1 | 46 ± 0 | 44 ± 0 | 44 ± 0 | 0 ± 0 | 0.61 | 0 (0.7%) |
| **4** | **$T_{pod}$ (°C)** | 19.7 ± 0.1 | 19.8 ± 0.1 | 19.3 ± 0.3 | 19.6 ± 0.2 | 19.6 ± 0.1 | 0.0 ± 0.2 | 0.58 | 0.1 (0.6%) |
| | **$RH_{pod}$ (%)** | 45 ± 1 | 45 ± 0 | 45 ± 0 | 45 ± 1 | 45 ± 1 | 0 ± 1 | 0.56 | 0 (0.9%) |
| **5** | **$T_{pod}$ (°C)** | 20.4 ± 3.1 | 21.2 ± 2.8 | 21.0 ± 2.9 | 20.8 ± 2.9 | 20.6 ± 2.6 | 0.1 ± 0.4 | 0.99 | 0.3 (1.5%) |
| | **$RH_{pod}$ (%)** | 47 ± 12 | 50 ± 13 | 50 ± 12 | 50 ± 12 | 51 ± 12 | 1 ± 1 | 1.00 | 1 (1.4%) |
| **6** | **$T_{pod}$ (°C)** | 28.3 ± 6.8 | 28.7 ± 6.4 | 28.3 ± 6.6 | 28.6 ± 6.1 | 28.6 ± 6.6 | 0.1 ± 0.9 | 0.99 | 0.6 (2.3%) |
| | **$RH_{pod}$ (%)** | 83 ± 23 | 83 ± 23 | 84 ± 22 | 84 ± 23 | 84 ± 23 | 0 ± 2 | 1.00 | 1 (1.9%) |
| **7** | **$T_{pod}$ (°C)** | 34.5 ± 7.9 | 34.4 ± 8.2 | 34.1 ± 8.2 | 33.9 ± 8.2 | 34.0 ± 8.1 | 0.1 ± 0.4 | 1.00 | 0.3 (1.1%) |
| | **$RH_{pod}$ (%)** | 88 ± 21 | 88 ± 21 | 88 ± 21 | 89 ± 21 | 88 ± 22 | 0 ± 1 | 1.00 | 1 (1.4%) |
| **8** | **$T_{pod}$ (°C)** | 37.5 ± 8.3 | 37.4 ± 8.3 | 36.4 ± 9.5 | 36.6 ± 9.4 | 36.7 ± 9.6 | 0.2 ± 1.7 | 0.99 | 1.2 (4.9%) |
| | **$RH_{pod}$ (%)** | 89 ± 20 | 89 ± 20 | 89 ± 20 | 89 ± 20 | 89 ± 20 | 0 ± 1 | 1.00 | 1 (1.2%) |
| **9** | **$T_{pod}$ (°C)** | 40.8 ± 8.9 | 40.2 ± 8.9 | 40.4 ± 9.2 | 40.5 ± 9.1 | 40.5 ± 9.0 | 0.1 ± 0.5 | 1.00 | 0.4 (1.0%) |
| | **$RH_{pod}$ (%)** | 92 ± 18 | 91 ± 19 | 91 ± 20 | 91 ± 20 | 92 ± 19 | 0 ± 1 | 1.00 | 1 (1.1%) |

Note: SD = standard deviation, $T_{pod}$ = pod temperature, $RH_{pod}$ = pod relative humidity, ICC = intraclass correlation coefficient, TEM = typical error of measurement, CV = coefficient of variation.

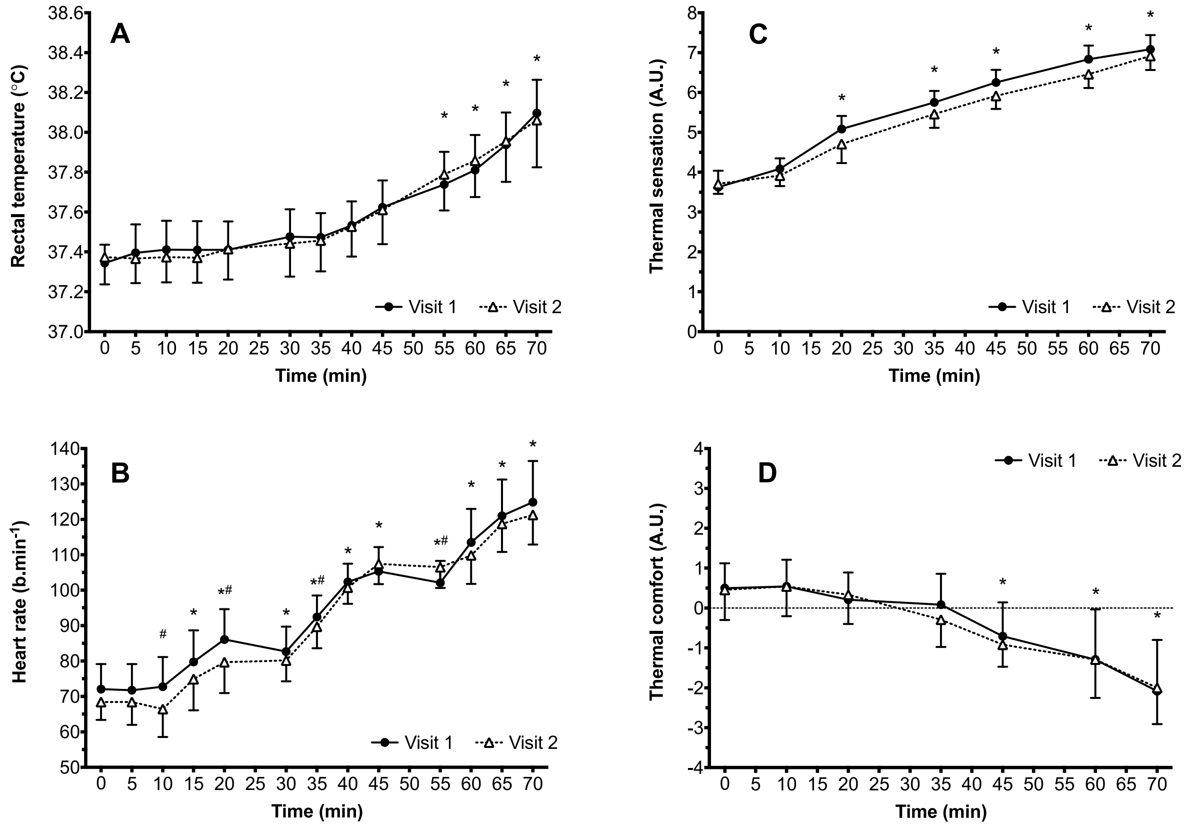


**Fig. 3.** Mean ± standard deviation physiological and perceptual responses (A: $T_{rectal}$ = rectal temperature; B: HR = heart rate; C: $T_{sensation}$ = thermal sensation; D: $T_{comfort}$ = thermal comfort) over the course of passive heating (n = 12). Note: * denotes difference from 0 min ($p < 0.05$), # denotes a difference between visit 1 and visit 2 ($p < 0.05$).

**Table 2**
Mean ± SD physiological and perceptual data, and reliability statistics for sauna visit 1 and 2 (n = 12).

| Measure | | Visit 1 | Visit 2 | Mean Bias ± SD | 95% LoA (upper, lower CI) | *p* | Correlation (*r*) | ES (Hedge's *g*) | TEM (CV) |
|---|---|---|---|---|---|---|---|---|---|
| Physiological data | | | | | | | | | |
| **$T_{rectal}$ (°C)** | **Mean** | 37.61 ± 0.19 | 37.60 ± 0.20 | 0.01 ± 0.14 | 0.54 (0.26, −0.28) | 0.84 | 0.77 | 0.0 | 0.10 (0.3%) |
| | **Peak** | 38.10 ± 0.26 | 38.08 ± 0.35 | 0.01 ± 0.18 | 0.71 (0.34, −0.33) | 0.81 | 0.88 | 0.1 | 0.13 (0.3%) |
| | **Δ** | +0.75 ± 0.28 | +0.69 ± 0.48 | 0.07 ± 0.32 | 0.96 (0.45, −0.51) | 0.65 | 0.84 | 0.1 | 0.17 (37.6%) |
| **$T_{tympanic}$ (°C)** | **Mean** | 36.5 ± 0.2 | 36.4 ± 0.3 | 0.2 ± 0.3 | 1.4 (0.5, −0.8) | 0.15 | 0.23 | 0.4 | 0.2 (0.7%) |
| | **Peak** | 37.6 ± 0.3 | 37.5 ± 0.3 | 0.1 ± 0.3 | 1.3 (0.5, −0.8) | 0.21 | 0.36 | 0.3 | 0.2 (0.6%) |
| | **Δ** | +1.1 ± 0.3 | +1.3 ± 0.7 | 0.2 ± 0.8 | 2.7 (1.5, −1.1) | 0.29 | 0.05 | 0.2 | 0.5 (70.7%) |
| **HR ($b.min^{-1}$)** | **Mean** | 96 ± 11 | 94 ± 10 | 2 ± 4 | 16 (6, −9) | 0.16 | 0.94 | 0.2 | 3 (2.9%) |
| | **Peak** | 126 ± 17 | 122 ± 13 | 3 ± 6 | 24 (9, −15) | 0.10 | 0.96 | 0.2 | 4 (3.3%) |
| | **Δ** | +52 ± 13 | +54 ± 14 | 2 ± 11 | 44 (23, −20) | 0.65 | 0.67 | 0.1 | 8 (16.7%) |
| **MAP (mmHg)** | **Mean** | 100 ± 6 | 95 ± 7 | 5 ± 4 | 17 (−14, 4) | 0.00 | 0.82 | 0.8 | 3 (3.3%) |
| | **Peak** | 113 ± 9 | 104 ± 8 | 9 ± 9 | 37 (−28, 10) | 0.01 | 0.40 | 1.1 | 7 (6.3%) |
| | **Δ** | −12 ± 7 | −10 ± 9 | 2 ± 11 | 41 (−18, 23) | 0.49 | 0.15 | 0.3 | 7 (%) |
| **SR ($L.hr^{-1}$)** | | 0.7 ± 0.3 | 0.7 ± 0.4 | 0.0 ± 0.1 | 0.4 (0.2, −0.2) | 0.75 | 0.97 | 0.0 | 0.1 (10.8%) |
| **Perceptual data** | | | | | | | | | |
| **$T_{sensation}$ (A. U)** | **Mean** | 5.8 ± 0.3 | 5.6 ± 0.5 | 0.3 ± 0.5 | 2.1 (0.8, −1.3) | 0.07 | 0.17 | 0.0 | 0.4 (7.3%) |
| | **Peak** | 7.1 ± 0.5 | 6.9 ± 0.6 | 0.2 ± 0.5 | 2.0 (0.8, −2.0) | 0.16 | 0.57 | 0.3 | 0.4 (5.4%) |
| | **Median (IQR)** | 6.0 (2) | 5.5 (1.5) | – | – | – | – | – | – |
| **$T_{comfort}$ (A.U)** | **Mean** | −0.5 ± 1.2 | −0.6 ± 1.1 | 0.1 ± 0.8 | 3.1 (1.5, −1.6) | 0.71 | 0.82 | 0.1 | 0.6 (–) |
| | **Peak** | 1.0 ± 1.3 | 0.7 ± 1.1 | 0.3 ± 1.0 | 3.8 (1.6, −2.2) | 0.36 | 0.73 | 0.2 | 0.7 (–) |
| | **Min** | −2.3 ± 1.4 | −2.0 ± 1.4 | 0.3 ± 1.1 | 4.3 (2.5, −1.8) | 0.30 | 0.73 | 0.2 | 0.8 (–) |
| | **Median (IQR)** | −0.5 (2.1) | −0.5 (1.3) | – | – | – | – | – | – |

Note: SD = standard deviation, LoA = limits of agreement, CI = confidence interval, *r* = Pearson correlation coefficient, ES = effect size, TEM = typical error of measurement, CV = coefficient of variation, $T_{rectal}$ = rectal temperature, $T_{tympanic}$ = tympanic temperature, HR = heart rate, MAP = mean arterial pressure, SR = sweat rate, $T_{sensation}$ = thermal sensation, A.U = arbitrary unit, $T_{comfort}$ = thermal comfort, Δ = change, IQR = Interquartile range.

after 45 min, and $T_{rectal}$ and $T_{tympanic}$ after 55 min and 65 min respectively.

### 4.1. Part 1: fixed heat stress

Given setting 9 achieved the highest temperature (44 °C) and longest duration of high humidity (99% for 51 min), with low mean bias, very high correlations (r = >0.9), low TEM and good CV (<5%) between pods, we recommend that this setting may be adopted for passive heating interventions, where inducing maximal heat stress is the objective. Further to this, our data also acknowledges that if maximal heat stress is not desired, the sauna pods can generate and maintain stable and reliable environmental conditions above 30 °C and at 99% RH for >40 min of passive heating when used on setting 6 or above. A notable issue with the portable steam sauna pod however was that no changes in pod temperature nor humidity were observed for settings 1–4. It appears the water steamer does not provide a heating stimulus for these settings and is therefore only effective for passive heating at setting >6.

When programmed to setting 9, the $T_{pod}$ (44 °C) is similar to that most commonly reported for active HA protocols (40 °C) (Tyler et al., 2016) and for post-exercise HWI (40–42 °C) (Heathcote et al., 2018), although the $RH_{pod}$ (99%) is far higher than that implemented in active HA studies (40%). This information provides context for alternate, passive heating interventions (e.g., portable steam sauna pod), although caution is advised when making comparisons between passive and active methods, as differences in activity level and physiological strain are experienced. When compared to other sauna-related literature, it is notable that the maximum $T_{pod}$ is inferior to traditional saunas that have been subject to experimental consideration (ambient temperatures ranging 55–100 °C [Ashworth et al., 2023; Campbell et al., 2022; Kirby et al., 2021; Kissling et al., 2022; Leppäluoto et al., 1986; Scoon et al., 2007; Stanley et al., 2015]). The overall heat stress may however be comparable to some previous work given traditional saunas typically elicit low humidity (<20%), whereas the portable sauna pods elicit a RH of 99%. To illustrate this, the steam sauna pod elicited an estimated wet bulb globe temperature of ~44 °C, which could also be elicited by air temperatures of 60 °C and a RH of 20%.

To achieve the desired thermal strain, users of the portable steam sauna should give consideration to the intersection between device setting, starting body temperature, and exposure duration and for those individuals seeking to elicit maximal heat stress, the highest temperature and humidity settings of the sauna pod will most closely reflect the heat stress of a traditional sauna. Users are also encouraged to consider health and safety implications when using the highest temperature settings and to avoid ill-effects of direct steam exposure (e.g., scalding). We therefore recommend the use of personal protective equipment when handling the water steamer and ensure manufacturer guidelines are following for maximum time and water capacity.

### 4.2. Part 2: physiological and perceptual responses

There were no main effect differences in physiological or perceptual responses, nor environmental conditions, between sauna visits 1 and 2. High-very high correlations, low TEM and good CV were found for our examined physiological e.g., $T_{rectal}$, HR and SR, and perceptual measures e.g., $T_{sensation}$ and $T_{comfort}$. It therefore appears the sauna pods induce reliable responses and generates replicable conditions between-visits when programmed to setting 9 and used for 60 min of passive heating. As such, the portable steam sauna could be considered an additional method of passive heating/heat-maintenance and may after further investigation, permit individuals to complete home-based heat interventions or where facilities are limited/restricted, e.g., nearby training area.

However, it is acknowledged that participant's $T_{rectal}$ did not reach a target temperature of 38.5 °C within the tested timeframe of heating (i.e., 60 min), with modest $T_{rectal}$ increases observed (mean: ~37.6 °C, peak: ~38.1 °C, Δ: ~0.7 °C). This may be considered a limitation of the steam sauna pod in the context examined (e.g. passive), because the 60 min protocol does not seem to achieve previously described desirable magnitudes of heat strain, nor magnitude of change required compared to recommendations for physiological adaptation for sport and occupational performance (Sawka et al., 2011). Additionally, the pods may not be able to induce sufficient thermal strain to initiate cellular and molecular responses related to heat adaptation (e.g., increased heat shock proteins [Gibson et al., 2016, 2014]). It is noted that minimum 'thresholds' for heat adaptation in clinical/health contexts are yet to be identified and may be lower than the $T_{rectal}$ of 38.5 °C (+1.5 °C from baseline), commonly stated as necessary for adaptation during active HA (Daanen et al., 2017; Gibson et al., 2020). Accordingly, the steam sauna pods may have merit for this application and require further investigation. Experimental work has identified that in young participants increasing core temperature by +1.5 °C can be achieved using dry sauna at 80 °C (three 15 min exposures [Gryka et al., 2014]) with +2.0 °C achieved in older participants at 73 °C (30 min continuous exposure). Whilst HR and SR data demonstrate reasonable change (circa +95 b $min^{-1}$, +0.7 L $h^{-1}$, respectively), overall, the physiological responses to the portable steam sauna are lower compared to other literature investigating isolated sauna use.

Within real-world applications, monitoring body temperature is an important safety consideration during heating interventions (Casa et al., 2015). As such, we also considered whether a commercially available temperature monitoring device (i.e., a tympanic membrane thermometer), can be used as an appropriate surrogate to $T_{rectal}$ monitoring. Significant differences were found between measures of $T_{rectal}$ and $T_{tympanic}$ within both passive heating visits, which reduces confidence in the ability for temperature to be monitored accurately using a tympanic membrane device. Temperature at the tympanic membrane is 0.5–0.7 °C lower than the temperature at the rectum at rest (Cotter et al., 1995; Ganio et al., 2009). In the present study, $T_{tympanic}$ demonstrated consistently lower mean temperatures (~1.1–1.2 °C difference *vs.* $T_{rectal}$) and low-moderate correlations with $T_{rectal}$. Whilst $T_{tympanic}$ has been demonstrated to track the increase in $T_{rectal}$ during indoor exercise in the heat (Ganio et al., 2009), our data does not support this response during portable steam sauna pod use. This discrepancy is likely affected by $T_{tympanic}$ being assessed at the external auditory canal-tympanic membrane where participants' heads are located outside of the pods. Therefore, users are cautioned to implement a valid measure(s) of assessing core temperature whilst using the steam sauna pod for passive heating.

Whilst the pods offer logistical (e.g. portable capability) and practical benefits (e.g. easy set up and minimal preparation/monitoring requirements for "plug in and passively heat") for HA implementation compared to HWI, to elicit the desired physiological responses, alterations to the use of the portable sauna pod may be required. A larger physiological strain during passive heating can be achieved when the heating follows prior exercise i.e., core temperatures maintained >38.5 °C, HR > 130 b $min^{-1}$, SR > 1.0 L $h^{-1}$ (Ashworth et al., 2023; Campbell et al., 2022; Kirby et al., 2021; Scoon et al., 2007; Stanley et al., 2015). Post-exercise passive heating (commonly via HWI) has demonstrated efficacy for inducing heat adaptation and enhancing physiological responses in athletes (Zurawlew et al., 2016, 2018), military personnel (Ashworth et al., 2023) and the elderly (Waldock et al., 2021). Given the apparently comparable responses and adaptations between post-exercise HWI and sauna interventions (Ashworth et al., 2023; Campbell et al., 2022; Kissling et al., 2022), the pods now require investigation to evaluate if $T_{rectal}$ can be increased or maintained >38.5 °C following exercise.

### 4.3. Limitations and future directions

Future studies should make direct comparisons across new and existing active and passive heating methods (e.g., portable infra-red systems, dry/wet saunas), and investigate how post-exercise use of the steam sauna pods may induce adaptation. Further to this, the pods may be a beneficial tool to elicit pre-exercise responses (Mee et al., 2018). Due to no female participants in this study, we acknowledge these data are directly relevant to recreationally trained, young healthy males only, and thus further investigation is warranted into responses across other populations who may consider passive heating as a worthwhile intervention (e.g., older cohorts, females, clinical groups, untrained or highly trained athletes). In addition, only a narrow range of common physiological responses were measured and examination of a wider array of thermally relevant dependent variables is required as well as understanding the range of thermal conditions incurred inside the pod. Finally, repeated exposure studies using the portable sauna (i.e., HA/heat therapy) are now required to determine whether the low cost, home-based intervention can induce thermally driven adaptations for athletes, occupational workers (e.g., military) and/or the general public.

## 5. Conclusion

Commercially available, low cost and portable steam sauna pods generate reliable environmental conditions, across pre-programmed heat stress settings 5–9. The highest setting is able to achieve a stable temperature of 44 °C for ~50 min and a RH of 99% for ~60 min. The highest setting also provides reliable, modest adjustments in physiological responses between-day with increases in core temperature of +0.7 °C achieved over a 60 min intervention. However, compared to other sauna interventions, lower environmental and rectal temperatures are achieved using the sauna pods for passive heating. Therefore, further investigations are required to determine the efficacy when implemented following exercise and also during heat acclimation.

## Credit statement

A.G.B Willmott (AGBW), C.A James (CAJ), M. Hayes (MH), N.S Maxwell (NSM), J. Roberts (JR), O. R Gibson (ORG). Conceptualization AGBW JR. Methodology AGBW JR OG. Formal analysis AGBW OG. Investigation AGBW. Writing - Original Draft AGBW. Writing - Review & Editing AGBW CAJ MH NSM JR OG. Visualization AGBW OG.

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## Declaration of competing interest

None.

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