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Assessing the validity of a novel core temperature monitoring tool at rest and during strenuous physical activity

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Abstract

Core temperature information is important for guiding prevention and treatment measures. Developing new physiological monitoring tools that provide reliable core temperature information is critical for heat injury prevention. The ThriveHRI sensor system is being developed as an efficient core monitoring tool in a smartwatch platform. The current study compared the ThriveHRI sensor/smartwatch to an Equivital LifeMonitor and a rectal thermistor. This study aimed to determine if the ThriveHRI sensor system provides an accurate and precise estimate of core temperature at rest and during physical activity, representing strenuous occupational tasks at elevated temperatures in healthy adults. Twenty-five healthy, physically active adults (N = 14 males; N = 11 females) between the ages of 19–45 years volunteered. Participants completed multiple rounds of deadlifting and treadmill walking in an environmental chamber set to 43.3°C and 50% relative humidity. Participants alternated between performing deadlifts and walking on the treadmill for 35 minutes. Core temperature was monitored continuously via a Datatherm rectal thermometer, Equivital Eq02+LifeMonitor, and a ThriveHRI heat watch. A significant difference in bias between devices was found for easy walking ($t(21)$ = 5.55, $p < 0.001$, g = 1.01), deadlift ($t(19)$ = 3.60, p = 0.002, g = 0.73), and treadmill ($t(16)$ = 2.42, p = 0.028, g = 0.60). A significant difference in precision between devices was found for easy walking ($t(21)$ = 4.23, $p < 0.001$, g = 1.21), but no significant difference in precision between devices was found for deadlift or treadmill (ps ≥ 0.067). This study demonstrates the agreeability between the Equivital EQ02+ LifeMonitor, ThriveHRI sensor, and the rectal thermometer remains consistent as core temperature increases and exposure to a heated environment is sustained.

1. INTRODUCTION

Tactical athletes are often exposed to extreme heat or frigid temperatures while wearing a required uniform or personal protective equipment (PPE). Required PPE for firefighters includes a helmet, heat-resistant hood, gloves, heat-resistant jacket and pants, boots, and self-contained breathing apparatus. Together, these PPE weigh upwards of 55 pounds (Hemmatjo, Motamedzade, Aliabadi, Kalatpour, & Farhadian, 2018; Hostler, Colburn, Rittenberger, & Reis, 2016; Kong, Beauchamp, Suyama, & Hostler, 2010; McEntire, Suyama, & Hostler, 2013; Walker, Argus, Driller, & Rattray, 2015). The on-shift uniform for police officers typically consists of a dress shirt, trousers, boots, badge, belt, hat, and duty belt, which are required equipment and weigh approximately 25 pounds (Srubas, 2016). PPE is needed and necessary to maintain safety. However, it restricts the dissipation of body heat generated during activity (Walker et al., 2015;

Wright et al., 2013). Tactical athletes perform an array of strenuous physical tasks throughout their day while wearing PPE, such as carrying ladders and other heavy equipment, moving debris and fallen objects, and crawling under thick clouds of smoke with low visibility (Hemmatjo et al., 2018). These occupational tasks increase metabolic heat production, which increases core temperature. The PPE restricts cooling through sweat evaporation, trapping the heat inside the PPE (Hirschhorn, DadeMatthews, & Sefton, 2021). Thus, the weight of PPE combined with exposure to dangerously high temperatures and strenuous physical activity can cause increases in core temperature, increasing the risk of heat injury (Hemmatjo et al., 2018; Walker et al., 2015; Wright et al., 2013).

The severity of the symptoms determines heat-related injuries and includes (from least to more severe) heat cramps, heat exhaustion, and heat stroke. Heat cramps are muscle contractions due to loss of electrolytes from dehydration or increased sweating, the body's primary cooling mechanism. Heat exhaustion occurs when the body cannot properly cool itself, resulting in dizziness and confusion. Heatstroke occurs when its core temperature rises above 40 ℃ (104 ℉). There are two types of heat stroke: classic heat stroke and exertional heat stroke. Classic heatstroke occurs from exposure to a heated environment coupled with poor thermoregulatory mechanisms (Bouchama et al., 2022; Epstein & Yanovich, 2019). Exertional heatstroke results from excess heat generated by the body. This can result from increased metabolic heat production after physical activity combined with a decrease in the dissipation of body heat due to external causes (e.g., PPE) or a lack of heat acclimatization (Hirschhorn et al., 2021).

Core temperature information is important to guide prevention and treatment measures and is essential for those working in severe environments, such as firefighters, military, law enforcement, and construction and farm workers. Current tools and protocols to mitigate the effects of heat and prevent heat injury include self-reporting symptoms to a superior and the development of acceptable work/rest and cooling schedules (Buller, Delves, Fogarty, & Veenstra, 2021). The development of new physiological monitoring tools that are easy to use and provide reliable core temperature information is critical for heat injury prevention. Devices that can track vital signs in the field/work environment and send warning alerts before dangerous levels are reached have the potential to reduce injury and save lives. For example, one core temperature monitoring tool that is currently commercially available is the Eq02+LifeMonitor. This measuring tool uses an algorithm that is regulated by physiological inputs such as heart rate to produce an estimated core temperature for the wearer (Agostinelli et al., 2023). New tools are constantly being developed as technology improves and our knowledge increases.

One monitoring system currently in development is the ThriveHRI sensor system, which uses the Samsung Galaxy 5 watch as a platform. An algorithm calculates estimated core temperature based on multiple inputs from the watch, including the individual's heart rate and exertion level, which are measured using an accelerometer within the watch, along with the ambient temperature and humidity of the surrounding environment. The core temperature warnings can be set at different levels, and environmental conditions can be programmed to improve accuracy. The gold standard for measuring core temperature in research settings includes esophageal and rectal thermometry and pulmonary artery catheters (Mah et al., 2021). Less complex and invasive methods, including ingestible thermometer pills and temporal thermometers, are also available. However, these methods come with significant limitations. The more accurate devices are challenging to use in the field, while the easy-to-use devices have significant accuracy limitations (Kolka, Quigley, Blanchard, Toyota, & Stephenson, 1993; McKenzie & Osgood, 2004; Roossien, Heus, Reneman, & Verkerke, 2020). An easily wearable sensor that correctly estimates core temperature could prevent heat injuries and deaths.

The current study compared the ThriveHRI sensor system to an Equivital LifeMonitor and a rectal thermistor, two validated core temperature measurement tools used in research. This study aimed to determine if the ThriveHRI sensor system provides an accurate and precise estimate of core temperature at rest and during physical activity, representing strenuous occupational tasks at elevated temperatures in healthy adults.

Based on our previous work (Agostinelli et al., 2023), we hypothesized that the ThriveHRI sensor system compared to the rectal thermistor gold standard and Equivital Black Ghost System for measuring core body temperature will be: 1) comparable to Equivital core body temperature estimates, and within 0.1°C of rectal thermistor core body temperature; 2) comparable to Equivital estimates at rest; and 3) less accurate than Equivital estimates during activity.

2. METHODOLOGY

Healthy, physically active adults between the ages of 19–45 (N = 14 males, 28 ± 4.0 yrs, 85.5 ± 11.1 kg, 169.3 ± 28.8 cm; N = 11 females, 26 ± 3.0 yrs 67.0 ± 6.6 kg, 164.2 ± 5.6 cm) volunteered. Inclusion criteria included being free of any disease or illness that would hinder their ability to complete the exercise protocol and ability to deadlift 50% of their body weight. Exclusion criteria included individuals with any musculoskeletal injury, cardiovascular disease, asthma, chest pain, or pregnancy. Participants were compensated $150 for their participation in the study. The Institutional Review Board of Auburn University protocol # 12-149 MR 2205 approved the study.

Participants consented to the study and were assessed for height and weight. A portable refractometer (V-Resourcing, Hunan, China) was used to evaluate urine specific gravity before the trial to ensure hydration and safety for each participant (Games et al., 2020). Blood pressure was also screened before the trial to ensure safety (Games et al., 2020). Participants were directed to a private restroom where they put on their Equivital EQ02+ LifeMonitor chest strap (Equivital, Cambridge, UK) and a DataTherm® II Temperature Monitor 2M Probe Sensor (RG Medical Diagnostics, Wixom, MI, USA) which they inserted into the marked line on the probe into the anal sphincter ~10 cm and then taped it in place to prevent movement (Agostinelli et al., 2023). A research team member then placed a ThriveHRI sensor system on the participant's left wrist. All participants wore the sensor system on their left wrist to ensure consistency. Once the watch fit was correct, the researcher activated the watch, entered environmental information, and connected the watch to a Samsung Galaxy S8 tablet (Samsung Electronics, Suwon-si, South Korea), enabling researchers to view the dashboard and retrieve the data from the watch. The participants entered the environmental chamber at 43.3°C and 50% relative humidity.

Inside the environmental chamber, participants were instructed to sit in the specified chair for 15 minutes while the sensor system calibrated to the participants' heart rate. Participants then began 10 minutes of light walking on the treadmill at 3.0 miles per hour at 0% grade. Next, they completed a 25-minute exercise protocol alternating between deadlifts and walking. They finished 20 deadlifts as quickly as possible using proper form during a five-minute timespan. They were allowed to rest for the remaining time in that five-minute block. Participants then transitioned to the treadmill, walking at three mph at 10% grade for five minutes. They transitioned back to the deadlifts and repeated the above sequence (see Figure 1 for the deadlift and treadmill set up). Participants performed three rounds of the deadlift task and two rounds of the treadmill task for 25 minutes. Heart rate, respiratory rate, skin temperature and core and estimated core temperature were collected at one-minute intervals via a rectal thermometer, Equivital EQ02+ LifeMonitor chest strap with BlackGhost software, and a ThriveHRI sensor system. After completing the 50-minute chamber protocol, participants exited the chamber, sat in the designated chair, and cooled at room temperature (approximately 22.22°C) for 60 minutes or until their core body temperature reached their baseline core temperature as measured by the rectal thermometer. During this recovery period, heart rate, skin temperature, respiratory rate, and core temperature were collected via the rectal thermometer, Equivital EQ02+ LifeMonitor chest strap, and ThriveHRI sensor system every minute. Additionally, the rate of perceived exertion via the Borg scale was collected every five minutes during the one-hour and 15-minute protocol. Chamber temperature and humidity were checked and recorded every 5 minutes throughout the protocol to ensure environmental consistency.

Figure 1. A) Set-up of the deadlift station inside of the heat chamber is depicted. B) Set-up of the treadmill station inside of the heat chamber is depicted.

2.1 Measures

Equivital EQ02+ LifeMonitor and ThriveHRI bias were assessed by computing the constant error between core body temperature (Tc) (measured via the rectal thermometer) and the estimated core body temperature ($\widehat{Tc}$) from the respective devices. Specifically, for each participant, $\widehat{Tc}$ minus Tc was calculated each minute, and the differences were averaged for each condition (easy walking, deadlift, and treadmill). Equivital EQ02+ LifeMonitor and ThriveHRI accuracy were assessed by computing the absolute error between Tc and $\widehat{Tc}$ from the respective devices. For each participant, the absolute value of the constant error was calculated each minute, and these values were averaged for each condition. Equivital EQ02+ LifeMonitor and ThriveHRI precision were assessed by computing the variable error between Tc and $\widehat{Tc}$ from the respective devices. The standard deviation of constant error was calculated for each condition. To avoid biased measures of accuracy, bias, and precision, the variables were only computed for a given minute when $\widehat{Tc}$ was reported for each device on the minute. To improve reliability of the variables, a participant's data for a given condition were only included if they had ≥ 10 $\widehat{Tc}$s from each device in that condition.

2.2 Statistical Analysis

Accuracy, bias, and precision between devices were evaluated with paired-sample Welch's *t*-tests in each condition. This approach was preferred over repeated-measures ANOVA with condition as a factor because some participants had missing data for one condition but not another. With an ANOVA, these participants' data would have been excluded even for conditions in which they had complete data. Alpha levels were set to 0.05 for all tests. R Studio version 3.0.1 (R Studio Team, Boston, MA, USA) was used for all statistical analyses.

3. RESULTS

3.1. Accuracy

No significant difference in accuracy between devices was found for any condition (*p*s ≥ 0.532). Descriptive data in Table 1 indicates that, on average, both devices were accurate within 0.40°C under all conditions. Figure 2 shows a graphical depiction of the distribution of accuracy data. Each rectangular box represents the interquartile range, and the horizontal line in the middle of each box identifies the median. The lines extending from each rectangular box are 1.5 x the interquartile range. Each dot represents an individual data point.

Table 1. Accuracy by Device and Condition *(°C)*

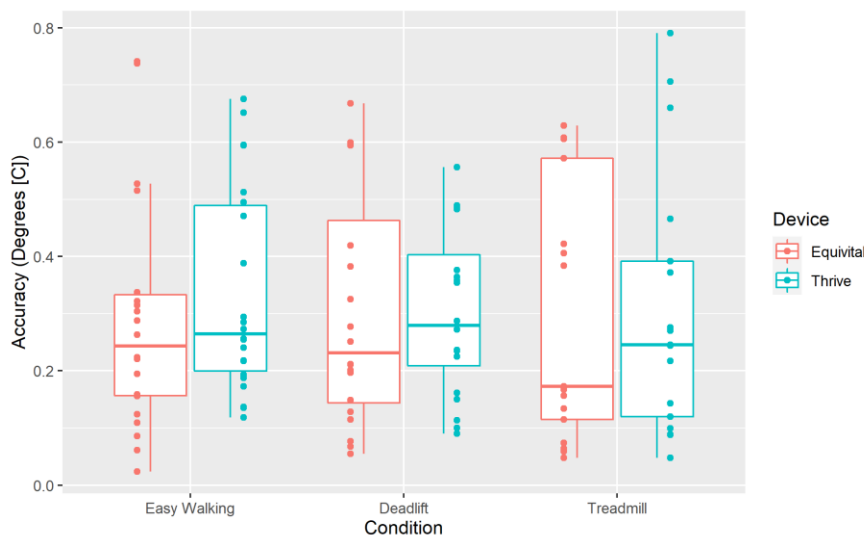| Device	Condition (M±SD)		
	Easy Walking	**Deadlift**	**Treadmill**
	(*n* = 22)	(*n* = 20)	(*n* = 17)
Equivital	0.30 ± 0.22	0.31 ± 0.20	0.31 ± 0.23
ThriveHRI	0.33 ± 0.18	0.30 ± 0.15	0.31 ± 0.23

M = mean; SD = standard deviation

Figure 2. Accuracy by Device and Condition

3.2. Bias

A significant difference in bias (closer to the measured core temperature) between devices was found for easy walking ($t(21)$ = 5.55, $p < 0.001$, g = 1.01), deadlift ($t(19)$ = 3.60, p = 0.002, g = 0.73), and treadmill ($t(16)$ = 2.42, p = 0.028, g = 0.60). Descriptive data in Table 2 indicates that the significant differences in bias between devices were due to the tendency of the Equivital system to overestimate Tc during easy walking, deadlift, and treadmill and the tendency of the ThriveHRI system to underestimate Tc during these conditions. The mean and standard deviation are in degrees Celsius.

Table 2. Bias by Device and Condition

Device	Condition		
	Easy Walking	**Deadlift**	**Treadmill**
	(*n* = 22)	(*n* = 20)	(*n* = 17)
Equivital	0.17 ± 0.33	0.17 ± 0.33	0.18 ± 0.33
Thrive	-0.17 ± 0.33	-0.08 ± 0.33	-0.05 ± 0.39

Figure 3 shows a graphical depiction of the distribution of bias data. Each rectangular box represents the interquartile range, and the horizontal line in the middle of each box identifies the median. The lines extending from each rectangular box are 1.5 x the interquartile range. Each dot represents an individual data point.
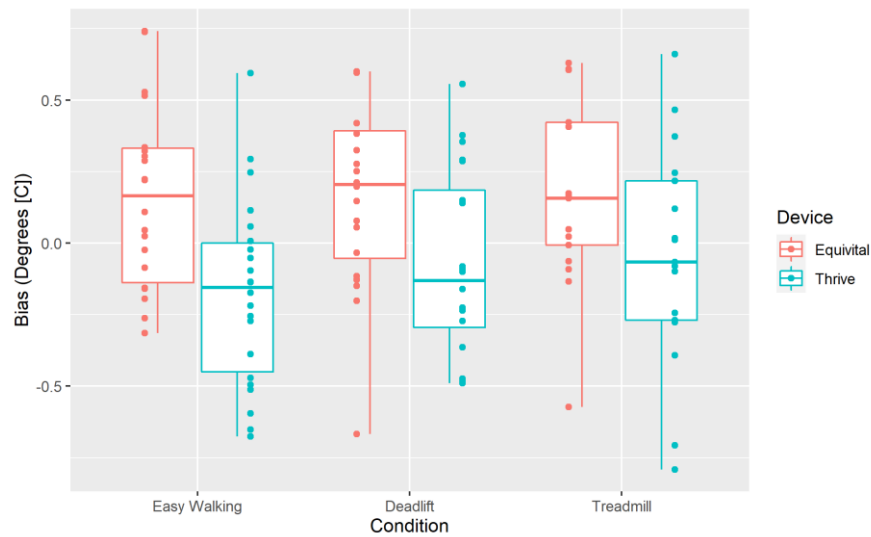
Figure 3. Bias by Device and Condition

3.3. Precision

A significant difference in precision between devices was found for easy walking ($t(21)$ = 4.23, p < 0.001, g = 1.21), but no significant difference in precision between devices was found for deadlift or treadmill (ps ≥ 0.067). Descriptive data in Table 3 indicates that the significant difference in precision between devices during easy walking was due to superior precision of the Equivital system during this condition. The mean and standard deviation are in degrees Celsius. Figure 4 shows a graphical depiction of the distribution of precision data. Each rectangular box represents the interquartile range, and the horizontal line in the middle of each box identifies the median. The lines extending from each rectangular box are 1.5 x the interquartile range. Each dot represents an individual data point.

Table 3. Precision by Device and Condition

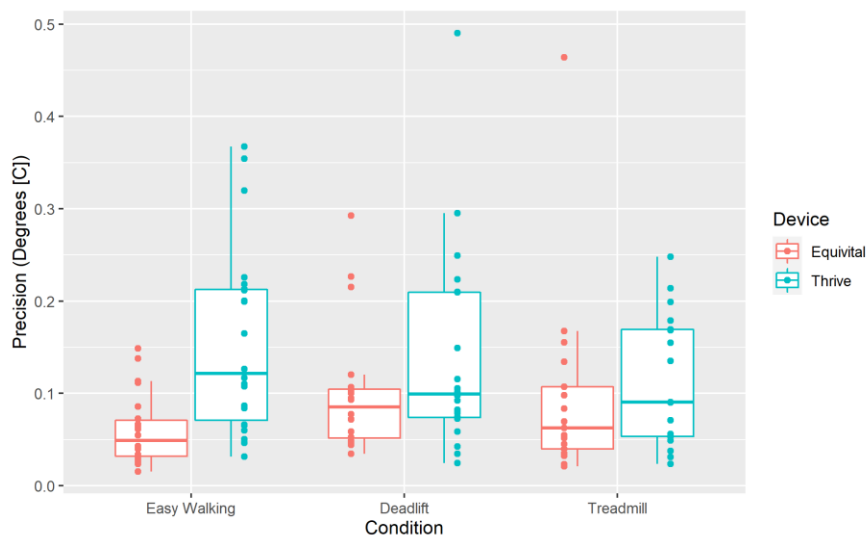|	Condition		
Device	**Easy Walking**	**Deadlift**	**Treadmill**
	(n = 22)	(n = 20)	(n = 17)
Equivital	0.06 ± 0.04	0.10 ± 0.07	0.10 ± 0.10
Thrive	0.16 ± 0.10	0.14 ± 0.11	0.12 ± 0.07

Figure 4. *Precision by Device and Condition.*

4. DISCUSSION

The goal of this study was to compare the ability of the ThriveHRI sensor system to accurately and precisely estimate core body temperature compared to measurement via a gold standard measuring tool, a rectal thermometer. Additionally, to compare the ThriveHRI estimate to the estimate provided by the commercially available Equivital EQ02+ LifeMonitor using the BlackGhost software package on the same individuals during the same testing sessions. We hypothesized that the ThriveHRI system would provide estimates within 0.1°C compared to rectal thermometer measurements and Equivital estimates at rest. The ThriveHRI system estimates would be less accurate than Equivital during activity. We believe that the ThriveHRI system would be less accurate than Equivital during physical activity due to heart-rate monitoring chest straps being more precise and reliable when compared to a wrist-worn device during high-intensity exercise (Gillinov et al., 2017; Muggeridge et al., 2021; Pasadyn et al., 2019), as heart-rate is an essential measurement used to calculate the heart-rate derived core temperature estimate.

Statistically, our data indicate no overall differences in accuracy between the estimates from the two devices. On average, the ThriveHRI and Equivital systems were accurate to within 0.4°C during all conditions. Differences were found between the two devices in bias for all conditions, and differences in precision between the two devices existed during easy walking.

Both devices were relatively precise (ranging from 0.06 to 0.19) across all conditions, with Equivital being more overall accurate. The ThriveHRI device had less bias overall (closer to the measured core temperature) and tended to underestimate the core temperature. Core body temperature must be held within very tight parameters to maintain proper physiological function. An average accuracy of 0.4°C would appear to be an excellent accuracy outcome. However, clinical changes of 0.4°C are substantial.

The ThriveHRI device estimates were closer to the measured core temperature (lower bias) under all conditions. However, it underestimated the core temperature. A low estimate is more likely to put the user at risk than a higher estimate. The Equivital device tended to overestimate the core temperature during all conditions, which is safer despite the greater difference.

In a previous study in our laboratory (Agostinelli et al., 2023), we compared the Equivital with BlackGhost software system to a rectal thermometer at 40.6°C (105ºF) with treadmill walking and deadlift as an exercise intervention. The study found the devices were different, but the mean difference was 0.1°C. This difference was consistent at varying temperatures and not clinically significant. The Equivital estimation was higher than the rectal measurement (thus safer). We conducted a smaller study (N=13) using a less intensive intervention (lower temperature and less intense exercise). A separate study assessed a version of the same watch sensor system as used in the current study (called 2B-Cool) in a cross-over study with 22 participants (Laxminarayan et al., 2023). They assessed the sensor system across three 7.5-hour trials and four environmental/clothing conditions. They found a mean bias of 0.16°C. Conditions were less extreme 36°C (96.8ºF) and 30% humidity; and 30°C (86) with 60% humidity. Additionally, the exercise protocol was more constant, moving between moderate to high-intensity exercise on the treadmill by gradually increasing and decreasing the speed and % grade of the treadmill.

The fourth condition, recovery, was omitted from the study due to inaccurate data collected by the ThriveHRI sensor. The ThriveHRI device uses environmental conditions inputted into the system when the watch is activated and then calibrates for 15 minutes to the specific environment. For the 15-minute calibration period, participants were instructed to sit in a designated chair inside the heat chamber until the calibration period elapsed and the exercise protocol began. During recovery, participants were removed from the environmental chamber and cooled in an air-conditioned lab. The watch was not re-activated nor recalibrated to the new environment, and the cooler conditions could not be entered into the ThriveHRI system. It is unknown if this resulted in a decrease in watch estimation performance. However, due to the environmental change and the watch not being recalibrated, this data was omitted so as not to skew the reader's perception.

Updated software packages now include the capability to update the conditions during data collection.

Future work should consider evaluating the core temperature estimation difference of 0.4°C to assess if it is consistent across activities, people, and temperatures and further assess the direction of the difference in a larger field study. This information will be important in providing actionable intel to the user. Future work should also consider developing a prediction capability feature within the dashboard that allows users to visualize approximately when an individual reaches a dangerous core temperature.

Tactical and non-tactical populations would benefit from an easy-to-wear, valid, affordable sensor system. Firefighters (both structural and wildland), military, law enforcement, emergency responders, construction workers and farm workers are at a greater risk of experiencing heat injury while completing their required duties (McEntire et al., 2013; Vrijkotte, Roelands, Meeusen, & Pattyn, 2016; Walker et al., 2015). Firefighters and law enforcement are especially prone to avoidable heat injury when working on hot tarmacs during traffic accidents and similar events (Raval et al., 2018). A revolutionary safety device would be a system that could predict a heat injury, giving the individual time to find a replacement for their position and initiate cooling prior to injury.

Limitations in this study include a homogeneous sample population, which potentially decreases the generalizability of the study as this does not represent the diversity of the United States military or firefighter population (Defense, 2020). Additionally, participants in this study did not wear any form of PPE during the exercise protocol. In the study conducted at the University of Connecticut (Laxminarayan et al., 2023), participants were instructed to wear either a t-shirt and shorts or their active combat uniform to simulate military training and combat scenarios. The addition of PPE during physical activity has been shown to increase the heat and physiological strain on the body due to its inability to dissipate an individual's body heat adequately coupled with the added weight of the gear (Barker et al., 2022; Grahn, Makam, & Craig Heller, 2018; Petruzzello, Gapin, Snook, & Smith, 2009; Xu, Gonzalez, Santee, Blanchard, & Hoyt, 2016).

5. CONCLUSIONS

This study indicates that the Equivital EQ02+ LifeMonitor and the ThriveHRI sensor performed well in estimating accuracy, precision and bias compared to the gold standard of rectal thermometer measurement. The ThriveHRI sensor has the potential to provide a reliable and less invasive measuring tool option for the continuous measurement of core temperature while performing physical activity. This study demonstrates the agreeability between the Equivital EQ02+ LifeMonitor, ThriveHRI sensor, and the rectal thermometer remains consistent as core temperature increases and exposure to a heated environment is sustained.

Authors' contributions: F.N and N.B. carried out the experiment. F.N. wrote the manuscript with support from N.B., M.M., P.A., and J.S., F.N. and J.S. helped supervise the project. F.N. and J.S. conceived the original idea. M.M. and P.A. analyzed and interpreted the results for the manuscript. All authors provided critical feedback and helped shape the research, analysis and manuscript

Institutional Review Board Statement: The Institutional Review Board of Auburn University protocol # 12-149 MR 2205 approved the study.

Informed Consent Statement: All participants in this study provided informed consent prior to their inclusion. They were given detailed information about the purpose of the research, the procedures involved, any potential risks or benefits, and their rights as participants. Participants were assured that their participation was voluntary and that they could withdraw from the study at any time without penalty. Confidentiality and anonymity were maintained throughout the research process, and data were handled in accordance with ethical standards.

Conflict of interest: The authors declare that they have no conflicts of interest. No financial, personal, or professional relationships have influenced the work reported in this article.

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