Reliability of intestinal temperature using an ingestible telemetry pill system during exercise in a hot environment

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Abstract

Ingestible telemetry pill systems are being increasingly used to assess intestinal temperature during exercise in hot environments. The purpose of this investigation was to assess the inter-day reliability of intestinal temperature during an exercise-heat challenge. Intestinal temperature was recorded as twelve physically active males (25 ± 4 yrs, stature 181.7 ± 7.0 cm, body mass 81.1 ± 10.6 kg) performed two 60-min bouts of recumbent cycling (50% of maximum aerobic power (W)) in an environmental chamber set at 35 °C 50% relative humidity 3-10 days apart. A range of statistics were used to calculate reliability including a paired t-test, 95% limits of agreement (LOA), coefficient of variation (CV), Standard error of measurement (SEM), Pearson's correlation coefficient (*r)*, intraclass correlation coefficient (ICC) and Cohen's *d*. Statistical significance was set at $P \leq 0.05$. The method indicated good overall reliability (LOA = ± 0.61 °C, CV = 0.58%, SEM = 0.12 °C, Cohen's *d* = 0.12, *r* = 0.84, ICC = 0.84). Analysis revealed a statistically significant ($P = 0.02$) mean systematic bias of -0.07 ± 0.31 °C and investigation of the Bland-Altman plot suggested the presence of heteroscedasticity. Further analysis revealed the minimum ‘likely' change in intestinal temperature to be 0.34 °C. Although the method demonstrates good reliability, researchers should be aware of heteroscedasticity. Changes in intestinal temperature greater than 0.34 °C as a result of exercise or an intervention in a hot environment are likely changes and less influenced by error associated with the method.

Key words: Core temperature, heat stress, telemetry pill, gastrointestinal tract, reproducibility

INTRODUCTION

Exercise in a hot environment challenges the function of cardiovascular (17), metabolic (14) and thermoregulatory systems (24); thus exposure to prolonged, intense exercise that raises body temperature increases the risk of heat illness (1) and impairs athletic performance. Subsequently, strategies have been designed to help athletes perform in hot environments, all of which are designed to regulate body temperature. A heat tolerance test is useful for assessing the ability to regulate body temperature and measurements of body temperature responses are integral to interpretation. Where improved heat tolerance is required, decisions regarding the most appropriate method and their specific derivatives are determined; these are usually grouped into 1) heat acclimation or acclimatization protocols and 2) cooling methods. The most appropriate method is context specific but the choice is driven by whether body temperature responses to a strategy are sufficient to improve safety and performance. Consequently it is important that practitioners use valid and reliable methods to monitor body temperature (6) to make well-informed and clear decisions about the success of the chosen method. Esophageal and rectal sites are most commonly used for assessing core body temperature (6, 30); however, ingestible telemetry pill systems that measure intestinal temperature are being increasingly used to overcome the impracticalities associated with traditional methods (5). Several studies provide evidence to suggest that telemetry pill systems are valid tools for assessment of core temperature (13, 15, 16, 25, 26); however, there are little data regarding the reliability of intestinal temperature measurement during exercise in a hot environment.

Ingestible telemetry pills are often used when environmental temperature is high (≥25 °C) to monitor core body temperature or detect treatment effects following the application of an

intervention (e.g. cooling). For example, the reported magnitude of intestinal temperature change following a treatment in a hot environment ranges from 0.30 to 1.8 °C (27, 35). As such, ingestible telemetry pill systems must demonstrate small test re-test error for practitioners to be confident that these changes are true and unlikely due to measurement error. Incorrect interpretation of intestinal temperature due to measurement error or failing to understand the limits of the system could place athletes at an increased risk of heat illness and impair athletic performance. To improve confidence when interpreting a change in a dependent variable it is important to identify the magnitude of measurement error within repeated measurements. Performing such an assessment assists in interpreting whether a change has occurred due to a treatment or because of inherent measurement error (biological or technical) and is also important for calculating sample size (3, 11, 20, 21 29).

To date only two studies have published data regarding the inter-day test re-test reliability of intestinal pill telemetry systems. Goosey-Tolfrey et al. (18) conducted a small reliability study (n = 5) using ingestible telemetry pills (CorTemp, HQinc, USA) in wheelchair athletes exercising at submaximal intensities (50% peak power output (W_{peak}) for 60-min in a hot environment (30.8 °C, 60.1% relative humidity (RH)). The authors reported a mean test-retest error of 0.30 °C (95% CI 0.20 - 0.40) and limits of agreement (LOA 95%) of ± 1.2 °C. In a cooler environment (15.0 °C, 60% RH), Gant et al. (16) investigated the reliability of telemetry pills (CorTemp, HQinc, USA) during intermittent shuttle running and reported excellent reliability with a near absent test-retest error of 0.01 °C (CI -0.02 – 0.05 °C) and LOA 95% of ± 0.23 °C.

Given that ingestible telemetry pill systems are increasingly being used to monitor core body temperature responses and that important health, treatment-effect and performance decisions

are made upon these assessments, it is important to establish the test-re-test reliability of this method. The purpose of this study is to investigate the inter-day reliability of intestinal core temperature using an ingestible telemetry pill system during exercise within a hot environment.

METHODS

Experimental Approach to the Problem

Subjects were asked to visit the exercise physiology laboratory on three separate occasions. Each visit was separated by a minimum of 3 days and maximum of 10 days. During visit 1, subjects performed an incremental exercise test to maximal volitional exertion for assessment of peak oxygen uptake ($\dot{V}O_{2peak}$) and associated power output (W_{peak}) at room temperature; (20 °C, 40% RH) followed by a 30-min exercise heat stress accustomisation trial within an environmental chamber (35 ˚C dry bulb temperature, 50% RH). During visits 2 and 3, subjects rested for 60 min in a temperature controlled environmental chamber set at 35 °C, 50% RH before cycling at a power output equivalent to 50% W_{peak} for 60 min. The combination of environmental conditions and intensity of exercise was chosen to induce moderate to high heat strain within ethically acceptable limit of (39.5 ˚C intestinal temperature). All exercise trials were performed at the same time of day and at least 3 hours after waking and 3 hours before sleep to minimise the circadian rhythm impact on body temperature and gastrointestinal function (28). All exercise trials were conducted using an externally-verified, electromagnetically-braked arm crank ergometer (Lode Angio, Groningen, The Netherlands) positioned for recumbent cycling.

Subjects

Twelve non-heat-acclimated physically active males (age 25 ± 4 yrs, stature 181.7 ± 7.0 cm, body mass 81.1 ± 10.6 kg) volunteered for the study which was approved by the Ethics Committee of Sheffield Hallam University and conducted according to the principles of the Declaration of Helsinki. The risks and experimental procedures were fully explained and all subjects provided written informed consent before the study. Subjects were instructed to refrain from strenuous exercise, caffeine and alcohol 24 h before each trial and food 3 h before each trial. Each subject recorded their diet 24 h prior to the first heat stress trial and replicated their diet for the re-test. Adherence to the standardised diet was verified by the investigator prior to each trial. All experimental trials were conducted between the months of October and January in the UK, where mean maximum ambient temperatures ranged from 14 - 7 °C).

Procedures: $\dot{V}O_{2peak}$ test and accustomisation trial

Subjects undertook a 10-min warm-up period prior to physiological testing. Peak oxygen uptake ($\dot{V}O_{2peak}$) and associated power output (W_{peak}) were assessed using a continuous incremental exercise test to maximal volitional exertion. The initial intensity of exercise was set at 50 W and was increased by 25 $W \cdot min^{-1}$ in a stepped manner. Pedalling frequency was self-selected in the range of 60 – 80 $rev \cdot min^{-1}$, and subjects were encouraged to continue to maximal volitional exertion. Breath-by-breath pulmonary oxygen uptake was measured continuously using a calibrated low dead space (20 ml) bi-directional differential pressure pneumotach and rapid response galvanic O_2 and non-dispersive infrared CO_2 analysers

(Ultima, CardiO_2, Medgraphics, USA). Peak oxygen uptake was calculated as the highest 30 s average value recorded before termination of the test. The power output at the last completed stage was used to determine W_{peak}. Heart rate was recorded continuously during exercise using short range telemetry (RS400, Polar OY, Finland).

After 60 min of rest in a temperate environment, subjects undertook 30 min of recumbent cycling within the environmental chamber (35 °C, 50% RH) at an intensity of 50% W_{peak} to accustomise with the experimental procedures. Nude body mass (kg) was recorded before and after the accustomisation trial along with volume of water ingested *ad libitum* during the trial. Sweat rate ($ml \cdot min^{-1}$) was estimated from the change in body mass adjusted for fluid intake and urine output. Fluid requirements (which matched sweat rate) were calculated for each subject and were closely adhered to in the main experimental trials. During the exercise session heart rate, rating of perceived exertion (RPE) and thermal perception (TP) (3) were assessed every 5 min.

Heat stress trials 1 and 2

These sessions were used to assess the reliability of intestinal temperature measurements. Subjects were instructed to replicate their diet 24 hours prior to each trial and consume 500 ml of non-caffeinated fluid in the preceding 2 hours to promote euhydration (2). On arrival subject's nude body mass (kg) and urine osmolality ($mOsmol \cdot kg^{-1}$ H_2O) (Advanced Model 3320 Micro-Osmometer, Advanced Instruments, Inc., USA) were assessed. A urine osmolality of $\leq$700 $mOsmol \cdot kg^{-1}$ H_2O was used to verify pre and post-trial euhydration status (8). Subjects drank 100 ml of cold water (4 °C) to verify the positioning of

the telemetry pill in the gastrointestinal tract. We observed changes in pill temperature greater than 0.1 °C for two subjects; in these instances tests were rescheduled. For all trials there was no change in pill temperature greater than 0.03 °C following cold water ingestion. After these initial measures, subjects rested for 60 min in the environmental chamber which was set at 35 °C, 50% RH to stabilise intestinal and skin temperature before commencing exercise. At rest and during exercise, subjects were encouraged to drink room temperature water (35 °C) to meet their individual fluid requirements. Measures of heart rate (HR), skin temperature (T_{sk}), intestinal temperature (T_{int}), RPE and thermal perception were recorded immediately prior to exercise (0 min) and at 5-min intervals throughout the exercise trial. The exercise test was terminated when one of the following criteria was met: 1) subjects voluntarily stopped exercising, 2) when intestinal core temperature reached 39.5 °C or 3) subjects completed 60 min of exercise.

Intestinal temperature

Intestinal temperature was assessed using a telemetric monitoring system consisting of an ingestible temperature sensor and a data logger (CorTemp, HQinc, USA). Prior to ingestion the temperature measurement of each pill was verified by immersion in a water bath at 4 temperatures (37, 38, 39 and 40 °C) according to recommended guidelines (22). Water temperature was verified using a calibrated thermometer. A linear regression relationship between measured (pill temperature) and actual (water bath) temperatures was derived and the resulting regression equation used to convert measured temperature during exercise to actual temperature. The coefficient of determination of this relationship was $r^2 = 0.99$ and the two methods demonstrated excellent agreement LOA 95% (-0.01 ± 0.09 °C). Subjects ingested temperature sensors at the same time of day, 6 h prior to each visit (5). This

ingestion time has been reported to be sufficient to allow the telemetry pill to pass into the gastrointestinal tract and produce valid intestinal temperature measurements (13).

Skin temperature

Four skin thermistors (Grant Instruments, Cambridge, UK) were attached to the left side of the body at the medial calf, anterior mid-thigh, anterior mid-forearm and chest using acrylic dressing (Tegaderm, 3M Healthcare, USA) and secured in place using hypoallergenic surgical tape (Transpore, 3M Healthcare, USA). Weighted mean skin temperature (T_{sk}) was calculated using the equation of Ramanathan (34). Mean body temperature (T_{body}) was calculated as $T_{body} = 0.66(T_{int}) + 0.34(T_{sk})$ at rest and $T_{body} = 0.79(T_{int}) + 0.21(T_{sk})$ during exercise (10).

Statistical analysis

Reliability of gastrointestinal temperature, which in this study refers to the reproducibility of day-to-day measurements at identical time-points during exercise, was assessed through a number of statistical analyses following the guidelines of Atkinson and Nevill (3). Bland-Altman plots (4) were generated to investigate systematic and random error trends. The presence or absence of heteroscedasticity was formally investigated by plotting a regression line through the data points of the Bland-Altman plots. A paired *t*-test was used to assess systematic bias between trials, with statistical significance set at $P \leq 0.05$. Coefficient of variation (CV), standard error of measurement and 95% limits of agreement (LOA) were utilised to assess absolute reliability. Relative reliability was assessed using Pearson's correlation coefficients and Intraclass correlation coefficients (ICC). Cohen's *d* was used as a

measure of effect size (ES) and data were evaluated according to small (0.2), medium (0.5) and large (0.8) effects (10). A paired *t*-test was used to assess between trial differences in environmental conditions, urine osmolality, skin temperature, sweat rate, fluid intake and heart rate. Statistical significance was set at $P \leq 0.05$. Gaussian distribution of data was assessed using Kolmogorov-Smirnov test and was accepted when $P \geq 0.05$.

We acknowledge that practitioners prefer to use different approaches when assessing reliability and that the acceptable levels of error may differ between researchers. Therefore we have presented a range of reliability statistics and avoided using stringent and pre-defined acceptable levels of error. To provide real-world practical context to reliability data we present hypothetical changes in intestinal temperature (when used in a comparison study is an approach used to determine the effectiveness of a treatment) and used the approach of Hopkins (21) to interpret magnitudes of change. This analysis determined the chance (probability) that a change was harmful, trivial or beneficial in context to the error (reliability) of the test and smallest worthwhile change. It also enabled identification of the minimum change in intestinal temperature that is deemed to be a likely-beneficial change (76% probability), which in the example was a decrease in intestinal temperature.

RESULTS

INSERT TABLE 1 here

Subjects' mean $\dot{V}O_{2peak}$ elicited during the incremental exercise test was 36.5 ± 5.2 ml·kg^{-1}·min^{-1} corresponding to a mean peak power of 293 ± 36 W. The mean duration of heat stress trials was 55.4 ± 9.4 min completed at 147 ± 18 W. There were no statistically significant differences for environmental temperature (P = 0.38) and relative

humidity (P = 0.74) between trial 1 (35.0 ± 0.2 °C, 49 ± 3% RH) and trial 2 (35.1 ± 0.4 °C, 49 ± 5% RH). Urine osmolality at the start of trial 1 (317 ± 179 mOsmol·kg^{-1}H_2O) was not significantly different (P = 0.95) from the start of trial 2 (313 ± 194 mOsmol·kg^{-1}H_2O). Intestinal temperature at the start of trial 1 was similar to the start of trial 2 (37.26 ± 0.23 °C vs. 37.26 ± 0.25 °C; P = 0.99). However, skin temperature was marginally lower at the start of trial 1 (35.43 ± 0.35 °C vs. 35.70 ± 0.37 °C, P = 0.01). Sweat rate did not differ markedly between trials 1 and 2 (29 ± 5 ml·min^{-1} vs. 28 ± 5 ml·min^{-1}; P = 0.63). *Ad libitum* fluid intake helped restrict body mass deficits in trial 1 to 0.82 ± 0.58% and trial 2 to 0.84 ± 0.52%, which were not significantly different (P = 0.87). Heart rate and skin and body temperatures progressively increased throughout the heat trials reaching peak values at the end of exercise as evidenced in table 1. There was no statistically significant difference in mean heart rate between trial 1 and trial 2 (P = 0.97).

Mean intestinal temperature after 60 min of exercise (table 2) indicates that the intensity and duration of exercise was sufficient to induce moderate-to-high levels of heat stress in both trials. The mean intestinal temperature bias between trial 1 and 2 was -0.07 ± 0.31 °C indicating a small but statistically significant systematic bias (P = 0.02). Visual inspection of figure 1 illustrates that intestinal temperature in trial 2 was consistently higher than trial 1 from 10 min onwards until termination of exercise.

INSERT FIGURE 1 HERE

INSERT FIGURE 2 HERE

Limits of agreement for intestinal temperature are presented in figure 2. The scattering of data points indicated a degree of both systematic and random error proportional to the measurement range of intestinal temperature. Although the slope of the relationship was close

to zero (-0.16) a statistically significant ($P < 0.01$) small correlation coefficient ($r = 0.26$) confirmed the presence of heteroscedasticity.

Reliability data for the entire trial and each 10-min segment of the trial can be found in table 3. Using data from the entire set indicates good overall reliability for all statistical methods. However, when data was grouped by time (table 3) small changes in error were evident over the exercise duration. The error displays a trend that increases from the onset of exercise, before peaking mid-exercise and decreasing towards the end of exercise.

INSERT TABLE 3 HERE

As the Bland-Altman plot suggested the presence of heteroscedasticity, the coefficient of variation (which assumes the largest test-retest error occur at higher values) was used to determine probabilities of a change in intestinal temperature in relation to the smallest worthwhile change using the approach of Hopkins (21) (Table 4). This analysis suggests that a change in intestinal temperature as a result of a treatment or intervention (e.g. cooling) of 0.34 °C is required to be interpreted as a likely beneficial change (≥76% chance).

INSERT TABLE 4 HERE

Discussion

The main finding of this study is that the measurement of intestinal temperature using intestinal telemetry pills demonstrated good test-retest reliability during submaximal recumbent cycling exercise in the heat. In accordance with recommendations suggested by Atkinson and Nevill (3), we used a range of reliability statistics to assess intestinal temperature. Inspection of Bland-Altman plots identified a small degree of systematic and random error proportional to the measured range of intestinal temperature and suggested the

presence of heteroscedasticity. Assessment of intestinal temperature is often used to determine the success of an intervention (e.g. prevent increases in 'core' temperature). To provide practical context to the reliability data and investigate whether hypothetical changes in intestinal temperature were likely greater than a smallest worthwhile change we utilised the approach of Hopkins (21). We identified that the smallest magnitude of change in intestinal temperature required to detect a likely beneficial change (76% chance) to be 0.34 °C. Changes less than 0.34 °C decrease confidence in interpretation and augment the uncertainty of the true effect of an intervention. This information might be useful for scientists interpreting changes in intestinal temperature due to an intervention and should be considered when decisions regarding body temperature need to be made from health, treatment-effect and performance perspectives. For example, a decrease in intestinal temperature of 0.25 °C as a result of an intervention has a 67% chance that it is a beneficial change, 19% chance trivial and 14% chance harmful (table 4). When the decrease in intestinal temperature is 0.5 °C there is an 88%, likely probable chance that this is a beneficial change and a 4%, very unlikely chance it is a harmful change. In this example, a decrease in core temperature may not always be a true decrease when considering the magnitude of change in context to the error of the system and smallest worthwhile change. It should be noted that to improve confidence in interpretation a smaller error (better reliability) would be required.

We observed a systematic error of -0.07 °C and LOA (95%) ± 0.61 °C which is lower than the mean bias of 0.30 °C and LOA (95%) of ± 1.2 °C reported by Goosey-Tolfrey et al. (18) despite a similar intensity of exercise, duration and environmental conditions in both studies. The differences may be explained by a smaller sample size (n = 5) and a large variation in intestinal temperature of one subject in the Goosey-Tolfrey et al. (18) investigation. The

mean bias in the present study is greater than that reported by Gant et al. (16) who observed a near absent test-retest systematic error of 0.01 °C and LOA of ± 0.23 °C during intermittent running in a cool environment. Furthermore, the values reported for correlation coefficients, ICC and CV indicate better reliability in the study by Gant et al. (16). This observation of larger systematic and random errors in intestinal temperature during exercise in hot environments is in agreement with data from Jetté et al. (23) who studied the reliability of rectal temperature during exercise in two different conditions in males wearing chemical protective clothing. At 20 °C, no statistically significant difference in mean rectal temperature change between trials was observed (-0.01 °C). However, at 40 °C the authors reported a statistically significant mean difference of -0.05 °C which is similar to the mean bias observed within the current investigation.

A potential explanation for the increased variation in intestinal temperature might be gastrointestinal (GI) function. The GI tract is a complex organ and the many potential interactions within it could serve to increase the variability observed in GI pill temperature in heat stressed humans. The recommended pill ingestion time of 6 hours prior to intestinal temperature measurement reflects a balance between sensor gastric emptying and expulsion time (5). We observed no changes in pill temperature greater than 0.03 °C when subjects ingested 100 ml of cold water 1 hour prior to exercise, confirming that the pill ingestion time of 6 hours provided sufficient time for gastric emptying. However, 2 tests out of 24 were rescheduled due to a change in observed pill temperature of greater than 0.1 °C. Wilkinson et al. (37) demonstrated that drinking cold water (5 – 8 °C) influenced pill temperature by up to 2 °C 8 hours after pill ingestion. The authors suggested that this temperature variation may be due to the pill residing in areas of the GI tract in close proximity to the stomach (e.g. duodenum and transverse colon). To reduce the potential for pill temperature fluctuations in

the present study, subjects ingested room temperature water (35 °C) at frequent intervals throughout the trial and as a result we observed no large variations in intestinal temperature.

In a further attempt to standardise GI function the subjects refrained from food three hours prior to each test and their diet was replicated in the preceding 24 hours. However, exercise speeds intestinal peristaltic velocity (36) and it is conceivable that peristaltic velocity might have been different between trials. Subsequently, this variation could have changed the position of the pill within the GI tract. Indeed, we observed an increase in temperature variability mid-exercise. As eluded to by Gant et al. (16), this mid-exercise variability may have been caused by peristalsis advancing the pill along the GI tract before reaching more compact faecal matter towards the end of exercise, thereby reducing temperature variability.

Several human studies provide indirect evidence to support the notion of a temperature gradient along the GI tract as GI pill temperature is consistently higher than rectal temperature (5). Further evidence is available from animal studies which demonstrate a temperature gradient along with GI tract as duodenum and ilium temperatures were significantly higher than stomach, large intestine and rectum (19). As a result one possible explanation for the observed variation in intestinal temperature is that variability in intestinal peristaltic velocity advances the pill to areas of the GI tract which may exhibit different temperatures. This interpretation suggests that although a pill ingestion time of 6 hours prior to exercise is sufficient for gastric emptying, perhaps a longer period is required to limit the effects of peristaltic velocity.

Several studies have presented data indicating that each pill has a bias from certified thermometry; as such it is recommended that each pill is individually calibrated. Following the recommendations by Hunt and Stewart (22), we noted excellent agreement (-0.01 ± 0.09 °C) between a verified electronic thermometer and intestinal pills. This agreement was similar to that reported within previous studies (7, 22, 37) and within the guidelines set by Moran and Mendel (30) who suggest random errors between thermometers should not be greater than ± 0.1 °C. To reduce potential systematic and random bias we applied a linear regression equation to each pill determined following verification. Therefore it is unlikely that the variation in intestinal temperature during exercise was due to invalid temperature measurement by the pills. Furthermore, the variation in intestinal temperature was not likely caused by a difference in total work between the two trials as there was no statistically significant difference between trials for mean HR ($P = 0.97$).

Our findings are only applicable to pill ingestion times of 6 hours. It is likely that different ingestion times will change pill location in the GI tract and influence reliability of the method. Although skin temperature, thermal perception and RPE were high, mean end-exercise intestinal temperature was ≈38.60 ± 0.4 °C, which is around 1 – 1.5 °C lower than reported voluntary exercise termination core temperature. As such our results should be applied with caution to temperatures exceeding 39 °C; however, during self-paced exercise, which is common in most sports, intestinal temperature may be regulated around 39 °C (31). We also applied pill-specific regression equations to account for bias, and as such our findings might only be applicable after corrections have been employed. We recommend following the verification guidelines of Hunt and Stewart (22) prior to dispensing telemetry pills for ingestion as conducted in the present study. Recumbent cycling was chosen as the mode of exercise as laser-Doppler flowmetry, which requires a stable upper body, was used to assess

forearm skin blood flow (data not presented). Generalisations to other modes of exercise should be applied with caution; however, it is likely that our results are applicable to other modes of exercise that produce similar energetic and thermoregulatory demands.

Practical Applications

We have assessed the reliability of intestinal temperature sensors using a range of statistical approaches and practitioners are encouraged to interpret these results using their preferred method. Using hypothetical data we have demonstrated that practitioners can be confident that observed changes in intestinal temperature greater than 0.34 °C as a result of an intervention in hot environment are likely beneficial and less influenced by error associated with the method. This interpretation is important from a safety perspective for monitoring athletes within hot environments, when determining the effect of a treatment on intestinal temperature responses, and when making performance-based decisions. For example, understanding the reliability of a method and obtaining reliable temperature measurements are important for prescription of appropriate training intensities in hot environments, especially at high intensities where body temperature can rise to induce considerable strain on cardiovascular, metabolic and thermoregulatory systems and place athletes at risk of heat illness. Heat tolerance tests are often used to determine whether athletes can regulate body temperature in hot environments or require acclimation/acclimatisation prior to competition. Reliable body temperature measurements are needed to ensure that athletes who are heat intolerant are not considered tolerant and vice versa as incorrect decisions because of measurement error can place athletes at risk of heat illness and waste vital training and adaptation time as well as financial resources. In instances where athletes require acclimation, intestinal temperature is often used to determine the effectiveness of the intervention. It is important that practitioners can be confident that changes in body temperature are the result of an adaptation to heat and not due to measurement error. Similarly where cooling methods

are required to lower core temperature prior to, during or after exercise, scientists require reliable measurements of core temperature to elucidate the most appropriate method and monitor the health of athletes. We have demonstrated that intestinal temperature measurement assessed using an ingestible telemetry pill system is capable of providing scientists with reliable temperature measurements so that health, treatment-effect and performance decisions can be made with confidence when accounting for the error within the method.

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Figure titles

Figure 1: Mean intestinal temperature (°C) during exercise. Error bars represent *SD*.

Figure 2: Bland-Altman plot exhibiting variations in intestinal temperature (°C) measurement recorded every 5-min during exercise (n = 145). Solid line represents mean intestinal temperature bias. Dashed lines represent the 95% limits of agreement (random errors).

Figure 1 legend