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# The effect of passive heat maintenance on elite swimming performance

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# Summary

## The effect of passive heat maintenance on elite swimming performance

The pre-event warm-up (WU) is a well-established pre-competition routine, acting as a means to prime the body for subsequent performance. Previous literature has demonstrated the beneficial effect it can have, highlighted by a recent meta-analysis reporting that 79% of studies established an improvement in performance following the completion of a WU (Fradkin et al., 2010). The benefits of an active WU have previously been attributed to an elevation in muscle ($T_{muscle}$) and/or core temperature ($T_{core}$) and the associated temperature related mechanisms. However, current regulations within international swimming competitions require athletes to enter a marshalled call room 20 minutes prior to racing, thus creating a time delay between WU and subsequent performance. Consequently, temperature related performance gains, achieved from the active WU, may be lost. This was highlighted in a study by Mohr et al. (2004), in which a decrement in $T_{core}$ of ~1.1°C and a decrease in $T_{muscle}$ of ~2.0°C were observed over a 15 minute rest period. Additionally, the decrease in $T_{muscle}$ was strongly correlated to a 2.4±0.3% reduction in sprint performance. Therefore, the current study was conducted to examine the use of a custom developed heat jacket (incorporating Reflexcell technology) as a device for passively maintaining $T_{core}$ when swimmers are in a marshalled call room. Twelve male and female elite swimmers (age 20.83±2.21 years; mass 72.86±9.43kg; height 180.41±7.65cm) participated in this research. Participants were assessed on time trial (TT) performance (stroke and distance specific) 20 minutes after completing an active WU. During the 20 minute rest period, participants were exposed to either; (1) a control condition or (2) a passive heat maintenance condition. Heart rate, $T_{core}$, blood lactate and RPE were measured at five time points; pre WU (baseline), post WU, pre TT, post TT and 3 minutes post TT. The TT performance was significantly improved following the passive heat maintenance condition (Control 126.7±21.3 seconds; Passive heat maintenance 125.6±20.8 seconds; p=0.013), which equated to a 0.8±0.1% improvement in performance. Heart rate, blood lactate and RPE showed a comparable response in both conditions across the time course (P>0.05), similarly $T_{core}$ was not significantly different between conditions when measured at pre TT (Control 37.67±0.37°C; Passive heat maintenance 37.85±0.29°C; p=0.297). Therefore, despite an improvement in swimming TT performance, it appears unlikely that $T_{core}$ was the primary underlying mechanism responsible for this improvement. Although speculative, if heat generated in the muscle is restricted by the conditions of the environment and/or implemented strategies, limited heat dissipation to the environment will occur. As a result, $T_{muscle}$ will remain elevated whilst $T_{core}$ returns to near baseline values, thus $T_{muscle}$ would positively impact on performance. Additionally the placebo effect may provide an alternative explanation for the improvement in swimming performance observed in the current study.

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# List of Abbreviations

1 maximum repetition – 1RM

Carbon dioxide – $CO_2$

Coefficient of variation – CV

Core temperature - $T_{core}$

Countermovement jump – CMJ

Easy warm-up – EWU

Gastrointestinal temperature - $T_{GI}$

Hard warm-up – HWU

Heart rate – HR

Individual medley – IM

Intensive training centre – ITC

Lactate inflection – LI

Lactate threshold – LT

Limits of Agreement – LOA

Maximal oxygen consumption –$VO_2max$

Maximal power – Pmax

Muscle fibre conduction velocity – MFCV

Muscle temperature - $T_{muscle}$

No warm-up – NWU

Oesophageal temperature - $T_{oes}$

Oxygen – $O_2$

Oxygen consumption – $VO_2$

Phosphocreatine – PCr

Rate of perceived exertion - RPE

Rectal temperature - $T_{rectal}$

Reference warm-up – RWU

Skin temperature - $T_{skin}$

Stroke rate – SR

Time trial – TT

Warm-up – WU

# Chapter 1 – Introduction

The pre-event, active warm-up (WU) is a well-established pre-competition routine utilised by athletes primarily to improve sporting performance. Previous literature has documented the beneficial effect it can have, highlighted by a recent meta-analysis reporting 79% of the examined studies demonstrated an improvement in performance following an active WU (Fradkin, Zazryn & Smoliga, 2010). Many of the suggested benefits have been attributed to increases in muscle temperature ($T_{muscle}$) and/or core temperature ($T_{core}$), with a number of mechanisms having been proposed to improve performance (e.g. Stewart, Macaluso & DeVito, 2003; Mohr et al., 2004). For example, a principal effect relating the improvement in performance to increases in temperature involves a decrease in the viscous resistance of muscles (Bishop, 2003a) resulting in the enhancement of mechanical efficiency (Koga et al., 1997). This can accordingly lead to an increase in speed and force of muscle contraction (Woods, Bishop & Jones, 2007). In addition, temperature elevation may accelerate oxygen consumption ($VO_2$) kinetics and improve aerobic energy production by improving the rate-limiting reactions associated with oxidative phosphorylation (Koga et al., 1997).

However, previous research has identified conflicting results when examining the influence of a WU on subsequent performance. For instance, Mandengue et al. (2005) illustrated an improvement in cycle time to exhaustion, increasing from 324.9±69.3 seconds in the control (no WU) to 440.2±121.5 seconds in the reference WU (RWU) condition. The improvement in performance was attributed to a 0.67±0.18°C increase in $T_{core}$. Conversely, Gray & Nimmo (2001) were unable to identify a significant improvement in a comparable performance test (cycle time to exhaustion) when preceded by an active WU in contrast to a control condition, this was attributed to a modest increase in $T_{core}$ of 0.2±0.1°C.

The disparity in the literature may, in part, be explained by the inability of the WU procedures to reach a threshold temperature to elicit a consequential increase in performance, as indicated by the lower temperature change in Gray & Nimmo's (2001) study. The meta-analysis completed by Fradkin et al. (2010) provides further support of this observation, highlighting that 20% of the studies reviewed stated no effect of WU and in many instances a decrease in performance was noted. The authors reported that many of the WU protocols utilised were insufficient in duration and/or intensity to increase $T_{muscle}$ or contained prolonged recovery periods resulting in dissipation of heat to the environment and a subsequent reduction in $T_{muscle}$ and/or $T_{core}$ (Fradkin et al., 2010). For example, a 45 minute recovery period following a WU has been associated with a 0.7±0.2°C decrease in $T_{core}$ (West et al., In Press).

The aforementioned work outlines a limitation of current WU protocols; a recovery period in a thermoneutral environment may influence $T_{muscle}$ and subsequent performance with a significant reduction in temperature likely following ~15-20 minutes of the cessation of exercise (Saltin, Gagge & Stolwijk, 1968). For example, within football, a decrease in $T_{muscle}$ and/or $T_{core}$ could occur during the 15 minute half time break as investigated by Krustrup, Mohr & Bangsbo (2002). It was observed that $T_{muscle}$ increased from 36.5°C (35.7 – 37.3°C) to 38.4°C (37.7 – 39.2°C) during the WU, however, the presence of a half time break resulted in $T_{muscle}$ decreasing markedly to 37.9°C (37.6 – 38.1°C) and 37.5°C (36.4 – 38.0°C) after 10 and 15 minutes respectively (Krustrup et al, 2002). Therefore, $T_{muscle}$ was 0.9±0.2°C lower before the second half than at the commencement of the first half, potentially explaining the 33% decrease in high intensity running in the initial 5 minutes of the second half.

Similarly, Mohr et al. (2004) investigated the effect of $T_{muscle}$ on sprint performance in sixteen soccer players. Within the control condition, $T_{muscle}$ was 39.7±0.2°C at the conclusion of the first half, decreasing 37.7±0.2°C; this was correlated (r=0.60) to a reduction of 2.4±0.3% in sprint performance. However, with the inclusion of an half time WU (running and exercises at 135beats$\cdot$min$^{-1}$), $T_{muscle}$ was re-established prior to the start of the second half (39.2±0.2°C versus 39.7±0.2°C at the end of the first half). This prevented a decrease in performance, as observed in the control condition. The above findings are supported by recent work from Lovell et al. (2011); the authors observed a 1.5±0.4°C decrease in $T_{muscle}$ during the half time break in soccer, this was associated with a 6.2% decrement in sprinting performance. The relationship between $T_{muscle}$ and performance has previously been established by Sargeant (1987) using a water immersion model. When subjects immersed both legs in 44°C water, $T_{muscle}$ was elevated from 36.6±0.5°C to 39.3±0.4°C improving maximal peak force and power by ~11%. In comparison, a reduction in $T_{muscle}$ was associated with an average decrease of 21% in maximal peak force when both legs were immersed in 12°C water.

Despite the highlighted benefits of elevating $T_{muscle}$ to improve sporting performance, it is important to acknowledge that many sports have significant time delays between the completion of a WU and the start of competition, with the inability to complete an active re-WU. For example, within swimming, athletes must adhere to strict marshalling regulations; requiring swimmers to report to a call room 20 minutes prior to racing. Therefore, swimmers are unable to complete WU within the reported optimal time of 5 to 20 minutes before racing (Bishop, 2003b). Furthermore, this period may cause significant decreases in $T_{muscle}$ and/or $T_{core}$ from post WU temperatures, potentially minimising any beneficial effects. This has been highlighted by West et al. (In Press) who demonstrated the benefits of completing a swimming specific WU 20 minutes prior to a 200m time trial (TT) performance in comparison to a 45 minute recovery period. Despite a faster performance in the 20 minute condition (125.74±3.64 versus 127.60±3.55 seconds respectively), a decrease in $T_{core}$ of 0.3±0.1°C was still observed. Subsequently, within sports where marshalling requirements prevent a WU being completed immediately prior to performance, alternative methods need to be implemented to maintain $T_{muscle}$ and/or $T_{core}$.

Accordingly, a review completed by Bishop (2003b) has highlighted the efficacious use of passive WU techniques as a supplement for maintaining temperature increases produced by an active WU, especially when an unavoidable delay is likely to occur. Surprisingly, no research to the author's knowledge has been conducted detailing the influence of passive heat maintenance on elite sporting performance. However, some support for this hypothesis can be drawn from the medical literature. For example, Sessler & Schroeder (1993) demonstrated that insulated blankets reduced heat loss by ~30%, preventing postoperative hypothermia. This is supported by Bennett et al. (1994) who investigated the use of passive heat maintenance devices in comparison to a control group during surgery. The results identified a decrease in the mean skin temperatures ($T_{skin}$) within the control group, whereas $T_{skin}$ and hand temperature ($T_{hand}$) remained unchanged within the passive group. Consequently, it was reported that a metallised plastic sheet was able to insulate the skin from radiant and convective heat losses when patients were in an environment of 19-21°C (Bennett et al., 1994).

Recently, a new passive heat maintenance device (i.e. Blizzard Survival heat jackets) introducing Reflexcell technology has been developed to prevent hypothermia within extreme conditions. This device provides opportunity within sport to maintain $T_{muscle}$ and/or $T_{core}$ when a delay is present between the completion of WU and subsequent performance. Therefore, in light of the above, the current study aimed to examine the use of custom developed heat jackets, incorporating Reflexcell technology, as a passive device for maintaining $T_{core}$ and improving subsequent elite swimming performance.

# Chapter 2 – Review of Literature

The active warm-up (WU) is a commonly observed practice in sport and physical activities (Pearce, Rowe & Whyte, 2012), acting as a means to prime the body for impending training or competition (Sporer, Cote & Sleivert, In Press). Evidence to support the positive aspects of an active WU on performance is extensive, for example, a recent systematic review with a meta-analysis highlighted that 79% of the examined studies demonstrated an improvement in performance following the completion of WU activities (Fradkin, Zazryn & Smoliga, 2010). In contrast, there appears to be little evidence to suggest that WU can be detrimental to sports performance.

The theoretical intention behind the interest afforded to WU is to reduce the potential risk of injury and enhance performance by increasing the muscle temperature ($T_{muscle}$) and/or core temperature ($T_{core}$) (Arnheim & Prentice, 1993). Previous literature has documented that the beneficial effects of an active WU are the consequence of temperature dependent physiological processes and metabolic changes. For instance, an increased temperature may improve performance through a decrease in the viscous resistance of muscles and/or by a speeding of rate limiting oxidative reactions (Bishop, 2003a).

However, significant barriers and challenges are present within sport, preventing the completion of an optimal WU; this includes time delays, the environment and logistics of sporting competition (Sporer et al., In Press). When specifically focusing on time delays, a prolonged period of rest between the completion of WU and subsequent performance can allow $T_{muscle}$ and/or $T_{core}$ to decrease to baseline values within 15 to 20 minutes of the cessation of exercise (Saltin et al., 1968). In some instances, time gaps between structured WU and competition time are in excess of 1 hour (Sporer et al., In Press).

With literature identifying the beneficial effect increased $T_{muscle}$ and/or $T_{core}$ can have on performance, it appears imperative that alternative methods are used to prevent temperature reducing to a normal physiological range (~36.8°C; Lim, Byrne & Lim, 2008) for optimal performance prior to the commencement of exercise (Bishop, 2003a). Therefore passive techniques may be important in maintaining temperature increases produced by an active WU when an unavoidable delay is present between the completion of WU and subsequent performance (Bishop, 2003b).

This review will provide a more in depth analysis of the benefit of an elevated $T_{muscle}$ and/or $T_{core}$ on performance. Also detailed will be the detrimental effects of allowing $T_{muscle}$ and/or $T_{core}$ to decrease over the period between active WU and subsequent performance. Furthermore, the review aims to provide applied information for sports researchers, practitioners and athletes on a passive heat maintenance device available to employ within sport to potentially improve performance. Below outlines the topics of focus within each section of the review:

**2.1** Active warm-up

**2.2** Temperature-related mechanisms

**2.3** Optimal temperature for performance

**2.4** Temperature responses following post warm-up recovery periods and the effect on subsequent performance

**2.5** Passive heating following an active warm-up

**2.6** Issues surrounding temperature assessments

**2.7** Conclusions

### 2.1 Active warm-up

The pre-event, active WU is a well-established practice preceding athletic events (Pearce et al., 2012). Within sport, WU has been most appropriately defined as a period of initial exercise used to enhance subsequent performance (Volianitis et al., 2001). This is supported by the views of athletes and coaches, who consider prior physical activity vital as an integral component of preparation for optimal performance (Houmard et al., 1991). Extensive scientific research into the effects of prior WU on subsequent performance has been conducted since the 1930's (Burnley, Doust & Jones, 2005). However, a more recent meta-analysis has reported WU improved performance in 79% of the 32 studies reviewed, with the degree of improvement varying from 1 to 20% (Fradkin et al., 2010). From this research, one study identified the positive effect of an active WU on cycling performance; an easy WU (EWU) (15 minutes, 5 minute segments at 70, 80 and 90% ventilatory threshold followed by 2 minutes rest) and a hard WU (HWU) (duplication of the EWU with the addition of 3 minutes at respiratory compensation threshold) were compared against a control condition (NWU) (Hajoglou et al., 2005). Statistical significance was established for the EWU and the HWU in comparison to NWU; in the first 1000m power output was 342±51W, 347±58W and 310±37W, respectively. Therefore a 48% and 53% increase in performance in the first 1000m was identified following the EWU and HWU when compared to NWU (Hajoglou et al., 2005). The importance of completing a WU is therefore evident within competitive sport to efficiently enhance and optimise subsequent performance.

#### 2.1.1 Variables of an active warm-up

Active WU protocols have traditionally incorporated generalised and specific activities in the areas of muscular strength, flexibility and cardiovascular endurance (Vetter, 2007). The theoretical intention behind the interest afforded to these areas is to reduce the potential risk of injury, enhancing performance by increasing the $T_{muscle}$ and the speed of the neuromuscular responses (Arnheim & Prentice, 1993). However, inadequate quantitative data on physiological responses to WU has been reported potentially due to the heterogeneity of different exercise protocols, therefore available data is often inconclusive due to different modalities (continuous, discontinuous or intermittent), durations (short term – maximal effort for $\leq$10 seconds; moderate – maximal effort for > 10 seconds but < 5 minutes or long term – fatiguing effort for $\geq$ 5 minutes), intensities (low < 50% maximal oxygen consumption - $VO_2$max; average 50-75% $VO_2$max; submaximal 80-95% $VO_2$max; maximal 100% $VO_2$max and supramaximal > 100% $VO_2$max) (Mandengue et al., 2005) and recovery durations (5 minutes to > 1 hour). These variations, both in literature and in practice make it difficult to draw any firm conclusions or guidelines on the optimum protocol for WU (Zochowski, Johnson & Sleivert, 2007). The structure of WU will be dependent on the task to be completed, capacity of the athlete and also the surrounding environment (Bishop, 2003b). The WU intensity, duration, mode and recovery period between the WU and performance will also depend on the physical requirements of the criterion task (Burnley et al., 2005). For example, sprint exercise requiring the generation of maximal muscle power may benefit from an active and/or passive WU. In contrast, the performance benefit of increased $T_{muscle}$ and/or $T_{core}$ during endurance exercise is clearly questionable as once a critical temperature (~39°C) is reached, reduced muscle activation can be detrimental to performance (Duffield, Coutts & Quinn, 2009). In addition, highly conditioned athletes have a more efficient thermoregulatory system and therefore may require an extended and more intensive WU (Bishop, 2003b). Therefore, WU structure can be manipulated accordingly, adjusting the modality, duration, intensity and recovery specific to different sporting disciplines to create the optimal preparation for each individual.

### 2.1.2 Modality and specificity

Different WU modalities have previously been investigated within the literature as displayed in Table 2.1; the traditional paradigm typically includes brief periods of low intensity aerobic exercise followed by static stretching (Thompsen et al., 2007). However, to produce a performance benefit, a dynamic WU appears to be preferable to static stretching. For instance, Fletcher & Monte-Colombo (2010) compared the effects of three WU protocols involving different modalities that included; running, static stretching and dynamic stretching. After one minute rest, two countermovement jumps (CMJ) and 3x20m sprints were performed. Vertical jump heights were 4.1% higher in the WU compared to the static stretching condition, likewise sprint time improved by 2% after the WU versus the static stretching condition (Fletcher & Monte-Colombo, 2010). In support, Holt & Lambourne (2008) investigated four modes of WU; a WU only, a WU plus static stretching, a WU plus dynamic stretching and a WU plus dynamic flexibility. The gain in vertical jump height in the static stretching group was significantly less than the enhancement in the other three conditions (Holt & Lambourne, 2008), thus highlighting the ineffectiveness of static stretching when aiming to improve performance. A potential explanation suggests that acute neural inhibition is thought to occur following static stretching, consequently decreasing the neural drive to the muscles (Fletcher & Monte-Colombo, 2010).

Additional research completed by Fletcher (In Press), identified an average improvement in jump height of 2.4% from pre to post WU, however when dynamic stretches were performed in conjunction with the general WU, an additional average increase of 4.8% in jump height was observed. This was further increased by incorporating heavy back squats into the pre-performance routine. The additional movements employed seemed to potentiate the agonistic muscles involved in jumping as verified by an increase in electromyographical activity, potentially a result of post activation potentiation (Fletcher, In Press).

Furthermore, if the priority of WU is to maximise performance, it also appears that WU protocols need to be specific to the demands of the sport (Thompsen et al., 2007) as highlighted above, by including the addition of back squats specific to jumping technique. Non-specific (general) techniques involve movements indirectly related to the activity to be performed, whereas specific WU includes practice of the activity or exercise to be performed. This raises temperature in comparable body parts by incorporating activities that are precise to the sport (Burkett, Phillips & Ziuraitis, 2005). Recent research has identified the positive aspects of completing a general followed by a specific WU (Abad et al., 2011), as outlined in Table 2.1. The general WU consisted of 20 minutes of moderate intensity (60% HRmax) aerobic exercise, a 3 minute interval was included prior to performing a specific WU. A longer (20 minute), general WU was elected in contrast to the recommended 5 minute WU to ensure $T_{muscle}$ was elevated, this follows reports suggesting $T_{muscle}$ rises by ~3°C and plateaus in 15 to 20 minutes (Saltin et al., 1968; Sargeant, 1987). Within the performance measure, participants had five attempts to obtain 1 maximum repetition (1RM) on a leg press exercise. The general and specific WU combined resulted in an 8.4% increase in strength values when compared to performing a specific WU only. It was thought that the general and specific WU induced temperature dependent neuromuscular adjustments that increased muscle force production capacity and hence increased strength values (Abad et al., 2011).

### 2.1.3 Intensity

Literature has reported that WU protocols aim to elevate $T_{muscle}$ to a level where the associated benefits of a WU are achieved, without a concomitant increase in metabolic academia, the depletion of high energy substrates (e.g. Phosphocreatine - PCr and/or Glycogen) or accumulation of Phosphate immediately prior to the task (Yaicharoen et al., In Press). The documented relationship between $T_{muscle}$ and exercise intensity dictates that a low intensity WU (<40% $VO_2max$) may not increase $T_{muscle}$ to the required level to evoke an ergogenic effect on short term performance (Bishop, 2003b). However, despite further elevations in $T_{muscle}$ following a greater intensity (Fletcher, In Press), increasing the intensity above 60% $VO_2max$ has been associated with increased depletion of high energy phosphate concentrations (Gregson et al., 2005). Therefore, a WU intensity of 40-60% $VO_2max$ may increase $T_{muscle}$ without causing a decrease in high energy phosphate concentrations (Woods, Bishop & Jones, 2007).

This is supported by Yaicharoen et al. (In Press) who investigated the effect of five WU intensities on subsequent intermittent sprint performance; WU1 was half the difference between the lactate inflection (LI) and lactate threshold (LT) below the LI level where LI is the first increase in lactate above resting level (Bishop, 2004) and LT is defined as the oxygen consumption above which energy production is supplemented by anaerobic mechanisms, causing a sustained increase in lactate (Wasserman, 1986), WU2 was at LI, WU3 midway between LI and LT level, WU4 was at LT and WU5 was half the difference between LI and LT above the LT level. Each WU lasted 10 minutes with a 2 minute recovery between the completion of WU and the onset of an intermittent sprint test involving 6x4 second sprints. From the performance test, total work, first sprint work, power output in the first sprint and percentage of work decrement were assessed. The results identified no differences between WU conditions in any of the performance assessments, however, a tendency for improvement in performance occurred following the completion of a WU performed midway between LI and LT (WU3). This intensity of WU equated to an intensity of 55% $VO_2$max, which as highlighted above has been acknowledged to have a positive influence on sprint performance (e.g. Stewart & Sleivert, 1998; Sargeant, 1987).

At this stage it is also important to identify that a poorly conditioned athlete may not require the same intensity or duration of WU as the well-conditioned athlete to achieve the same elevation in $T_{muscle}$ (Woods et al., 2007). Consequently, training status becomes a consideration; a given absolute intensity of exercise is a lower relative intensity for a trained athlete as opposed to an untrained person (Fradkin et al., 2010). Furthermore, age and gender variations may have an influence; varying age levels and genders can illicit differing reactions in terms of performance ability and the fatiguing effect of WU on the individual (Fradkin et al., 2010).

Research completed by Mandengue et al. (2005) investigated the difference in WU intensity on $T_{core}$, heart rate (HR) and performance. Four WU intensities were incorporated; a reference WU (RWU) completed at 62% of maximal power (Pmax), a 10% increase in RWU (RWU + 10%) equivalent to 68% Pmax, a RWU minus 10% intensity (RWU-10%) (56% Pmax) and a control condition (NWU). The results identified the RWU caused a 56% improvement, the RWU+10% evoked an 11% improvement and the RWU-10% resulted in a

33% improvement in performance in comparison to NWU, attributed to the increases within $T_{core}$ and HR.

Therefore, Mandengue et al. (2005) reported that a WU intensity ranging from 54-72% Pmax performed for 8 to 18 minutes was optimal to improve cycle time to exhaustion. This agrees with the WU intensity recommended by Stewart & Sleivert (1998) of 60-70% $VO_2$max for 5 to 10 minutes to also improve time to exhaustion. The intensities in both studies were similar as supported by the HR levels achieved, 150-165beats$\cdot$min$^{-1}$ versus 152-162 beats$\cdot$min$^{-1}$ within Stewart & Sleivert (1998) and Mandengue et al's. (2005) research, respectively. Thus suggesting a lower intensity is sufficient when the WU is longer in duration. Mandengue et al. (2005) also identified that three subjects displayed a higher performance in the NWU compared with the RWU+10% condition. Stewart & Sleivert (1998) reported a similar finding; subsequent performance did not improve following a WU completed at 80% $VO_2$max. Explanations outline that an intense WU will further increase the baseline oxygen consumption ($VO_2$), however if the WU is too intense and subsequent recovery too brief, performance may be impaired due to a decrease in high energy phosphate stores and/or accumulation of $H^+$ (Bishop, 2003b).

Following the research presented, it has been reported that $VO_2$max is not considered the most appropriate method for equating exercise intensity; 80% $VO_2$max may be above the anaerobic threshold for some subjects (untrained), but below anaerobic threshold for elite athletes as previously discussed. Therefore Bishop, Bonetti & Dawson (2001) completed a similar study with the Institute of Sport kayak athletes. Parameters for WU were maintained in accordance with Stewart & Sleivert's (1998) study (see Table 2.1), however intensity was determined by aerobic threshold (WU1), anaerobic threshold (WU3) or midway between the two (WU2). No significant differences were observed for power, peak $VO_2$, total $VO_2$ or accumulated oxygen deficit. However, when the average power during the first half of the maximal test was determined, WU2 displayed significantly different results to WU3. This was attributed to the blood lactate values observed; WU1 resulted in 1.5±0.4mmol$\cdot$L$^{-1}$, WU2 produced an average of 2.2±0.5mmol$\cdot$L$^{-1}$ of blood lactate whereas WU3 resulted in a concentration of 5.1±1.4mmol$\cdot$L$^{-1}$, consequently the higher blood lactate negatively impacted on performance. Although blood lactate was not measured within Stewart & Sleivert's (1998) study, no impact of WU was identified when intensity was increased to 80% $VO_2$max; therefore the results presented by Bishop et al. (2001) provide a valid explanation for the decrement in performance observed within Stewart & Sleivert's (1998) research.

In addition, several high intensity, short duration repetitions within WU have been reported to achieve temperature related benefits. For example, Bishop, Bonetti & Spencer (2003) compared a continuous and intermittent WU on performance of a 2 minute supramaximal kayak ergometer test. The continuous WU was completed at 65% of power output at $VO_2$max for 15 minutes; the comparative intermittent WU consisted of a 15 minute WU with 5x10 second sprints performed at an intensity of 200% power output in the last 5 minutes. The study identified an intermittent, high intensity WU improved kayak ergometer performance. Therefore, to enhance performance, the reviewed literature (Table 2.1) generally recommends a WU of 60-70% $VO_2$max or midway between the aerobic and anaerobic threshold with the incorporation of short duration high intensity repetitions specific to the activity to be performed.

### 2.1.4 Duration

In addition to intensity, duration can be manipulated to produce different performance responses. Burnley et al. (2005) investigated three prior exercise interventions varying in intensity and duration. The first was a 6 minute bout of heavy exercise, the second condition was moderate exercise performed for 10 to 12 minutes replicating the external work performed during the heavy exercise and finally, the third condition was a 30 second all out sprint. An improvement of ~2-3% in severe cycling performance was identified following the moderate and heavy intensity conditions; however the 30 second WU was insufficient to have any performance benefit consequence of the limited duration. From a physiological perspective, reports suggest that an increase in $T_{muscle}$ occurs within 3 to 5 minutes of initiation of exercise and reaches a relative plateau after 10 to 20 minutes (Saltin et al., 1968); therefore a 30 second WU was insufficient to elevate temperature and improve subsequent performance.

Supporting evidence is provided from the meta-analysis completed by Fradkin et al. (2010) comparing thirty-two studies of which 17% discovered a negative impact of WU on performance; this was attributed to an insufficient WU duration to elevate $T_{muscle}$. Duration of WU has previously been recognised to produce optimal performance by increasing $T_{muscle}$ when exercise is completed for 10 to 20 minutes (Burnley et al., 2000), whilst being individualised according to the athlete's physical capabilities and in consideration with environmental factors which potentially influence the temperature response (Shellock & Prentice, 1985). A 20 minute WU at 40% $VO_2max$ produces a greater peak performance than WU at 40% $VO_2max$ for 4 minutes as increased $T_{muscle}$ has been suggested to be dependent on WU duration (Bishop, 2003b). Consequently, the importance of sufficient WU durations to maximise the increase in $T_{muscle}$, whilst causing minimal fatigue has become apparent (Bishop, 2003b).

Multiple studies have recognised variations in performance due to inconsistency in the duration of WU. Fradkin, Sherman & Finch (2004) reported that within golfing literature WU times ranged from 4 to 45 minutes. Church et al. (2001) included a 5 minute WU and Vetter (2007) incorporated a 6 minute WU to identify an improvement in both jump and sprint performance. The inclusion of a 30 second WU in comparison to a 6 minute or 10 to 12 minute WU is insufficient to improve performance (Burnley et al., 2005). In contrast a prolonged WU duration of $\geq 50$ minutes may have an adverse effect on performance. Tomaras & Macintosh (2011) investigated a traditional WU used by athletes to prepare for sprint track cycling events involving a general WU followed by a series of brief sprints lasting $\geq 50$ minutes in total. A WU of this duration could cause significant fatigue and impair subsequent performance, therefore the effect of a reduced duration WU on performance was investigated (Tomaras & Macintosh, 2011). The traditional WU comprised of 20 minutes of cycling with a gradual intensity increase from 60% to 95% maximum HR followed by four sprints performed at 8 minute intervals (Tomaras & Macintosh, 2011). The comparison experimental WU was manipulated to include 15 minutes of cycling with an intensity increase from 60% to 70% of maximum HR followed by the completion of one sprint (Tomaras & Macintosh, 2011). The Wingate performance was significantly improved after the experimental compared with the traditional WU; peak power output was 1390±80W versus 1303±89W, respectively (Tomaras & Macintosh, 2011). Therefore the results suggest that the traditional WU caused fatigue in the athletes, whereas a shortened WU permitted an improved performance.

### 2.1.5 Recovery

Performance can also be influenced by the recovery interval following WU. An adequate recovery can reduce fatigue and accelerate the rate of physiological regeneration (Bompa, 1994). Depending on the intensity and duration of the WU, short term performance is likely to be improved if the recovery interval allows PCr stores to be significantly restored (Bishop, 2003b). However, if recovery is prolonged, $T_{muscle}$, HR and $VO_2$ will return to baseline values having limited physiological impact on performance (Zochowski et al., 2007). Research articles that have reported the recovery period between WU and the event have ranged from no recovery to 45 minutes recovery (Table 2.1). For example, in the study conducted by Fletcher & Monte Colombo (2010), jump tests were performed 1 minute after the WU protocol. By comparison, Burnley et al. (2005) included a 10 minute rest period, with West et al. (In Press) and Zochowski et al. (2007) including rest periods of 45 minutes. Although speculative, it is possible that fatigue from a short rest period and prolonged recovery from a long rest period may offset any potential benefit from an active WU protocol (Thompsen et al., 2007).

When exercise is immediately preceded by a low intensity active WU (30-60% $VO_2max$), maximal peak power and exercise time to exhaustion have been enhanced (Bishop, 2003b). Whereas after a higher intensity WU (70-100% $VO_2max$), a decrement in these performance parameters has been identified (Bishop, 2003b). With the addition of a 5 to 10 minute recovery between a high intensity WU and exercise, there is the potential that an improvement in maximal peak power will be observed. An offered explanation concerns the resynthesis of PCr stores, an expeditious process that is complete within ~5 minutes of exercise (Dawson et al., 1997), therefore following 5 minutes near complete resynthesis would have occurred. This has been acknowledged by Needham, Morse & Degens (2009) investigating the acute effect of different WU protocols on anaerobic performance (Table 2.1). Subjects completed a WU 6 minutes, 3 minutes and immediately prior to performing a CMJ followed by 10m and 20m sprint tests. Performance was enhanced at 3 minutes in comparison to immediately after with an improvement being maintained after 6 minutes.

Whilst a longer recovery period (up to 20 minutes) may be necessary for the complete resynthesis of PCr stores, if prolonged, a significant decrease in $T_{muscle}$ may be observed (Bishop, 2003b). Depending on the intensity and duration of WU and the environmental conditions, $T_{muscle}$ is likely to significantly drop following ~15 to 20 minutes recovery (Saltin, Gagge & Stolwijk, 1968). Therefore, a recovery greater than 5 minutes but less than 15 to 20 minutes has been suggested to enhance performance (Bishop, 2003b). However, for most sporting events there is often a time delay between WU and performance in which $T_{muscle}$ could decrease. This has been highlighted by Galazoulas et al. (In Press), who investigated changes in performance of basketball players during rest, ranging from 10 to 40 minutes after an active WU. The performance measures included CMJ and 10- and 20m sprint tests. The results demonstrated a decrease of 20% in the CMJ performance following 40 minutes rest; this was paralleled with a decrease in $T_{core}$ from 36.9°C to 36.2°C.

The outlined study is one of a few reports that have investigated the direct effect of the recovery duration on performance; most other reported studies have proved impractical to transfer into athletic competition. For example, some sports enforce strict marshalling regulations that prevent an active WU being completed as close as preferred to performance. Zochowski et al. (2007) investigated the difference between a 10 minute and a 45 minute recovery on swimming performance, however, within swimming competitions there is a compulsory 20 minute recovery period in which athletes must enter a marshalled call room and therefore cannot WU 10 minutes prior to a race. West et al. (In Press) continued this research to overcome practical issues, examining the difference between a 20 minute and a 45 minute recovery period between WU and 200m time trial (TT) performance. Eight international swimmers demonstrated a 1.5±1.1% improvement in performance under 20 minutes compared to 45 minutes (125.74±3.64 versus 127.60±3.55seconds respectively); attributed to a higher $T_{core}$ in the 20 minute (37.8±0.2°C) compared with the 45 minute condition (37.5±0.2°C). However, despite a faster performance in the 20 minute condition, a decrease in $T_{core}$ of 0.3±0.1°C was still observed. Subsequently within sports, including swimming, when marshalling requirements prevent WU being completed immediately prior to performance, alternative methods need to be implemented to maintain $T_{muscle}$ and/or $T_{core}$.

### 2.1.6 Summary

Improvements in performance have repeatedly been identified when preceded by an active WU; the resultant improvements appear to be largely attributable to an increase in $T_{muscle}$. However, available data is often inconclusive as the presented work outlines different modalities, durations, intensities and recovery periods may influence $T_{muscle}$ and subsequent performance. These variations limit conclusions regarding the optimal WU, for example if the WU protocol is too intense, the availability of high energy phosphates and/or the accumulation of $H^+$ has been reported to decrease performance. Within this instance, performing such WU has no further impact on performance than completing no WU. When examining WU duration, it needs to be of adequate length to elevate $T_{muscle}$, consequently a 30 second WU has been insufficient whereas a 6 to 20 minute protocol has been identified to improve performance, beyond 20 minutes and WU begins to have a fatiguing effect. Recovery is also an important component, too short and PCr stores will not be restored. However, if prolonged, $T_{muscle}$, HR and $VO_2$ will return to baseline values. Therefore, a WU performed at <60% $VO_2$max for 10 to 20 minutes with a recovery of 5 to 10 minutes is likely to cause minimal phosphate depletion, maximise the increase in $T_{muscle}$ and significantly improve short term performance. However, the optimal combination of intensity, duration and recovery remains to be determined as variation should occur amongst individuals based on training status, age and gender.

**Table 2.1:** Summary of studies investigating the effect of WU on subsequent performance

| Study (data) | Subjects | Warm-up Protocol | Performance test | Recovery period | Findings |
|---|---|---|---|---|---|
| Abad et al. (2011) | 13 male, strength trained | General: Cycle for 20 minutes, 60-70rpm, 60% $HR_{max}$<br>Specific: 8 reps at 50% 1RM, 3 reps at 70% 1RM | 1 RM | 3 minutes | General and specific WU increased performance compared to a specific WU alone |
| Bishop et al. (2001) | 8 (4 women, 4 men) kayakers | 15 minutes at AT, AnT or between the 2 intensities | 2 minute maximal kayak ergometer performance | 5 minutes | No difference following an increased intensity WU |
| Bishop et al. (2003) | 7 male kayakers | Continuous: 15 minutes at 65% $VO_2max$<br>Intermittent high intensity: 10 minutes at 65% $VO_2max$, 5 minutes of 5x10 second sprints at 200% $VO_2max$ | 2 minute maximal kayak ergometer performance | 5 minutes | Performance is improved after an intermittent rather than a continuous WU |
| Brown et al. (2008) | 10 male soccer players | Active: running for 10 minutes at 70% $VO_2max$<br>Passive: water bath set at 40.1±0.2˚C until $T_{core}$ reached that of the active WU | Repeated sprint test (10, 6 second sprints with 30 seconds recovery) | 10 minutes | Repeated sprint ability improved after an active and passive WU compared to no WU |
| Brunner-Ziegler et al. (2011) | 20 untrained males | Active: cycling for 20 minutes at 55% $VO_2max$<br>Passive: water bath for 20 minutes set at 39˚C | Incremental cycling ergometer, seated leg press of dynamometer | 3 minutes | A metabolic steady state is reached faster after an active WU |
| Burnley et al. (2005) | 12 well trained cyclists * | (1) 6 minutes of heavy exercise<br>(2) 12 minutes completing the same amount of external work as (1)<br>(3) 30 second all out sprint | 7 minute trial, 2 minute constant work-rate and 5 minutes at maximal PO | 10 minutes | Moderate and high intenisty WU can improve cycling performance by 2-3% |
| Fletcher (In Press) | 16 male collegiate athletes | 10 minutes cycle ergometer at PO 100W, 2x10 reps of dynamic stretches, heavy back squats:<br>3 reps at 30% 1RM<br>3 reps at 70% 1RM<br>2 reps at 90% 1RM | SJ, CMJ, DJ | 4 minutes | Increase in jump height from pre to post WU, further increase with dynamic stretches and again after back squats |

| | | | | | |
|---|---|---|---|---|---|
| Fletcher & Monte-Colombo (2010) | 27 males, semi-professional soccer players | (1) 5 minutes jog<br>(2) 5 minutes jog + static stretching<br>(3) 5 minutes jog + dynamic stretching | CMJ,<br>20m sprints | 1 minute | Vertical jump heights and sprint times improved in WU compared with WU and static stretching |
| Galazoulas et al. (In Press) | 8 male & 8 female elite basketball players | 27 minutes, consisting of a general WU lasting 7.5 minutes, dynamic stretching for 8.5 minutes & specific WU lasting 11 minutes | CMJ,<br>20m sprints | 10, 20, 30 or 40 minutes | Performance decreased with longer rest periods |
| Genovely & Stamford (1982) | 5 males, physically active | 60 minutes on a cycle ergometer at either 40% or 60% $VO_2$max | 2, 40 second bouts of 'all out' pedalling against a 5.5kg resistance separated by 5 minutes | 10 minutes | WU performed above the anaerobic threshold impaired maximal performance |
| Gray & Nimmo (2001) | 8 males # | Active: cycle for 5 minutes at 40% maximum PO, 4x15 second sprints at 120% of maximum PO | 30 seconds at 120% of maximal PO and 1 minute later cycle to exhaustion at 120% of maximal PO | 5 minutes | No difference in exercise time to exhaustion between the active and control trial |
| Hajoglou et al. (2005) | 8 well trained cyclists * | EWU: 15 minutes, 5 minutes at 70, 80 and 90% VT<br>HWU: EWU + 3 minutes at intensity of RCT | 3km cycle | 2 minutes | EWU and HWU increased performance by 48% and 53% compared to NWU |
| Houmard et al. (1991) | 8 highly trained collegiate swimmers * | Intensity specific: 4x45.7m<br>Mild intensity, long duration: 1371.6m at 64.7±3.3% $VO_2$max<br>Intensity specific + mild intensity, long duration | Paced 365.8m (440yard) swim | 5 minutes | Performance was not directly measured, data demonstrated the benefit of WU |
| Lovell et al. (2005) | 7 professional soccer players * | Active: cycling or repeated sprints for 7 minutes at 70% HRmax | 2 intermittent endurance tests of 16.5 minutes | 15 minutes | $T_{core}$ decreased during half time, active re-WU during HT prevented this decrease preventing decrement in performance. |

|  |  |  |  |  |  |
|---|---|---|---|---|---|
| Mandengue et al. (2005) | 9 males, 6 football players, 3 runners | RWU: 62% Pmax<br>RWU +10% intensity: 68% Pmax<br>RWU-10% intensity: 56% Pmax | Cycle time to exhaustion at Pmax |  | Improvements in performance were identified after the RWU in comparison to a control trial. |
| Mitchell & Huston (1993) | 10 male collegiate swimmers | 366m swim at 70% $VO_2$max, 4x46m swims at 110% $VO_2$max | 183m freestyle at 110% $VO_2$max | 5 minutes | Varying the intensity of WU protocol can elevate lactate but does not affect performance |
| Mohr et al. (2004) | 16 soccer players * | 7 minutes running and exercises at ~135bpm or 70% peak HR from the match | Soccer match | 15 minutes | Decrease in $T_{muscle}$ at half time correlated to reduction in sprint performance |
| Needham et al. (2009) | 20 elite youth soccer players * | 5 minutes low intensity jog plus:<br>(1) Static stretching<br>(2) Dynamic stretching<br>(3) Dynamic stretching and 8 front squats + 20% body mass | CMJ, 10- and 20-m sprint test | Immediately, 3 and 6 minutes | Dynamic WU produces a superior sprint and jump performance compared to a WU consisting of static stretching, performance was enhanced at 3 & 6 minutes |
| Pearce et al. (2012) | 18 healthy males & females | Run for 5 minutes at 65% predicted HRmax | Central & peripheral neuromuscular conduction time | Immediately | Improvement in muscular conduction time & subsequent improvement in performance post WU |
| Stewart & Sleivert (1998) | 9 males, Senior rugby union players | 15minutes at 60, 70 or 80% $VO_2$max | Treadmill test time to fatigue at 13km/hr | 30-60 seconds | Anaerobic performance improved with a 15minute WU at intensity of 60-70% $VO_2$max by 10% and 13% |
| Vetter (2007) | 26 college males and females, physically active | (1) Walk and Run (WR)<br>(2) WR + small exercise jumps<br>(3) WR + dynamic stretching and small exercise jumps<br>(4) WR + dynamic stretching<br>(5) WR + static stretching and small exercise jumps<br>(6) WR + static stretching | 30m sprint run and CMJ | No recovery | The data indicate that a WU including static stretching may negatively impact jump performance |

| | | | | | |
|---|---|---|---|---|---|
| West et al. (In Press) | 8 elite swimmers, male & female | 400m freestyle, 400m kick/pull<br>200m drill, 200m individual medley (above completed at 40-60 beats below HRmax)<br>4x50m race pace<br>200m easy | 200m swimming TT | 20 minutes or 45 minutes | Performance improved after a 20 minute compared to 45 minute recovery period |
| Wittekind & Beneke (2010) | 11 males, Cyclists or triathletes | EWU: 6 minutes at 40% peak aerobic power<br>MWU: 5 minutes at 40%, 1 minute at 80% peak aerobic power<br>HWU: 5 minutes at 40%, 1 minute at 110% peak aerobic power | 1 minute cycle sprint | 10 minutes | WU reduced glycolytic rate, although sprint performance may be maintained due to increased oxygen utilization |
| Yaicharoen et al. (In Press) | 9 male, team sport participants | WU1 – half the difference between LI and LT below LI level<br>WU2 – at LI<br>WU3 – midway between LI and LT<br>WU4 – LT<br>WU5 – half the difference between LI and LT above the LT level | 6x4 second intermittent sprints | 2 minutes | No significant difference, however WU3 displayed a tendency for improved performance |
| Zochowski et al. (2007) | 10 national swimmers, male & females | 300m easy swim<br>6 x 100m – kick and pull<br>10 x 50swim including sprint and race pace<br>100 loosen | 200m swimming TT | 10 minutes or 45 minutes | Swimming performance was improved after a 10 minute recovery compared to a 45 minute recovery |

*Gender not provided #Training status not provided

**Key**: WU – warm-up; CMJ – counter movement jump; SJ - squat jump; DJ - drop jump; PO – power output; RM – repetition maximum; EWU – easy warm-up; MWU – moderate warm-up; HWU – hard warm-up; VT – ventilator threshold; RCT – respiratory compression threshold; HR – heart rate; Reps – repetitions; LI – lactate inflection; LT – Lactate Threshold; TT – time trial; AT – aerobic threshold; AnT – anaerobic threshold; Pmax – maximal power; HT – half time; $T_{muscle}$ – muscle temperature; $T_{core}$ – core temperature

## 2.2 Temperature related mechanisms

Previous literature has documented the beneficial effects of an active WU, resultant of the temperature dependent physiological processes and metabolic changes. However, the majority of the proposed benefits have been specifically attributed to increases in $T_{muscle}$ and/or $T_{core}$ achieved via active movements of the major muscle groups (Bishop, 2003a). Within 3 to 5 minutes of the onset of moderate intensity exercise, $T_{muscle}$ rises by approximately 2°C (Saltin et al., 1968), while $T_{core}$ increases gradually over a 30 minute period (Stewart & Sleivert, 1998). Once steady state exercise is reached, the observed temperature increase plateaus, however if exercise is intense, heat production does not level (Gonzalez-Alonso, 2012).

A review completed by Bishop (2003a) reported an increased temperature may improve performance through a decrease in the viscous resistance of muscles and/or by a speeding of rate limiting oxidative reactions. An elevation in $T_{muscle}$ can also increase blood flow to the working muscles, thereby lowering the activation energy rates of metabolic chemical reactions and increasing the aerobic contribution to the energy metabolism (Robergs et al., 1991) consequently enhancing performance. Furthermore, the speed of nerve transmissions may also increase with an elevated temperature, in turn increasing contraction speed and reducing reaction time (Woods et al., 2007). Further details of the aforementioned mechanisms are outlined below.

### 2.2.1 Decreased resistance of muscles and joints

Increasing temperature has revealed the potential to improve performance by causing a decrease in the internal viscous resistance of muscles and joints (Zochowski et al., 2007). This can enhance mechanical efficiency (Koga et al., 1997) producing an increase in speed and force of muscle contraction (Woods et al., 2007). A decreased $T_{muscle}$ has revealed an increase in muscle viscosity (Depino, Webright & Arnold, 2000) reducing flexibility and increasing the likelihood of hamstring strains (Dadebo, White & George, 2004). This is supported by Rahnama, Reilly & Lees (2002) who identified that the period of exercise after half time has been associated with an elevated incidence of muscular injuries, specifically of hamstring strains (Woods et al., 2004). Therefore, Woods et al. (2007) highlighted that WU can have a positive effect on the reduction of muscle injuries and decreasing the viscosity of the muscle, which results in a smoother contraction (Woods et al., 2007).

In addition, inactivity increases the number of actin and myosin bonds, leading to an increase in muscle stiffness (Zochowski et al., 2007). Minimisation of muscle fibre stiffness during contractions is a benefit produced by an active WU, due to increased $T_{muscle}$ (Zochowski et al., 2007). Warm-up may disturb actin-myosin bonds and thereby reduce the passive resistance of muscle and increase flexibility (Bishop, 2003a). This may contribute to an increased rate of force development and an increase in power output during short duration tasks (Bishop, 2003a). However, studies have identified that increased flexibility, consequence of an elevated $T_{muscle}$ is not directly accredited to decreased muscle stiffness. Instead it has been related to an increased elasticity of the muscle-tendon unit (Safran et al, 1988). Furthermore, the temperature effect on both muscle elastic properties and decreased muscle stiffness is temporary (Zochowski et al., 2007), with muscles returning to a stiffer state after a short period of rest (Lakie & Robson, 1988). Therefore this prevents any beneficial effects on performance and thus it is the decrease in viscosity rather than reduced stiffness that has been suggested to enhance performance.

### 2.2.2 $VO_2$ kinetics and increased oxygen delivery to the muscles

In previous research, reports suggest WU acts as a mobilising stimulus for systems used in the utilisation and transportation of oxygen ($O_2$) (Gutin, et al., 1973). However, the mechanisms controlling the rate of the $VO_2$ responses at the onset of exercise are still questionable. Researchers suggest that $VO_2$ kinetics are primarily determined by the rate of $O_2$ delivery, associated with increased blood flow to the active muscles (Bishop, 2003a). Alternatively, results propose that the capacity of muscle $O_2$ utilisation determines the $VO_2$ responses (Xu & Rhodes, 1999). Therefore prior exercise performed 5 to 10 minutes before the next bout of exercise can elevate pulmonary and muscle oxygen uptake kinetics (Bansgbo et al., 2001).

Further explanation has been provided by Koga et al. (1997) in which an elevation in $T_{muscle}$ may speed $VO_2$ kinetics by causing a rightward shift of the oxyhaemoglobin dissociation curve. Reports have illustrated that $O_2$ dissociates from haemoglobin twice as quickly at 41°C than at 36°C, suggesting that a temperature increase would elevate the rate of $O_2$ delivery and dissociation to muscles (Zochowski et al., 2007). In addition, faster aerobic priming can be enhanced by the decreased haemoglobin and myoglobin affinity for oxygen. The increase in blood temperature may therefore facilitate unloading of $O_2$ into the muscle capillaries to be utilised by the working muscles accordingly, increasing aerobic contribution during performance (Bishop, 2003a). However, due to the denaturation of metabolic enzymes a temperature elevation of this magnitude may be counterproductive.

Faster $VO_2$ kinetics have also been proposed to increase $O_2$ delivery consequence of the maintained reactive hyperaemia (Robergs et al., 1991). This can occur as a result of the vasodilatory effect of an active WU on the blood vessels and the local effect of increased metabolites on the capillaries of the exercised muscle fibres (Stewart & Sleivert, 1998). Convective $O_2$ delivery might contribute to the $VO_2$ kinetics during transitions from rest to $VO_2max$ (Grassi, 2003). Despite this, neither active WU (Burnley et al., 2000; Koppo & Bouckaert, 2001) nor passive heating of the thighs (~ 40°C) (Koga et al., 1997) has been reported to speed $VO_2$ kinetics during exercise halfway between the LT and $VO_2max$. There are two possible explanations for this finding (Bishop, 2003a). Firstly, in individuals with adequate muscle perfusion and/or $O_2$ delivery, greater convective $O_2$ delivery may not affect $VO_2$ kinetics during transitions to exercise at less than $VO_2max$. Secondly, the increase in blood flow typically achieved by WU (active or passive) could be insufficient to significantly speed $VO_2$ kinetics (Bishop, 2003a).

Therefore, although increased $VO_2$ kinetics have not been revealed following WU, prior activity can allow subsequent tasks to begin with an elevated $VO_2$ baseline. As a result, less of the initial work is completed anaerobically (Bishop, 2003a). This will occur if the period between WU and competition is not extended, otherwise $VO_2$ will return to baseline levels (Zochowski et al., 2007) having no subsequent effect on performance.

Alternatively, an increase in $O_2$ transport and utilisation in the working muscles allows individuals to utilise aerobic metabolism more readily at the onset of exercise (Gray & Nimmo, 2001). This can reduce initial $O_2$ deficit allowing the anaerobic system to contribute to the energy supply for a greater period of time (Stewart & Sleivert, 1998), creating a larger potential for the removal of lactate, carbon dioxide ($CO_2$) and $H^+$ from the muscle (Edwards et al., 1972). Furthermore, aerobic contribution may be enhanced by improved mitochondrial functioning to utilise $O_2$ (Bishop, 2003a). Increased $T_{muscle}$ has been reported to elevate $O_2$ consumption of isolated mitochondria due to the $Q_{10}$ effect (the effect of temperature on the reaction rate where the ratio of the reaction rates at 2 temperatures is 10°K apart) (Xu & Rhodes 1999). This can cause a decrease in the ratio between ADP production and mitochondrial $VO_2$ (Koga et a., 1997). However, a study involving isolated mitochondria has shown that when the $T_{muscle}$ is increased by 6°C, the efficiency of mitochondrial respiration decreases by 20% (Willis & Jackman, 1994). Although research has identified that increased $T_{muscle}$ will increase $O_2$ delivery; aerobic energy production will only be raised if $VO_2$ kinetics are limited by $O_2$ delivery (Bishop, 2003a).

### 2.2.3 Speeding of rate-limiting reactions

Alterations in metabolic response during exercise have formally been associated with elevations in $T_{muscle}$ (Gray & Nimmo, 2001). An acceleration of muscle glycogen breakdown in humans exercising at high ambient temperatures was first described in 1975 by Fink, Costill & Van Handel (Bishop, 2003a). Since, an increase in $T_{muscle}$ has been suggested to improve aerobic energy production by accelerating rate-limiting reactions associated with oxidative phosphorylation (Koga et al., 1997). A proposed explanation arises from the research by Robergs et al. (1991) stating aerobic contribution is enhanced during high intensity exercise. This was a consequence of temperatures direct effect on the activity of several enzymes involved in the glycolytic pathway, decreasing the partial inhibition of glycolysis at Phosphofructokinase. Consequently, this results in an increased rate of glycolysis, glycogenolysis and high energy phosphate (ATP & PCr) degradation as previously identified during short duration intense cycling (Febbraio et al., 1996). If increased $T_{muscle}$ does speed rate limiting oxidative reactions, this should be accompanied by a speeding of $VO_2$ kinetics (Bishop, 2003a). However, it appears unlikely that a speeding of rate-limiting oxidative reactions associated with an elevation in $T_{muscle}$ achieved by current WU procedures improves performance, due to different variables within WU protocols (Bishop, 2003a).

### 2.2.4 Increase cross bridge cycling rate and skeletal muscle contractile properties

Skein et al. (2012) have reported that an increase in local $T_{muscle}$ can improve nerve conduction rates and contractile properties of the active musculature, shown by potentiated twitch peak torque, time to peak torque and relative relaxation rates. This is supported by Pearce et al. (2012) demonstrating an improvement in muscular conduction time (reduced time to peak twitch force) and subsequent improvement in athletic performance following an active WU. Furthermore, findings have been consistent irrespective of whether $T_{muscle}$ was elevated as a consequence of exercise or passive heating (Skein et al., 2012).

Several studies have also examined the influence of temperature on aspects of energy turnover during whole body dynamic exercise, however conflicting results have been identified. For instance, prior passive elevations in $T_{muscle}$ had a limited effect on pulmonary $O_2$ uptake in subsequent cycling exercise. However, a change in cross bridge cycling activity (Ferguson et al., 2006) is an alternative temperature related mechanism potentially responsible for the change in energy turnover during exercise, as observed by Sargeant (1987). It was recognised that this mechanism was responsible for the improvement in power output during high intensity activity. Further research supports this finding with demonstrations illustrating that ATP turnover, indicative of a greater rate of cross bridge cycling, was higher during intense dynamic exercise when muscle was heated (Febbraio et al., 1996).

Temperature is also an important determinant of skeletal muscle contractile and metabolic properties (Ranatunga, 1998). A principle effect of elevated $T_{muscle}$ is to alter both the force/velocity and power/velocity relationships of the muscle (Gray et al., 2006). Reports have suggested that the temperature dependent contractile properties are a function of myofibrilar ATPase activity which as with other enzymatic processes are temperature dependent (He et al., 2000). This can result in an improved maximal shortening velocity and a related change in the force velocity relationship (Racinais & Oksa, 2010), potentially contributing to the greater maximal power output under elevated $T_{muscle}$ conditions.

Neuromuscular factors may also have an effect on ATP turnover and subsequent performance (Gray et al., 2006), considering that all aspects of neuromuscular function (mechanical, biochemical and neural) are deteriorated with lowered $T_{muscle}$ (Racinais & Oksa, 2010) and improved by warming of muscle (Bishop, 2003a). Muscle fibre conduction velocity (MFCV), for instance, is the average value of conduction thus it can reflect the motor control strategies and provide important information regarding the contractile properties of the muscle (Andreassen & Ardent-Nielsen, 1987). A greater MFCV under elevated $T_{muscle}$ conditions may contribute to individual sarcomeres being rapidly activated, resulting in an enhanced contractile speed of the whole fibre (Gray et al., 2006). This close association between ATP turnover and MFCV highlights the relationship between muscle activation and energy turnover (Gray et al., 2006). Potentially the temperature dependent increase in power output may be caused by faster muscle activation and thus MFCV (Gray et al., 2006). Gray et al. (2006) also highlighted that elevating temperature to increase MFCV may be a consequential effect of a temperature mediated effect on voltage gated $Na^+$ channels alongside the elevated ATP turnover (Gray et al., 2006). At higher temperatures, the opening and closing of these channels accelerate, allowing less $Na^+$ to enter the cell

(Gray et al., 2006), promoting a rapid onset of depolarisation, producing a faster MFCV (Rutkove, Kothari & Shefner, 1997). The accelerated action potential delivery to the muscle fibres will induce a greater $Ca^{2+}$ release from the sarcoplasmic reticulum, leading to a faster rate of cross bridge cycling, requiring the greater rate of ATP turnover (Gray et al., 2006).

An increase in $T_{muscle}$ also contributes to improved performance by augmenting the function of the nervous system (Bishop, 2003a). Woods et al. (2007) reported the speed of nerve transmission may increase with an elevation in temperature, consequently increasing contraction speed and reducing reaction time. Therefore, improved nervous system functions may be especially important for tasks that demand high levels of complex body movements or require rapid reactions to a variety of stimuli (Ross & Leveritt, 2001).

### 2.2.5 Summary

Many of the proposed benefits of an active WU have been attributed to the increase in $T_{muscle}$ and/or $T_{core}$. An elevation in $T_{muscle}$ can decrease resistance of muscles and joints and potentially enhance the mechanical efficiency through an increased force and speed of muscle contraction. A speeding of $VO_2$ kinetics and increased oxygen delivery may reduce the initial $O_2$ deficit whilst also allowing the anaerobic system to contribute to the energy supply for a greater period of time. Alternatively, a speeding of rate limiting reactions has been suggested to improve aerobic energy production by accelerating rate limiting reactions associated with oxidative phosphorylation. Furthermore, research has identified that increased $T_{muscle}$ may improve performance through an increase in cross bridge cycling rate, illustrated by ATP turnover, thus contributing to the greater maximal power output achieved. Therefore, several temperature dependent mechanisms, whether combined or individual, may have a positive impact upon sporting performance.

## 2.3 Optimal temperature for sporting performance

The beneficial effects of performing an active WU prior to supramaximal exertion have previously been revealed (Stewart, Macaluso & De Vito, 2003). Performance enhancement has been primarily attributed to an increase in $T_{muscle}$ and/or $T_{core}$ commonly observed as a consequence of an active WU (Shellock & Prentice, 1985). This section will explore the literature relating the effects of temperature and the consequential impact on sporting performance.

### 2.3.1 Muscle temperature

The importance of changes in $T_{muscle}$ on subsequent performance have been established by Sargeant (1987), demonstrating that for every 1°C rise in $T_{muscle}$ there is a concomitant 4% improvement in leg muscle power. Conversely, reports have suggested that precooling can be beneficial to athletes competing in shorter sprint type events because a reduction in systematic and local temperature initiates vasoconstriction near the skin to increase central blood volume (Marsh & Sleivert, 1999). However, this has been opposed by Sargeant (1987), investigating the effect of decreasing $T_{muscle}$. Subjects immersed both legs in water set at 12°C and 18°C, subsequent reductions in $T_{muscle}$ of 7.6°C (29.0±1.7°C) and 4.7°C (31.9±0.7°C) were observed. This was associated with average reductions of 21% and 12% respectively in maximal peak force (Figure 2.1). This equates to a 3% decrease in performance of a 20 second exercise on an isokinetic cycle ergometer per °C fall in temperature compared with the normal resting conditions. Research has reported that the rate of deterioration in muscle performance is strongly associated with a decrease in $T_{muscle}$ and slower muscle contraction (Racinais & Oksa, 2010). Within Sargeant's (1987) study, it was suggested that the decrease in $T_{muscle}$ affected the neural transmission, with subjects reporting a marked sensation of leg stiffness following cold water immersion.

In support of the previous research, a recent study by Skein et al. (2012) investigated the effects of pre-exercise cooling and heating on intermittent sprint performance in a hot environment. Subjects were submersed in an ice bath and exposed to passive heating before 50 minutes of intermittent sprint exercise. Maximal isometric contractions were performed to determine maximal voluntary torque, activation and contractile properties. The results obtained were similar to the findings of the study conducted by Sargeant (1987). Maximal sprint performance was negatively affected such that overall mean sprint times were significantly ($p<0.05$) slower within the initial 10 minutes of the ice bath condition compared to passive heating. This was attributed to a lower $T_{muscle}$ decreasing peak force from reduced muscle blood flow, decreased glycolytic enzyme activity and/or decreased nerve conduction velocity (Bishop, 2003a). Improvements following passive heating were possibly due to the altered contractile properties (Bishop, 2003a).

An elevated $T_{muscle}$ has also been reported to have a positive influence on the performance of activities involving explosive power. For example, vertical jump performance has previously been reported to improve following 3 to 5 minutes of moderate intensity jogging (7.2% -7.8%; Goodwin, 2002). Similarly, Burnley et al. (2005) reported a 6 to 12 minute WU improved severe cycling performance by 2-3%. Although these authors did not report changes in $T_{muscle}$, this is supported by Stewart et al. (2003) who investigated the effect of an active WU on maximal instantaneous power output as detailed in Table 2.2. The active WU involved low intensity 70% ventilatory threshold cycling, performed for 15 minutes until an increase in $T_{muscle}$ of 3°C was achieved. Muscle and skin temperatures were significantly higher in the WU (36.8±0.5°C and 33.0±0.8°C respectively) compared to the control trial (33.8±0.4°C and 30.2±0.1°C respectively). Instantaneous power output of three squat jumps performed on a force platform also improved following an active WU; 3569±919W and 3324±866W respectively, identifying a 7% improvement in performance. This was attributed to the faster activation of muscle fibres in addition to elevated $T_{muscle}$ which was maintained during the 2 minutes recovery between contractions using a fleece blanket, ensuring adequate recovery without a decrease in $T_{muscle}$ (Stewart et al., 2003). The improvement in performance equates to a similar increase in performance reported by Goodwin (2002), supporting the theory that previous improvements in performance could have been temperature dependent.

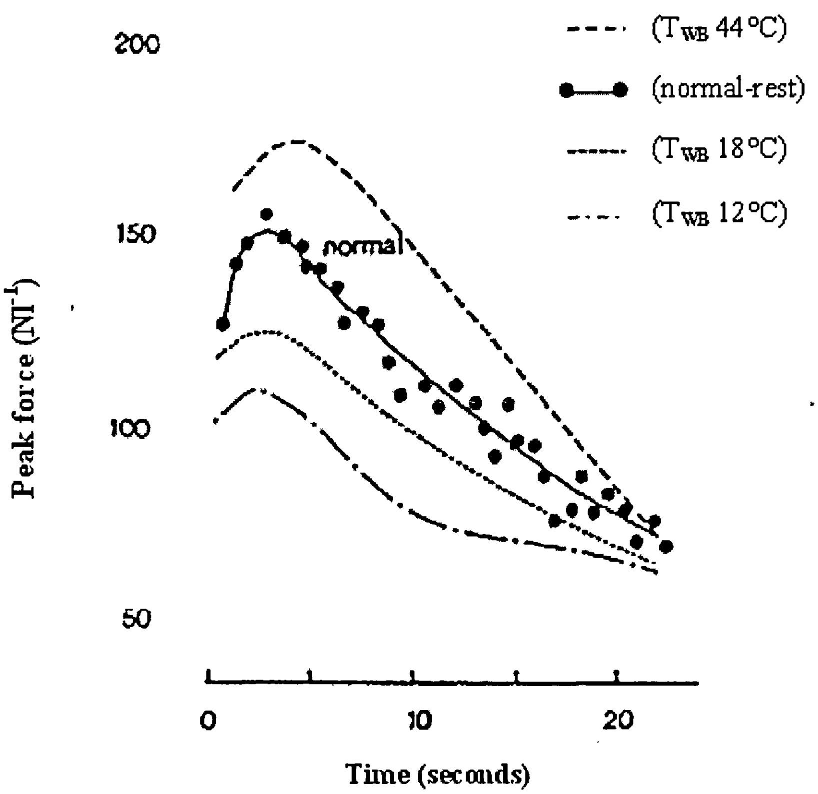

**Figure 2.1:** Changes in peak force during 20 seconds maximal effort exercise on an isokinetic cycle ergometer (Sargeant, 1987)

### 2.3.2 Core temperature

As identified in Table 2.2, additional research has highlighted the positive changes in $T_{core}$ induced by an active WU and the effect on subsequent performance. For example, Brown, Hughes & Tong (2008) acknowledged repeated sprint performance improved significantly after an active WU compared to no WU, the result of an 8% decrement in fatigue and a 10.8% increase in peak speed. This was attributed to the elevated $T_{core}$ identified at pre-exercise (37.7±0.3°C) achieved from an active WU compared to the control (37.2±0.2°C). Furthermore, Mandengue et al. (2005) illustrated WU improved cycle time to exhaustion within nine male subjects. Cycle time to exhaustion increased from 324.9±69.3 seconds in the control to 440.2±121.5 seconds in the WU condition. The improvement in performance was attributed to a 0.67±0.18°C increase in $T_{core}$, potentially having a significant influence on $VO_2$ kinetics and decreasing muscle viscosity to enhance performance. In contrast, Gray & Nimmo (2001) were unable to identify a significant improvement in cycle time to exhausation when preceded by an active WU, accredited to the marginal increase in $T_{core}$ from 36.9±0.1°C to 37.1±0.1°C (0.2°C) in comparison to the control trial, in which $T_{core}$ was 37.0±1.0°C. Disparity in the results between Brown et al. (2008) and Gray & Nimmo (2001) cannot be explained by variation in subjects as both studies investigated the effect of WU on male subjects, eliminating gender differences. Performance tests did differ between the studies; within the research by Brown et al. (2008) a repeated sprint test measured performance, whereas Gray & Nimmo (2001) incorporated a performance cycle to exhaustion at 120% maximal power output. Therefore, WU may aid repeated sprint ability, nevertheless time to exhaustion may not be extended, identifying a potentially alternative explanation to limited improvement in performance within Gray & Nimmo's (2001) study. However, this is opposed by the research mentioned by Mandengue et al. (2005) as cycle time to exhaustion was increased following the RWU.

Similarly, Genovely & Stamford (1982) identified a WU performed at 68% $VO_2$max decreased the work output (642.4±37.9W versus 709.5±21.5W) during a supramaximal performance, when compared against a lower intensity. This is opposed by the research carried out by Stewart & Sleivert (1998) in which supramaximal performance significantly improved after an active WU for 15 minutes at 60% and 70% $VO_2$max, by 10% and 13% respectively. The increase in performance could be attributed to the mean $T_{core}$ being significantly raised prior to the anaerobic test, stating over a 1°C increase in $T_{core}$ following WU (Stewart & Sleivert, 1998). A rectal thermister probe was used for measurements, therefore providing accurate and reliable results. The elevation in temperature could have positively influenced performance through an increased $O_2$ circulation and decreased haemoglobin and myoglobin affinity for $O_2$, enabling amplified unloading to the working muscles (Stewart & Sleivert, 1998). However, Genovely & Stamford (1982) also identified an increase of ~1.5°C in $T_{core}$ when measured by a rectal thermister. Therefore, differences in the result of the studies could be attributed to the varying nature of anaerobic tests conducted. Genovely & Stamford (1982) measured performance of 2x40 second bouts of maximal cycling, whereas Stewart & Sleivert (1998) carried out a maximal run to exhaustion. Genovely & Stamford (1982) measured lactate, however Stewart & Sleivert (1998) did not, therefore comparisons regarding metabolic acidaemia and the relating effects of the two different tests on performance cannot be established and consequently could be the underlying difference seen in the results.

### 2.3.3 Summary

To summarise, the beneficial effects of performing an active WU have previously been attributed to the increase in $T_{muscle}$ and/or $T_{core}$ commonly observed as a consequence of WU protocols. Based on the literature, ~0.7 to 1.0°C increase in temperature has been associated with an improvement in performance, below this, subsequent performance appears to be limited (Table 2.2). In particular, a 1°C rise in $T_{muscle}$ can result in a 4% improvement in performance, with decreased temperature having significant detrimental effects on performance due to the potentially negative effect on neural transmission. It therefore appears of significant importance to elevate $T_{muscle}$ and/or $T_{core}$ prior to both exercise time to exhaustion and explosive power activities to improve subsequent performance.

**Table 2.2:** Pre WU, post WU, the difference in WU temperatures and the subsequent effect on performance across the WU related literature

| Study | Site of temperature measurement | Pre-WU temperature (°C) | Post-WU temperature (°C) | Difference (°C) | Effect on performance |
|---|---|---|---|---|---|
| Brown et al., 2008 | Core (rectal) | 37.4±0.4 | 37.8±0.2 | 0.4 | Active WU improved performance compared to the control |
| Cochrane et al., 2008 | Muscle<br>Core | 35.6±0.7<br>37.2±0.3 | 37.2±0.9<br>37.3±0.3 | 1.6<br>0.1 | Peak power increased with elevated $T_{muscle}$ |
| Duffield et al., 2009 | Core (intestinal) | 37.25 | ~37.8 | 0.6 | $T_{core}$ correlated with high intensity running and moderate intensity running |
| Gray & Nimmo, 2001 | Muscle<br>Core | 33.9±0.1<br>36.9±0.1 | 36.9±0.2<br>37.1±0.1 | 3.0<br>0.2 | No improvement in performance |
| Krustrup et al., 2002 | Muscle | 36.5 | 38.4 | 1.9 | High intensity sprint performance improved |
| Mandengue et al., 2005 | Core (rectal) | 37.04±0.2<br>37.18±0.35 | 37.73±0.14<br>37.84±0.25 | 0.7<br>0.7 | Both improved performance compared to a control |
| Mohr et al., 2004 | Muscle<br>Core | 36.0±0.2<br>37.2±0.1 | 39.4±0.2<br>38.2±0.1 | 3.4<br>1.0 | $T_{muscle}$ increased sprint performance compared to no WU |
| Stewart & Sleivert, 1998 | Core (rectal) | 34.8<br>34.8<br>35.0 | 35.5<br>35.8<br>36.4 | 0.7<br>1.0<br>1.4 | A difference of 0.7 and 1.0°C improved performance |
| Stewart et al., 2003 | Muscle | 33.8±0.4 | 36.8±0.5 | 3.0 | Improved muscle performance |
| West et al. (In Press) | Core (intestinal) | 37.3±0.2 | 38.1±0.3 | 0.8 | Improved performance |

## 2.4 Temperature responses following post warm-up recovery periods and the effect on subsequent performance

During exercise, the release of energy as heat and the associated rise in $T_{core}$ may suggest that powerful physiological mechanisms promote heat loss (Wendt, Van Loon & Van Marken Lichtenbelt, 2007). With the onset of exercise, increased heat production causes the $T_{muscle}$ to raise causing heat to be transferred down a gradient from muscle to blood and subsequently to the core body (Wendt et al., 2007). The rate of heat transfer from the core to the skin is determined by the temperature gradient between these two components (Wendt et al., 2007). Once metabolic heat is transferred to the skin, heat can be lost to the surrounding environment through radiation, conduction, convection and evaporation.

### 2.4.1 Mechanisms of heat loss

Radiation is the loss or gain of heat in the form of infrared heat rays; all objects not at absolute zero emit such rays (Wendt et al., 2007). When the $T_{core}$ and/or $T_{muscle}$ is higher than that of its surroundings, a greater quantity of heat radiates from the body, accounting for approximately 60% of heat loss from the body (Brooks, Fahey & White, 1995). The transfer of heat from a body to an object is conduction (Wendt et al., 2007), at a comfortable room temperature only 3% of total body heat loss occurs as a result of this mechanism (Wendt et al., 2007). Heat transfer via a moving gas or liquid is called convection; a small amount of convection always occurs as a consequence of the tendency of air surrounding the skin to rise as it becomes heated (Wendt et al., 2007). An individual who is placed in a thermally comfortable room without considerable air movement loses ~15% of heat by convection to the air (Wendt et al., 2007). Finally, evaporative heat loss occurs by means of water loss and sweating. At rest, in a comfortable environment ~25% of heat loss is due to evaporation (Brooks et al., 1995).

### 2.4.2 Effect of heat loss on subsequent performance

Currently, a major limitation of WU protocols is the presence of a recovery period in a thermoneutral environment between WU and performance. This potentially allows $T_{muscle}$ and/or $T_{core}$ to decrease to resting levels via mechanisms outlined above. In some instances, this recovery period can be in excess of 1 hour, as demonstrated within snowboarding (Sporer et al., In Press). This can cause significant barriers and challenges in performing an optimal pre-performance routine (Sporer et al., In Press).

Reports have suggested that $T_{muscle}$ will return to near baseline values within 15 to 20 minutes of the cessation of exercise (Saltin et al., 1968). For example, within sport the incorporation of a half time break involving at least a 15 minute rest period can cause a decrease in $T_{muscle}$ and/or $T_{core}$. Krustrup, Mohr & Bangsbo (2002) observed that $T_{muscle}$ increased from 36.5°C (35.7 to 37.3°C) to 38.4°C (37.7 to 39.2°C) during WU within a group of assistant referees. However, the presence of half time resulted in $T_{muscle}$ decreasing markedly to 37.9°C (37.6 to 38.1°C) and 37.5°C (36.4 to 38.0°C) after 10 and 15 minutes, respectively (Krustrup et al, 2002) (Figure 2.2). Muscle temperature was therefore 0.9±0.2°C lower before the second half than at the start of the first half, potentially explaining the 33% decrease in high intensity running in the initial 5 minutes of the second half and a decrease of 30% in distance completed of sideways running.

A similar phenomenon has been reported in soccer players over the 15 minute half-time interval. Literature has proposed that top class players perform less high intensity running in the initial phase of the second half compared with the first half when WU was present (e.g. Krustrup & Bangsbo, 2001). It was unknown if this was due to fatigue or lack of physical preparation for the second half, especially as little or no activity is performed during the intermission causing major decreases in $T_{core}$ and/or $T_{muscle}$ at half time (Mohr et al., 2004). Therefore, Mohr et al. (2004) accordingly investigated the effect of $T_{muscle}$ on sprint performance in soccer.

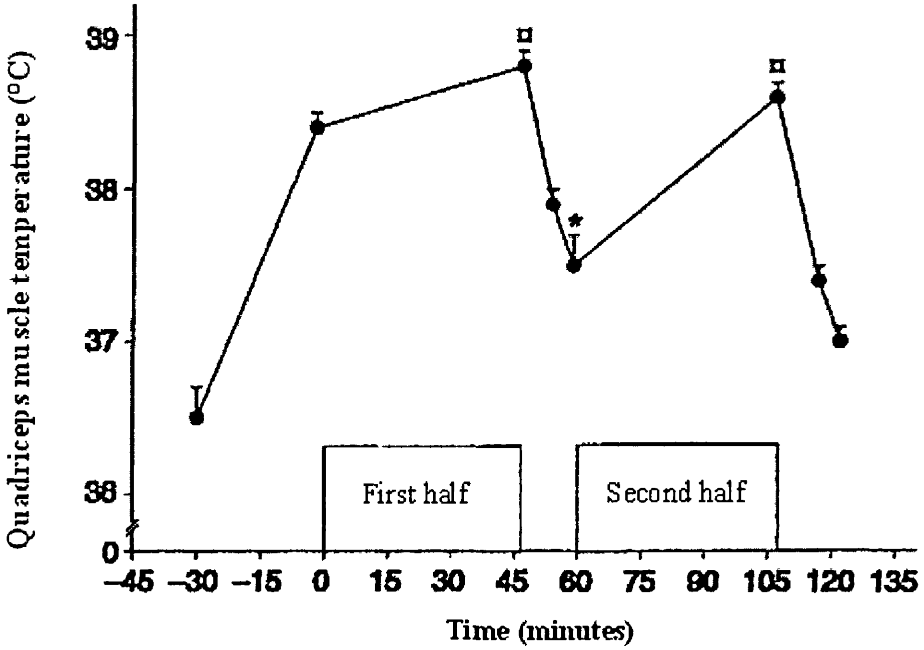

**Figure 2.2:** Quadricep $T_{muscle}$ before, during and after a soccer game. * Significant difference ($p<0.05$) between the first and second halves (Krustrup et al., 2002)

The study by Mohr et al. (2004) aimed to investigate the fluctuations in $T_{muscle}$ and/or $T_{core}$ during a soccer match. Two conditions were incorporated; a control condition that required athletes to passively recover (seated) and an active re-WU consisting of running and soccer specific skills at moderate intensity (~135beats$\cdot$min$^{-1}$) for 7 minutes, finishing 1 minute prior to the start of the second half. Familiarisation tests were completed; therefore changes in performance could not be attributed to this. It was identified that $T_{muscle}$ within the control condition was 39.7±0.2°C at the end of the first half, this decreased to 37.7±0.2°C at half time (Figure 2.3); displaying a similar pattern to the results of Krustrup et al. (2002). Muscle temperature was ~2.0°C lower before the second half than prior to the first half, providing an explanation for the reduction of 2.4±0.3% in sprint performance. However, when an active re-WU was performed, $T_{muscle}$ prior to the second half (39.2±0.2°C) replicated the temperature at the termination of the first half (39.7±0.2°C). Before the second half, $T_{muscle}$ was 1.5°C higher in the re-WU than in the control condition. Core temperature demonstrated a similar pattern, within the control condition, a decrease from 38.9±0.1°C to 37.8±0.1°C occurred during half time; however within the re-WU condition $T_{core}$ did not decrease. Therefore a positive relationship between an elevated $T_{muscle}$ and subsequent improvement in performance has been highlighted. Alternatively, it has been demonstrated that pulmonary and muscle $O_2$ uptake kinetics are enhanced by prior exercise performed within 5 to 10 minutes of the next bout of exercise (Bangsbo et al., 2001). Thus, the subjects that performed a re-WU at the interval may have had a greater $O_2$ uptake during and after sprints, shortening the time required to recover from a sprint (Mohr et al., 2004).

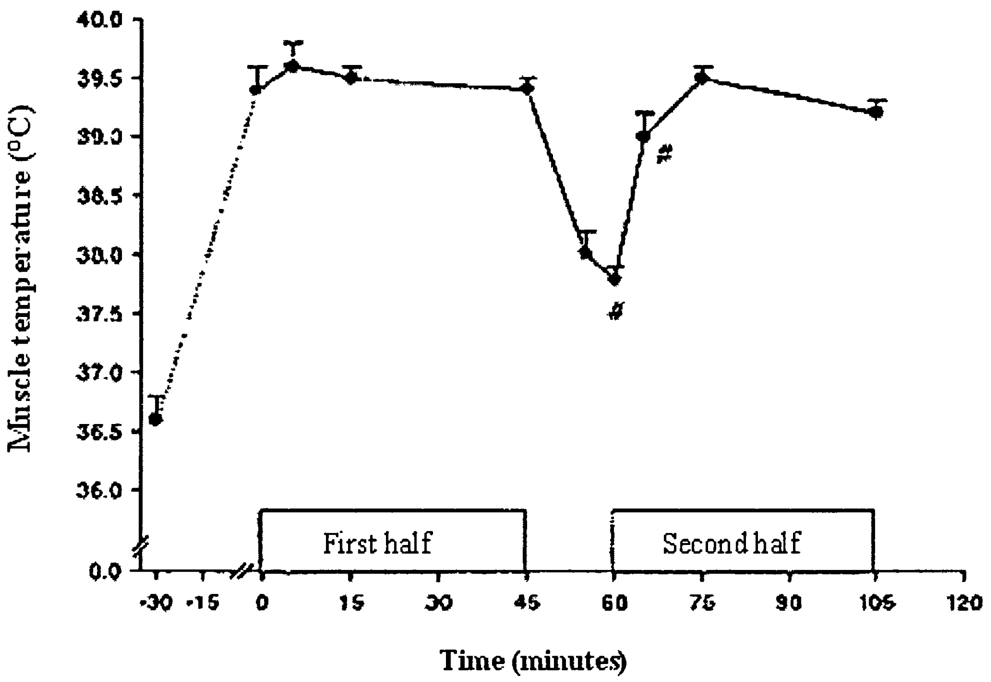

**Figure 2.3:** Muscle temperature of field players during a soccer match. Values are displayed as Means ± SEM. # identifies significant differences between the first and second halves ($p<0.05$) (Mohr et al., 2004)

As identified by Mohr et al. (2004), a ~2.0°C reduction in $T_{muscle}$ observed after the half time interval has been purported as the primary mechanism decreasing sprint performance. However, Mohr et al. (2004) completed data collection during a non-competitive match, while this provides a higher degree of ecological validity, its applicability could be questioned due to the large degree of match-to-match variability in high speed activities. Therefore, Lovell et al. (2011) completed a laboratory based study comparing a re-WU and a control during a 15 minute half time period on physical performance measures during a simulated soccer game. The re-WU was completed between 9 and 14 minutes of the half time period, incorporating an intermittent agility exercise test (i.e. re-WU). The results support the previously reported decrease in $T_{muscle}$ during the control trial, identifying a reduction of 1.5±0.4°C over the 15 minute period. This was associated with significant differences between conditions, as $T_{muscle}$ only decreased by 0.5±0.4°C following the re-WU. The primary finding of this study was that re-WU attenuated the decrease in $T_{muscle}$ and subsequent soccer sprint, power and dynamic strength performance observed after a passive half time interval. The extent of the decrease in $T_{muscle}$ during the half time interval was equivalent to that reported by Mohr et al. (2004). However, Lovell et al. (2011) observed a greater decrement in performance (6.2 versus 2.4%) following a control (seated) half time condition. Differences could be accounted for given the variation in nature of performance tests; laboratory versus field based. Potentially conclusions could be drawn from Lovell et al. (2011) as sprint performance was measured within standardised bouts of intermittent exercise providing greater practical significance as the sprint distance covered was more indicative of that undertaken during match play (Carling et al., 2008).

However, in many sports there can be significant time delays between the WU and subsequent competition, in which strict marshalling guidelines prevent the completion of an active re-WU. This may allow $T_{muscle}$ and/or $T_{core}$ to decrease significantly compared to post WU temperatures, as highlighted above and previously demonstrated by Galazoulas et al. (In Press). The authors aimed to examine changes in performance and biochemical parameters of basketball players while resting after WU. A structured WU was performed, after which $T_{core}$ was measured and players performed CMJ and 20m run tests before resting for 10, 20, 30 or 40 minutes. Temperature and performance measures were repeated at each rest interval, allowing the results to identify that both $T_{core}$ and jump performance decreased gradually during the rest period (temperature decreased from 36.9°C to 36.2°C and jump performance decreased by 20% during the 40 minute rest). Furthermore, the time to complete a 20m run increased by 6.3% at 40 minutes rest (Galazoulas et al., In Press). The conclusions identify that with prolonged inactivity, basketball players display a decline in jumping and running performance.

This is supported by Zochowski et al. (2007) reporting that varying the recovery period after a standardised WU might affect subsequent performance. The study aimed to determine the effects of varying post WU recovery times on a subsequent 200m swimming TT performance. Ten national swimmers completed a 200m simulated race preceded by either 10 minutes or 45 minutes of passive recovery after the active WU. It was identified that the TT significantly improved after 10 minutes as opposed to 45 minutes recovery (136.80±20.38 versus 138.69±20.32 seconds). However, as $T_{muscle}$ and/or $T_{core}$ were not measured within Zochowski et al's. (2007) study an increase in performance could not be attributed to the influence of temperature mechanisms. Furthermore, during swimming competitions, strict marshalling regulations are enforced, the athletes must report to a marshalled call room 20 minutes prior to racing; consequently the presented study has limited practical application.

In light of the previously mentioned research, West et al. (In Press) completed an investigation into the influence of swimming performance following a 20 and 45 minute recovery period between WU and a 200m TT performance. The swimmers demonstrated a 1.5±1.1% improvement in performance under 20 minutes compared to 45 minutes; 125.74±3.64 versus 127.60±3.55 seconds, respectively (Figure 2.4). A key finding was at pre-TT measurement, $T_{core}$ was greater under 20 minutes versus 45 minutes; 37.8±0.2°C versus 37.5±0.2°C respectively (Figure 2.4). However, despite a smaller decrease in $T_{core}$ over the 20 minute rest period, a decrease in $T_{core}$ was still observed. Consequently within sports, including swimming, when marshalling requirements prevent an active WU being completed $\leq$5 minutes before competing, an alternative method needs to be implemented to maintain $T_{muscle}$ and/or $T_{core}$.

### 2.4.3 Summary

Metabolic heat can be lost to the surrounding environment through radiation, conduction, convection and evaporation. Currently, a major limitation of WU protocols is the presence of a recovery period within a thermoneutral environment between WU and performance that results in the loss of metabolic heat. Several studies within soccer have highlighted the significant decrease in $T_{muscle}$ following a 15 minute half time interval; however when an active re-WU is introduced during this period $T_{muscle}$ is maintained, preventing the decrement in sports performance previously observed (2.4-6.2% deterioration). This has outlined the importance of maintaining $T_{muscle}$ within recovery periods; however within sports such as swimming, strict marshalling regulations prevent WU being completed immediately prior to competition performance. A time delay is therefore present, providing opportunity for a reduction in $T_{muscle}$. This was highlighted within the literature; a 20 minute recovery period was preferable to a 45 minute recovery as performance was improved, despite this, a decrease in $T_{core}$ was still observed during the 20 minutes. Consequently, alternative methods need to be implemented within such sports to maintain $T_{muscle}$ and/or $T_{core}$ and prevent the subsequent decrement in performance described.

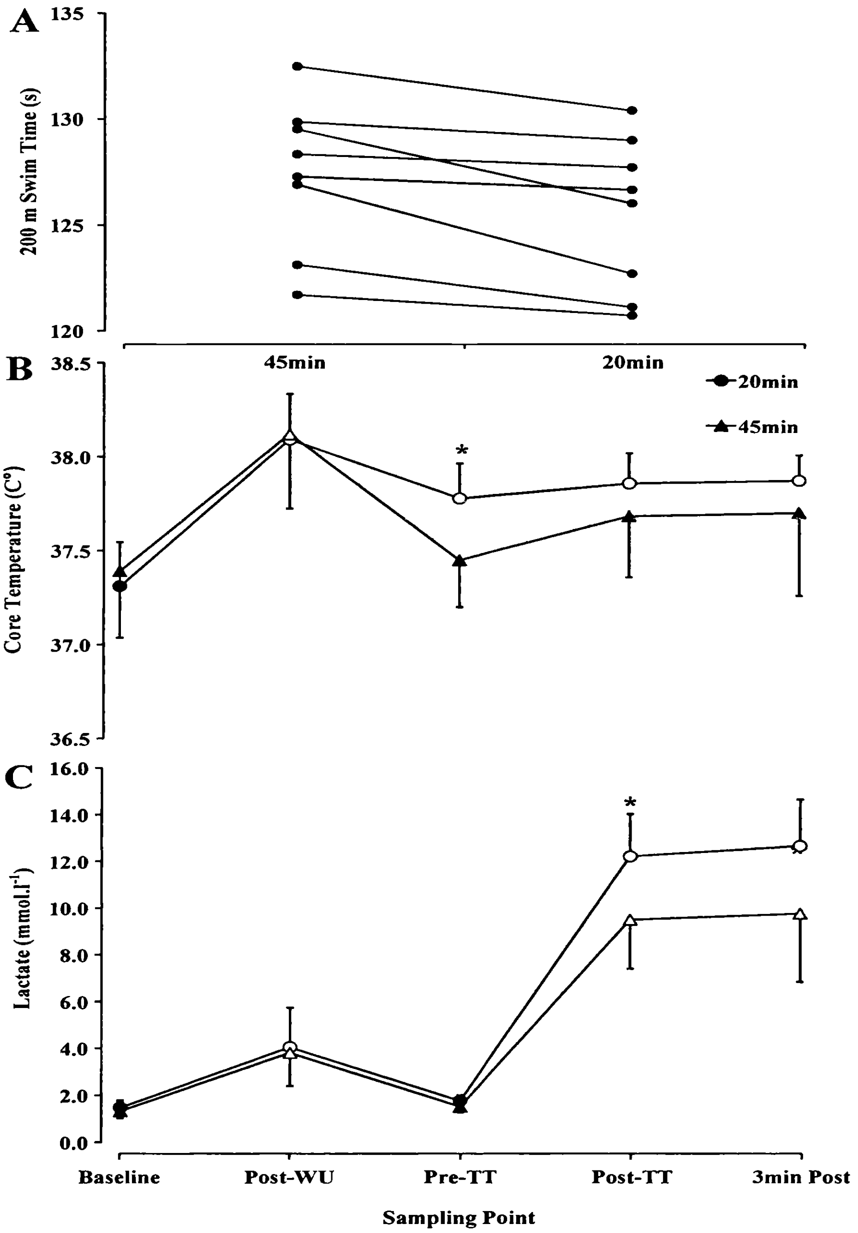

**Figure 2.4**: The performance (A), $T_{core}$ (B) and lactate (C) responses to a 20 minute versus 45 minute rest period *indicates significance ($p<0.05$) (West et al., In Press)

## 2.5 Passive heating following an active warm-up

### 2.5.1 Passive warm-up techniques

Passive WU techniques may be important to maintain temperature increases produced by an active WU when an unavoidable delay is present between WU and performance (Bishop, 2003b). The magnitude and type of response may be dependent on the method of heating. From the review of literature completed by Bishop (2003a), two studies have reported passive WU to improve performance (Muido, 1946; Carlile, 1956). Prior to these studies, it was considered that pre-race passive heating would be detrimental to performance (Carlile, 1956). Muido (1946) specifically investigated the influence of $T_{core}$ on swimming performance. It was reported that passive heating improved swimming performance over both 50m (0-2%, n=3) and 200-400m (1.3-3.9%, n=3). Warming was completed using a hot water bath (40-43°C for 15 to 18 minutes), identifying an increase in rectal temperature ($T_{rectal}$) of 1.0-1.6°C, resulting in an average $T_{rectal}$ of 38.1°C. However, it was reported that when $T_{muscle}$ was allowed to return to baseline, but $T_{rectal}$ to remain elevated, a performance improvement remained.

Carlile (1956) also investigated the effect of passive heating on swimming performance. A statistically significant improvement was identified in swimming performance preceded by an 8 minute hot shower. Average speed of pre-heated swims was compared with a control condition; a significant difference was established, identifying an average improvement 0.9% in performance relating to an increase in temperature to 100.39°F following passive heating versus 100.01°F within the control condition. The performance tests consisted of a 40yard swim; however this prevents comparison to the results of the study completed by Muido (1946). Despite that, it was reported that relatively short distances were utilised to prevent variation due to faulty pacing judgement. Furthermore, within this study the stop-clock began when the swimmers feet were judged to have left the starting board, therefore although this decreased experimental error it reduced the practical applicability the findings have to a competition. The results also oppose those reported by Mudio (1946) in which performance was not closely related to $T_{rectal}$. Muscle temperature was stated to vary independently of $T_{rectal}$, with $T_{muscle}$ having an additional influential effect on performance (Carlile, 1956).

Further to the studies reviewed by Bishop (2003a), as previously discussed, Sargeant (1987) researched the effect of 45 minutes of passive warming on performance of a 20 second maximal sprint. Four subjects were involved in the study, with their legs immersed in water baths set at 44, 18 and 12°C for 45 minutes. A rest condition was also included in which there was no experimental manipulation. Muscle temperature within the rest condition was 36.6±0.5°C, at 44°C $T_{muscle}$ was 39.3±0.4°C compared to 31.9±0.7°C and 29.0±1.7°C at 18 and 12°C respectively. Warming to 39.3±0.4°C improved maximal peak force and power by ~11%. This study identified increasing local $T_{muscle}$ can improve performance especially as the increase in performance was greater than those previously reported. However, Sargeant (1987) did not report a recovery period between passive heating and the performance test, therefore influencing the benefit of passive heating on performance.

In contrast to Sargeant (1987), Morrison, Sleivert & Cheung (2004) suggested that a passively induced increase in $T_{core}$ may inhibit maximal force production and voluntary activation. The author's passively heated subjects, elevating $T_{rectal}$ from 37.3±0.3°C to 39.4±0.1°C, with the overall aim of determining the relative roles of $T_{skin}$ and $T_{core}$ on the previously described factors. It was identified that passive heating reduced voluntary activation by 11% and maximal isometric force production by 13% even when cardiovascular strain was only moderate. However, a $T_{core}$ of 39°C is referred to as the critical temperature at which the subject experiences hyperthermia. It is well documented that heat strain, consequence of an elevated $T_{core}$, is a major cause of reduced performance (Duffield et al., 2009). One potential contributor to hyperthermia induced fatigue can be impaired central neuromuscular activation (Nybo & Nielson, 2001). Hyperthermia directly affects the functioning of the brain by altering the central blood flow, metabolism and decreasing the level of central cognitive or neuromuscular drive. This can cause decreased muscle function or alteration of effort perception (Cheung & Sleivert, 2004), therefore, this may provide an explanation for the reduction in maximal force production and voluntary activation.

Further support for the use of passive heating arises from research completed by Linnane et al. (2004), investigating the metabolic and performance responses to whole body passive heating during high intensity exercise. Prior to exercise, $T_{core}$ was elevated to 38.1±0.3°C in the hot trial compared to 37.1±0.3°C within a control condition. Following heating, mean power output and peak power output were significantly higher, attributable to a faster pedal cadence. Results of this study suggest an elevation in $T_{core}$ of 1°C can improve performance during an initial bout of high intensity cycling by 6%. The improvement in sprint performance with passive heating may have resulted from an increased cross bridge cycling rate coupled with an improved capacity for ATP resynthesis in the heated muscle (Linnane et al., 2004). This suggestion is supported by a higher pedal cadence during heating, a function of a rightward shift in the power/velocity characteristics of the muscle, a consequence of an increase cross bridge cycling rate (Linnane et al., 2004).

### 2.5.2 Passive heat maintenance

However, whilst passive heating has an important contribution in elevating $T_{muscle}$ and/or $T_{core}$, it can still be impractical for some athletes (Bishop, 2003a). Nevertheless, it appears imperative that $T_{muscle}$ and/or $T_{core}$ are not allowed to reduce below a normal physiological range prior to the commencement of exercise (Bishop, 2003a). Hence maintenance of temperature between an active WU and competition through passive methods is of high priority; however research has not been completed on the use of passive heat maintenance in sport. To date, research to support this rationale has been complete within a medical environment; nonetheless these methods could have great transferability into sport and performance improvement.

Bennett et al. (1994) measured aural canal ($T_{core}$) and $T_{skin}$ in 45 patients during surgery. Patients were randomly assigned to 3 groups; (1) the control group (n=15) who received no warming device, (2) a passive condition using a metallised plastic sheet (n=15) and (3) an active skin surface warming condition involving the use of an air blanket (43°C). Mean skin and hand temperatures decreased within the control group, however remained unchanged in the passive maintenance group. Consequently, it was reported that a metallised plastic sheet was able to insulate the skin and hands from radiant and convective heat losses when patients were in an environment of 19-21°C (Bennett et al., 1994). This was supported by Sessler & Schroeder (1993) reporting insulated blankets reduced heat loss by 33±5% and were preferable in patients for temperature preservation since they were superior in heat conservation (Torossian, 2008). Furthermore, Sessler, McGuire & Sessler (1991) investigated the use of six methods of passive heat maintenance within anaesthetised patients. Heat loss decreased significantly (100±3W) within the control conditions as compared to a 69±6W average decrease when passive heat maintenance methods were utilised. The Thermodrape was the most effective passive method of maintaining temperature (heat loss of 61±6W), reported to be 13% more effective than an ordinary surgical cloth (Sessler et al., 1991). The Thermodrape is made with a reflective metal backing that faces the patient and is intended to minimise heat loss by radiation, likely trapping air between the covers and skin surface providing a large fraction of insulation (Sessler et al., 1991).

Recently, a new development introducing Reflexcell technology has been designed to prevent hypothermia within extreme conditions. Allen et al. (2010) measured the use of Reflexcell technology within the US army for military combat situations. An in-vitro 'torso' model constructed with fluid bags acted as the control; this was warmed to 37°C prior to the commencement of the study. The first group of products consisted of three devices with active heating systems, whereas the second group of products incorporated five methods of passive heat maintenance. Temperature was recorded every 5 minutes for 120 minutes to identify the decrement and/or maintenance of temperature. The authors concluded that active heating products prevented heat loss more efficiently than passive prevention methods. However, under conditions near room temperature the Blizzard blanket incorporating Reflexcell technology (passive heat maintenance) was effective when compared with the active warming devices. Despite this, research was based on a fluid model that did not consist of a biological organism and had no basal metabolic activity, therefore extrapolation to the effect of heat loss prevention in humans may be limited (Allen et al., 2010).

Further research has substantiated passive heat maintenance methods within extreme conditions; however this is yet to be complete within sport. Blizzard Survival UK helped support British winter sport athletes with competition strategies by optimising WU preparation (http://www.blizzardsurvival.com). Custom developed, full length heat jackets were designed to improve performance in sports such as skeleton bobsleigh to maintain temperature between WU and race completion. The heat jackets incorporated Reflexcell technology, the cellular construction of this material traps warm air allowing the still air to provide insulation, furthermore the elastication draws the material to the body reducing cold spaces and heat loss by convection and finally the silvered surfaces block heat loss by radiation (http://www.blizzardsurvival.com) (Figure 2.5).

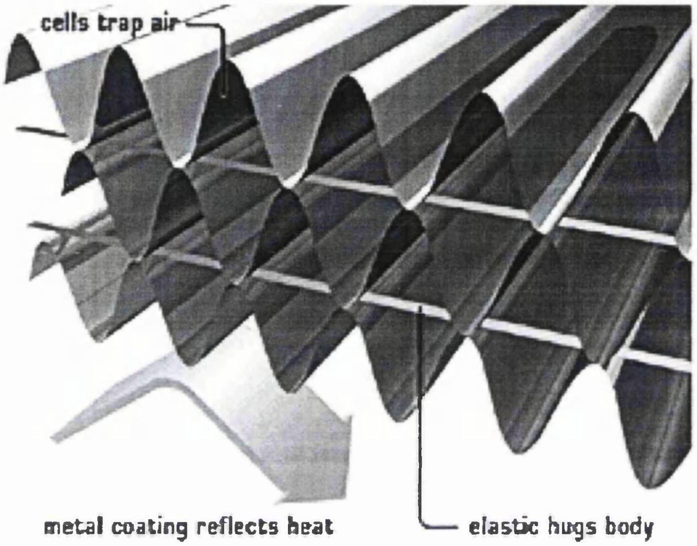

**Figure 2.5:** The construction of Reflexcell technology used in the Blizzard Survival heat jackets (http://www.blizzardsurvival.com)

### 2.5.3 Summary

Passive heating has previously been shown to elevate $T_{muscle}$ and/or $T_{core}$ causing an improvement in subsequent performance. However, passive heating can be impractical in some sports, yet the importance of maintaining $T_{muscle}$ and/or $T_{core}$ remains. Therefore, methods of passive heat maintenance may provide an important role in sport and performance enhancement by sustaining temperature elevations previously associated with improved performance. To date, research in this area has been completed within a medical environment; nonetheless it could have great application and transferability into sport. A recent development has introduced Reflexcell technology, for the use in survival blankets to prevent hypothermia within extreme conditions. This technology has been incorporated into custom developed, full length heat jackets that can be worn within a recovery period between WU and performance, whilst sat in a thermoneutral environment to prevent temperature decreases associated with a performance decrement.

## 2.6 Issues surrounding temperature assessment

### 2.6.1 Core versus muscle temperature

Comparison of temperature results outlined within the literature can be problematic as either $T_{muscle}$ or $T_{core}$ have been reported, however, rarely have both been measured (Bishop, 2003a). With the onset of moderate intensity exercise (80-100% of the LT), $T_{muscle}$ rises rapidly from resting levels (~35°C) and within 3 to 5 minutes exceeds $T_{core}$ and reaches a relative equilibrium after ~10 to 20 minutes of exercise (Bishop, 2003). The results of the study conducted by Stewart & Sleivert (1998) follow a similar time course as reported by Bishop (2003), with $T_{core}$ showing a significant increase throughout the 15 minute WU and a continued drift upward thereafter. This is supported by Robergs et al. (1991), who reported $T_{muscle}$ was significantly elevated after a 15 minute WU compared with no WU and $T_{muscle}$ was still elevated after a 10 minute rest period prior to a maximal sprint.

Mohr et al. (2004) unusually recorded both $T_{muscle}$ and $T_{core}$ responses during a soccer match. Muscle temperature was measured in the medial section of *m. Vastus lateralis* by a needle thermister having a precision of 0.1°C, measurement was taken at 3cm. Core temperature was measured in the rectum at a depth of ~2cm using an electronic clinical rectal thermometer having a precision of 0.01°C. Within the control condition, $T_{muscle}$ was 37.7±0.2°C before the second half compared to 39.1±0.2°C prior to the first half and 39.7±0.2°C at the end of the first half, therefore $T_{muscle}$ decreased by ~2°C during half time (Mohr et al., 2004). Core temperature also decreased from 38.9±0.1°C to 37.8±0.1°C during half time, however only a reduction of ~1.1°C was observed. Furthermore, it was the decrease in $T_{muscle}$ at half time that was correlated ($r=0.60$, $p>0.05$, $n=16$) to the reduction in sprint performance that was identified within this study, identifying that an almost linear relationship is observed between $T_{muscle}$ and sprint performance (Figure 2.6).

An alternative study that has recently investigated the effect of $T_{muscle}$ and $T_{rectal}$ on repeated sprints has been conducted by Yaicharoen et al. (In Press). The study examined the effect of WU intensities on performance; however one aim was to determine which temperature measurement (muscle, rectal or body) best correlated with performance. Changes in $T_{muscle}$ and $T_{rectal}$ can be identified in Table 2.3. As can be highlighted, $T_{muscle}$ increased at a higher rate in all conditions compared to $T_{rectal}$. However, while $T_{muscle}$ increased to a larger extent in WU1, when viewing the absolute values, $T_{muscle}$ remained lower than $T_{rectal}$ (Muscle 37.1±0.6°C; Rectal 37.4±0.3°C). This reflects the lower workload employed in WU1 and the importance of measuring $T_{muscle}$ as well as $T_{core}$ during temperature related investigations due to the noticeable difference in response. However, as absolute values rather than change in temperatures were correlated against performance, no correlation between any temperature measurements and performance were identified within this study.

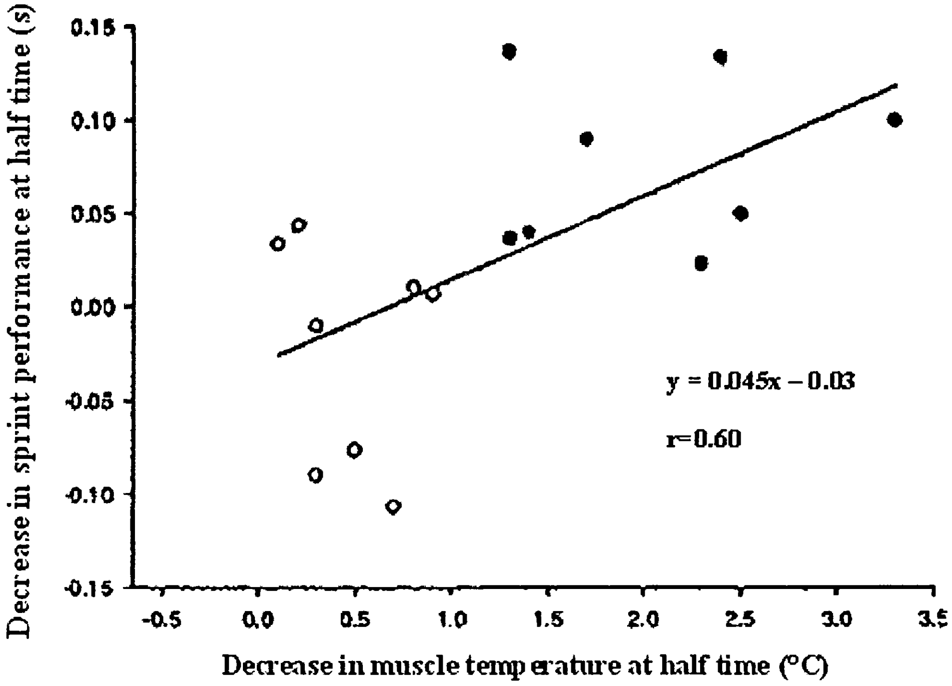

**Figure 2.6**: The relationship between the decrease in $T_{muscle}$ and sprint performance at half time (Closed circles are control group; open circles completed a re-active WU) (Mohr et al., 2004)

**Table 2.3**: The change in temperature recorded pre to post WU across five different WU intensities

| | WU1 | WU2 | WU3 | WU4 | WU5 |
|---|---|---|---|---|---|
| Change in rectal temperature (°C) | 0.1 | 0.2 | 0.2 | 0.3 | 0.4 |
| Change in muscle temperature (°C) | 0.8 | 1.5 | 1.7 | 2.2 | 2.8 |

(Yaicharoen et al., In Press)

Saltin & Hermansen (1966) specifically investigated the response of oesophageal temperature ($T_{oes}$), $T_{rectal}$ and $T_{muscle}$ during submaximal exercise performed for 1 hour. Muscle temperature was consistently higher across submaximal exercise (Table 2.4); displaying the greatest increase from rest to exercise of 2.92°C compared to an increase of 1.94°C in $T_{oes}$ and 2.05°C in $T_{rectal}$. The study also highlighted that a difference of 0.7°C was always present between $T_{oes}$ and $T_{muscle}$ at all measurement stages.

A more recent comparison of $T_{muscle}$ and $T_{oes}$ has been completed by Kenny et al. (2003). Both $T_{muscle}$ and $T_{oes}$ were measured before, during and after exercise. Subjects rested in an upright seated position for 60 minutes in an ambient condition of 22°C, performing 15 minutes of isolated bilateral knee extensions (60% $VO_2max$) followed by 60 minutes recovery. Resting $T_{oes}$ was 36.80°C whereas resting $T_{muscle}$ at the deepest sensor ($T_{m10}$) was 36.14°C, the additional muscle sensors at 15mm ($T_{m25}$) and 30mm ($T_{m40}$) from the tip measured 35.86°C and 35.01°C respectively. Therefore it was identified that the $T_{muscle}$ to $T_{oes}$ gradient was equal to -0.66, -0.94 and -1.79°C in relation to $T_{m10}$, $T_{m25}$ and $T_{m40}$. Oesophageal temperature then increased gradually reaching a maximal rate of 0.55±0.02°C·$min^{-1}$ between 6 and 9 minutes of exercise; however it remained consistently lower than the increase in $T_{muscle}$. A rapid decrease was then observed (-0.04°C·$min^{-1}$) during the initial minutes after the cessation of exercise. After the initial 5 minutes, $T_{oes}$ was 0.35°C above baseline, by the end of the 60 minutes $T_{oes}$ was 0.3°C above baseline (i.e. majority of temperature decrement occurred during the first 5 minutes). Whereas $T_{muscle}$ increased by 2.00, 2.37 and 3.20°C for $T_{m10}$, $T_{m25}$ and $T_{m40}$, remaining elevated above baseline at 0.92, 1.05 and 1.77°C $T_{m10}$, $T_{m25}$ and $T_{m40}$, respectively at the end of recovery.

**Table 2.4**: A comparison of temperature measurements taken at rest and across submaximal exercise over a 1 hour period

| | Oesophageal (°C) | Rectal (°C) | Muscle (°C) |
|---|---|---|---|
| Rest | 36.55±0.27 | 36.61±0.26 | 36.28±0.28 |
| Submax I | 37.29±0.21 | 37.41±0.20 | 37.97±0.33 |
| Submax II | 38.01±0.12 | 38.15±0.09 | 38.71±0.37 |
| Submax III | 38.49±0.24 | 38.65±0.18 | 39.20±0.45 |

Mean±SD (Saltin & Hermansen, 1966)

It is difficult to draw any firm comparisons between the study completed by Saltin & Hermansen (1966) and Kenny et al. (2003) as the depth of muscle thermister for data collection was not stated within Saltin & Hermansen's (1966) study. The variation in muscle thermister and rectal probe depth identify reasoning for the conflict of results in previous studies. As a result, it is difficult to draw firm conclusions due of the effects of $T_{muscle}$ and $T_{core}$ on performance and the disagreement as to which one influences performance. It appears an increase in $T_{muscle}$ occurs in parallel to an increase in $T_{core}$; however, if $T_{core}$ increases too dramatically then this may be a limiting factor to performance, whereas elevated $T_{muscle}$ potentially increases force of contraction and consequently improves performance. Standardisation of muscle and rectal depth measurement needs to occur within future studies to draw accurate comparisons.

### 2.6.2 Validity of intestinal core temperature measures

Rectal and oesophageal temperatures are widely accepted measurements of $T_{core}$ but are a cause of discomfort and are unlikely to be accepted by users (Lim, Bryne & Lee, 2008). Gastrointestinal temperature ($T_{GI}$), measured using an ingestible temperature sensor, has been reported to provide an acceptable level of accuracy as a measure of $T_{core}$ without causing discomfort to the user (Lim et al., 2008), whilst allowing continuous measurement within the field. The telemetry systems offer a means to monitor $T_{core}$ using a swallowed pill as a sensor which transmits temperature information to outside the body, detected by a hand-held monitor. A meta-analysis completed by Bryne & Lim (2007) investigated the agreement between $T_{GI}$, $T_{rectal}$ and $T_{oes}$. The results established that a stronger agreement exists between $T_{GI}$ and $T_{oes}$ than between $T_{GI}$ and $T_{rectal}$ (Figure 2.7), highlighting $T_{GI}$ responds faster to changes in temperature than rectal measurements (Byrne & Lim, 2007). Within this analysis, to ensure the temperature sensor was sufficiently in the gastrointestinal tract, the temperature sensor was swallowed 4 to 8 hours before measurement as readings can be influenced by water and food intake if the sensor is ingested too near the time of measurement (Wilkinson et al., 2008).

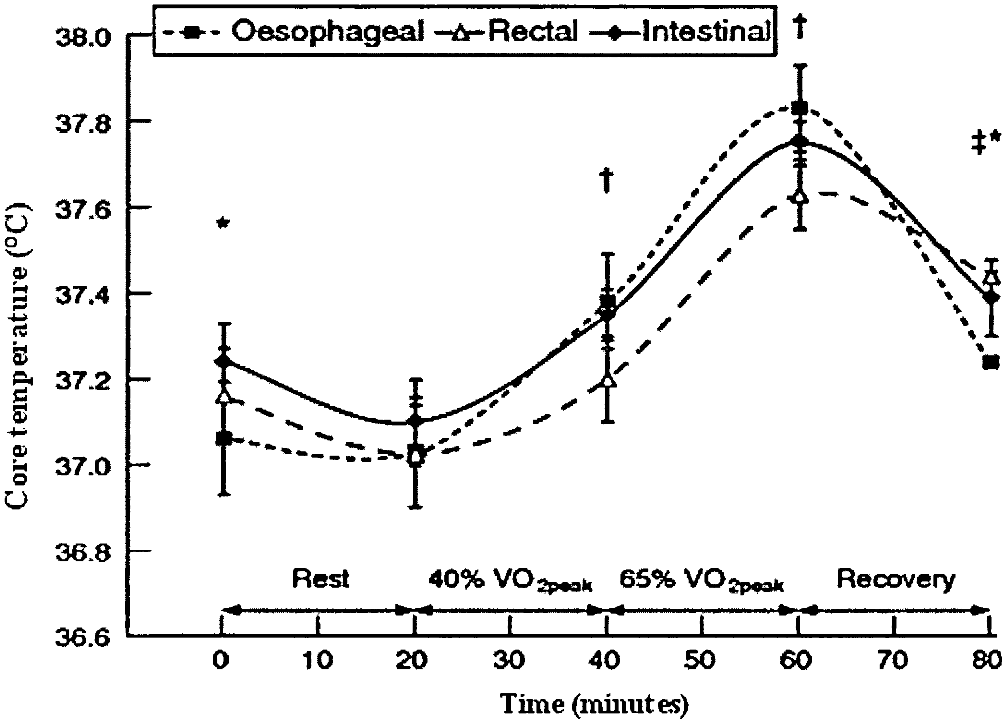

**Figure 2.7:** Oesophageal, rectal and intestinal temperatures measured simultaneously during rest, submaximal cycling at 40% and 65% $VO_{2peak}$ and during passive recovery. Values are mean±SE. *Intestinal temperature significantly higher than oesophageal temperature ($P<0.05$), † rectal temperature significantly lower than oesophageal temperature ($p<0.05$), ‡ rectal temperature significantly higher than oesophageal temperature ($p<0.05$) (Bryne & Lim, 2007)

Supplementary studies have revealed mixed findings on the positive and negative direction of bias between the telemetry pill and $T_{rectal}$. Two studies have determined that $T_{rectal}$ reads significantly higher (by 0.18°C and 0.76°C) than $T_{GI}$ (Kolka et al., 1993; Sparling, Snow & Millard-Stafford, 1993). Whereas two studies identified $T_{rectal}$ was significantly lower than $T_{GI}$ (by -0.07°C and -0.20°C) ($p<0.05$) (Lee, Williams & Schneider, 2000; Gant, Atkinson & Williams, 2006). Furthermore, McKenzie & Osgood (2004) reported no significant differences in mean $T_{rectal}$ (36.96°C) and $T_{GI}$ (36.93°C). This is supported by the review completed by Byrne & Lim (2007) who reported that ingestible telemetric temperature sensors have previously shown to provide valid results of $T_{core}$. Within this review, it was identified that ten of twelve validation studies (83%) reported levels of agreement supporting the conclusion that $T_{GI}$ provides a valid index for $T_{core}$.

Furthermore, the telemetry pill is accepted to be valid when $T_{core}$ is increased, decreased or at a steady state, accurate to within ±0.1°C of the criterion standard (O'Brien, Hoyt & Buller, 1998). O'Brien et al. (1998) compared the agreement between $T_{core}$ measurements obtained using an ingestible temperature pill telemetry system with those obtained from rectal and oesophageal thermocouples under conditions of both increased and decreased $T_{core}$. The study investigated nine subjects, required to swallow the temperature pill 10 to 12 hours prior to testing after which subjects fasted. Four trials were incorporated, creating conditions of constant, decreasing or increasing $T_{core}$. Root mean squared deviation was calculated; zero indicated perfect agreement between measures. Root mean squared deviation of the temperature pill and the $T_{oes}$ ($0.23\pm0.04$) was lower than for the temperature pill and $T_{rectal}$ ($0.43\pm0.10$). The telemetry pill temperature and response time was midway between $T_{rectal}$ and $T_{oes}$. These results propose the telemetry pill system provides a valid measurement of $T_{core}$ during conditions of decreased as well as elevated $T_{core}$ and during steady state. The telemetry pill system is of great advantage providing an alternative to the invasive methods of $T_{oes}$ and $T_{rectal}$ that also involve wired connections (O'Brien et al., 1998).

Additionally, Kolka et al. (1993) reported $T_{oes}$ and $T_{GI}$ reached a steady state faster during moderate exercise than $T_{rectal}$. Within this study, $T_{GI}$ was extensively compared to $T_{oes}$ and $T_{rectal}$. At rest, the $T_{GI}$ did not differ from $T_{oes}$, but was 0.2°C lower than $T_{rectal}$, a trend which continued during moderate exercise. Upon arrival of the experimental trials, eight male subjects were required to swallow the telemetry pill with water and a light breakfast, the rectal probe was then inserted to a depth of 10cm and an oesophageal probe was also inserted. Two hours after swallowing the telemetry pills the subjects were taken to the environmental test chamber to complete a 40 minute cycle at 40% peak $VO_2$ followed by a 15 minute rest, before three cycles at 80% $VO_2$ peak were completed; allowing detection of rapid change in the ingestible pill. Average resting temperatures were reported; $T_{oes}$ was 36.66±0.26°C, the $T_{GI}$ was 36.75±0.29°C and $T_{rectal}$ was 36.94±0.22°C. The rate of increase in $T_{core}$ (°C·min$^{-1}$) during moderate exercise was higher for $T_{oes}$ (0.050±0.013°C·min$^{-1}$) than for the temperature pill (0.031±0.014°C·min$^{-1}$) and $T_{rectal}$ (0.018±0.005°C·min$^{-1}$). The time to observe a 0.1°C change during exercise or rest from exercise was also calculated. Oesophageal temperature increased from 4.4±2.7 minutes after the start of moderate exercise compared to 7.5±4.8 minutes for the temperature pill and 12.3±3.0 minutes for the $T_{rectal}$ (Table 2.5). The telemetry temperature pill responded to changes in body temperature, reaching a steady state faster than $T_{rectal}$. Gastrointestinal temperature was revealed to be abnormally low during moderate exercise; this is potentially explained through the sensor still being located in the stomach as it was only ingested 2 hours prior to testing. Recent research has published a recommended pill ingestion time of 4 to 8 hours prior to testing as previously discussed (Wilkinson et al., 2008). However, the pill's response improved markedly as the experiment continued, presumably as the pill become located in the intestines. The telemetry systems as a $T_{core}$ data acquisition system was reliable provided that preliminary screening by water bath calibration eliminated those sensors which measured temperature inaccurately. However, as divulged by Kolka, Levine & Stephenson (1997) rarely was a sensor inaccurate.

The research undertaken by Kolka et al. (1997) investigated $T_{core}$ measured by $T_{oes}$ and a swallowed telemetry sensor in women during exercise when wearing clothing with high thermal resistance. The combination of exercise, clothing and ambient temperature (30°C) caused $T_{oes}$ to increase to 38.67±0.28°C and the temperature pill ($T_{GI}$) to increase to an average of 38.71±0.33°C during an hour of treadmill walking. Within this investigation the temperature pills were calibrated and then swallowed 2±0.5 hours prior to testing. Gastrointestinal temperature was not significantly different from $T_{oes}$ during exercise and the total change in $T_{GI}$ during the 60 minute experiment was not significant, thus opposing the result of the previous study completed by Kolka et al. (1993). The temperature sensor therefore provides an accurate, usable $T_{core}$ data device during logistically difficult experimental conditions in comparison to the obtrusive oesophageal method (Kolka et al., 1997).

Similarly, Gant et al. (2006) investigated both validity and reliability of $T_{GI}$ during prolonged intermittent shuttle running. Within the reliability measures, nine men performed two 90 minute bouts of shuttle running separated by seven days, $T_{rectal}$ and $T_{GI}$ (ingested 10 hours prior) were monitored. The mean systematic bias of -0.15°C was stated between $T_{rectal}$ and $T_{oes}$ during exercise (Gant et al., 2006), with the limits of agreement (LOA) analysis recognising no significant bias (-0.01°C) and 95% LOA of -0.22°C to +0.24°C indicating reliability of this measure. The mean change between repeated trials was negligible 0.01°C (Gant et al., 2006), concluding the telemetry pill system provides an accurate measurement of $T_{core}$.

Literature has recognised limitations of the telemetry pill concerning the location of the pill in the intestinal tract which may affect the temperature and measured response (Edwards & Clark, 2006). In the early stages of digestion, the pill is located in the stomach or the upper intestinal tract, in this location measurements could be influenced by the ingestion of food, saliva or liquid (Edwards & Clark, 2006). Previous studies have reported subjects to swallow the pill 2 to 3 hours before data collection and these reports suggested that pill temperature could be subject to variation as it passes through the intestinal tract (Kolka et al., 1993; Kolka et al., 1997). O'Brien et al. (1998) suggested that greater stability of measurement could be achieved 12 hours after pill ingestion, however this can be impractical. In comparison, Sparling et al. (1993) acknowledged no difference between $T_{rectal}$ and $T_{GI}$ when subjects swallowed the pill 3 to 4 hours before exercise than those who swallowed the pill 8 to 10 hours before testing. Therefore, presence of water in the stomach or meal ingestion will most likely only affect the pill if taken < 3 hours prior to testing.

**Table 2.5**: A comparison of the time course and rate of $T_{core}$ change at the onset or cessation of exercise when measured at intestinal and rectal sites

| | Intestinal | Rectal |
|---|---|---|
| **Time for 0.1°C change from start of exercise (minutes)** | | |
| Kolka et al.,1993 | 7.5±4.8* | 12.3±3 |
| Kolka et al., 1993 | 3.8±1.5* | >0.5±0 |
| Lee et al., 2000 | 14±1.2 | 15.7±1.6 |
| **Rate of change during exercise (°C/min)** | | |
| Kolka et al., 1993 | 0.031±0.014 | 0.018±0.005 |
| Kolka et al.,1993 | 0.066±0.035* | 0.018±0.009 |
| Lee et al., 2000 | 0.021±0.004 | 0.016±0.004 |
| **Time to steady-state temperature during exercise (minutes)** | | |
| Kolka et al., 1993 | 25.2±9.1* | 37.3±4.6 |
| **Time for 0.1°C change from end of exercise (minutes)** | | |
| Kolka et al., 1993 | 6.5±3.1 | 12.2±3.3 |
| Lee et al., 2000 | 7.1±1.5 | 10.6±1.9 |
| **Rate of change during recovery (°C/min)** | | |
| Lee et al., 2000 | -0.023±0.003* | -0.010±0.003 |

*indicates significantly ($p<0.05$) different from rectal measurement (Adapted from Byrne & Lim, 2007)

**Table 2.6**: Summary of studies comparing the agreement between $T_{core}$ measurements recorded simultaneously from an ingestible telemetric temperature sensor and an oesophageal and/or rectal probe

| **Author** | **Comparison** | **Subjects** | **Protocol** | **Valid** | **Rectal vs Intestinal LoA** | **Bias ±95%** |
|---|---|---|---|---|---|---|
| Ducharme et al., 2001 | Rectal | 11 males | Rest, walking, running | Yes | | |
| Gant et al., 2006 | Rectal | 19 males & females | Intermittent shuttle running | Yes | -0.37 to +0.07 | -0.15 |
| Kolka et al., 1993 | Oesophageal, rectal | 8 males | Cycling | No | -0.27 to + 0.65 | +0.18 |
| Kolka et al. 1997 | Oesophageal | 4 females | Running, treadmill | Yes | | |
| Lee et al., 2000 | Oesophageal, rectal | 7 males & females | Rest, cycling | Yes | -0.41 to +0.27 | -0.07 |
| McKenzie & Osgood, 2004 | Rectal | 10 males & females | Circadian monitoring | Yes | | |
| O'Brien et al., 1998 | Oesophageal, rectal | 9 males & females | Resting, cycling | Yes | | |
| Sparling et al., 1993 | Rectal | 6 males | Running, cycling | No | +0.88 to +1.44 | +0.76 |

(Adapted from Byrne & Lim, 2007)

### 2.6.3 The influence of body fat for heat maintenance

Heat dissipation varies between individuals depending on their sweat rate, body composition and size (Zochowski et al., 2007). Marino et al. (2000) researched the advantages of a smaller body mass during distance running in sixteen highly trained runners, quantified by heat storage capacity measured from $T_{rectal}$ and mean $T_{skin}$. A lower body mass may have a distinct thermal advantage in which heat dissipation mechanisms are at their limit before athletes with higher body mass, therefore lighter runners produce and store less heat at the same running speed. Although advantageous during exercise, athletes with a lower body mass may experience a greater heat loss in the period between WU and the event thus having a negative influence on performance. For instance, Chudecka & Lubkowska (2010) investigated the effect of physiological and morphological factors on changes in $T_{skin}$ within a handball training session. Body composition was obtained prior to the completion of training through skinfold measurements and bioimpedence, with percentage of body fat ranging from 5.6-34.1%. A statistically significant relationship was established between estimated body fat percentage values and the rate of temperature loss after exercise; individuals with higher estimated percentage body fat values cooled significantly slower than those with lower levels of body fat (Chudecka & Lubkowska, 2010). However, it is important to acknowledge only $T_{skin}$ was measured within this research, subsequently it cannot be assumed that similar responses would be observed when investigating the role of $T_{core}$ change.

Similarly, Xu et al. (2007) investigated the relationship between body fat percentage and heat maintenance, additionally measuring $T_{core}$ within males when submersed in cold water of 10°C and 15°C. Subjects were divided into a normal fat (15.0-19.0%) or low fat group (<14.7%); results recognised that individuals with normal body fat retained heat more efficiently than those with low percentages of body fat. This finding therefore suggests that a greater percentage of body fat may positively correlate to the maintenance of $T_{core}$.

Keatinge (1960) supports this result, investigating the effectiveness of adipose tissue as an insulative layer in preventing heat loss in water. A group of subjects were immersed into 15°C water for 30 minutes and compared skinfold thickness to heat losses from the body as measured by $T_{rectal}$. A linear relationship between the amount of body heat loss and the reciprocal of the skinfold thickness was observed, thus supporting the research conducted by Xu et al. (2007).

### 2.6.4 Summary

Comparison of temperature results can be difficult due to the variation in $T_{muscle}$ or $T_{core}$. Literature has highlighted that $T_{muscle}$ is usually elevated above $T_{core}$, with variation in responses following exercise and also recovery. It appears $T_{core}$ increases gradually in comparison to $T_{muscle}$ during exercise, yet displays a greater decrease initially after the cessation of exercise. Furthermore, differences in the measurement protocols regarding the depth of insertion for both rectal probes and muscle thermisters provides further variation in the results that should be considered when reviewing the literature.

When focusing on temperature measurement, $T_{GI}$ measured using the ingestible temperature sensor has been reported to provide an acceptable level of accuracy, without causing the discomfort associated with rectal and oesophageal measurements. Reviews have established that the ingestible telemetric sensor is a valid measure of $T_{core}$, with 83% of a validation study reporting levels of agreement. Furthermore, the telemetry pill has been accepted to be valid when $T_{core}$ is increased, decreased or at a steady state, responding faster for a 0.1°C change from the start of exercise than rectal measurements. The ingestible pill has also displayed a negligible change in temperature between repeated trials, concluding it provides reliable measurements. The literature has recognised limitations of the telemetry pill concerning its location in the intestinal tract and subsequent influence water and food ingestion may have. However, if taken >3 hours prior to testing the pill does not seem to be affected.

Consideration also needs to be provided to the influence of body fat on heat maintenance; a lower percentage of body fat results in an increased amount of body heat lost to the surrounding environment. Athletes with a lower percentage of body fat and/or skinfold thickness would therefore need additional mechanisms during recovery periods to prevent a reduction in $T_{core}$.

## 2.7 Conclusions

Despite the advantageous effect of completing an active WU prior to completing sporting performance, sometimes the logistics and regulations of competitions prevent the achieved benefits of an active WU to be optimised. Lengthy time delays or rest periods between the completion of an active WU and performance allow $T_{muscle}$ and/or $T_{core}$ to return below a normal physiological range. If the opportunity is present to complete a re-WU or utilise passive heating techniques (e.g. water baths), this appears to prevent the significant decreases observed. However, in sports such as swimming when strict marshalling rules are enforced, alternative passive heat maintenance devices, as reported within the medical literature, may provide an alternative mechanism to maintain temperature elevations achieved from an active WU, improving subsequent performance. Prior to implementation, these techniques need to be investigated within a sporting environment.

# Chapter 3 – Method

## 3.1 Experimental approach to the problem

A recently conducted study has demonstrated an improvement in swimming performance of 1.5±1.1% following a 20 minute recovery period compared to a 45 minute recovery period between the completion of warm-up (WU) and subsequent time trial (TT) performance (West et al., In Press). The authors attributed the improvement in performance to the enhanced core temperature ($T_{core}$) maintenance observed during the 20 minute trial, however, despite the greater $T_{core}$ maintenance, a reduction in $T_{core}$ was still evident over the 20 minute recovery period. Therefore, within the present study, a passive heat maintenance strategy (Blizzard survival heat jacket) was implemented with the aim of minimising the decrease in $T_{core}$ during the 20 minute recovery period. The study consisted of two interventions; (1) a control condition and (2) a passive heat maintenance condition. Both conditions were followed by a TT completed in the swimmers preferred competition event (distance and stroke specific) under simulated race conditions. Measurements of heart rate (HR), rate of perceived exertion (RPE), blood lactate and intestinal $T_{core}$ were also recorded at the following time points; pre WU (baseline), post WU, pre-TT, immediately post-TT and 3 minutes post-TT.

## 3.2 Participants

Twelve elite swimmers aged 18-24 (Table 3.1) from the British Swimming Intensive Training Centre (ITC) in Swansea, Wales, participated in this study. All participants had at least 9 years of competitive swimming experience and had previously represented their country at both national and international senior events. Testing was conducted in a stable phase of training to minimise week-to-week variations in training volumes; weekly training consisted of five land-based training sessions in addition to ten swimming sessions covering 60,000 to 65,000m per week (Appendix A; Table 1).

Prior to participant recruitment, the study was approved by the University ethics committee (refer to Appendix B). Participants were given verbal and written descriptions of the experiment and were fully informed of the risks and discomforts associated with the experiment prior to obtaining their written informed consent to participate (subject information sheet and informed consent, Appendix C & D). The American College of Sports Medicine pre-participation screening questionnaire (AHA/ACSM, 1998) was also completed in advance of testing (Appendix E). All participants had previously been involved in research and were familiar with testing procedures; nonetheless participants were still informed they could withdraw from testing at any stage. The participants maintained a consistent diet throughout the experiment and refrained from alcohol 24 hours before testing.

### 3.3 Experimental procedure

The study followed a repeated measures crossover design, with each participant completing two TT (i.e. passive heat maintenance condition versus control condition), separated by a seven day interval. Trial order was randomised and counterbalanced, with all testing sessions carried out in an Olympic 50m swimming pool, lasting 95 minutes in total. To control for varying levels of weekly fatigue, testing was conducted on the same day of the week and also at the same time of day (14.35-16.00) to eliminate the hormonal and temperature effect associated with the circadian rhythms. Water and air temperature at the swimming pool were consistent throughout the testing period, maintained at 28.57±0.05 and 27.54±0.27°C respectively.

On arrival for the experimental trials, stature and body mass measurements were recorded after which participants rested for 10 minutes before pre-WU (baseline) measures of HR (Polar FT1; Polar Electro, Finland), RPE, capillary blood lactate (Biosen C-Line Sport, EFK-diagnostic GmgH, Barleben, Germany) and $T_{core}$ (CorTemp$^{TM}$; HQ Inc, USA) were taken. During this time participants were familiarised with the trial procedures. Once the baseline measures were collected, participants entered the water and completed a standardised, race specific, 36 minute WU as prescribed by the ITC head coach (Table 3.2). Warm-up intensity was monitored using HR and blood lactate measurements; this results from authors suggesting that an elevation in blood lactate concentration may provide a marker of appropriate training intensities (e.g. Weltman et al., 1992; Henritze et al., 1985). Furthermore, reports have suggested that metabolic reference points occur not only at different blood lactate concentrations, but also at different HR values (Bishop, 2004). Therefore, HR and blood lactate are accepted and verified measures of WU intensity. For example, Bishop et al. (2001) determined two WU intensities at aerobic threshold and anaerobic threshold by measuring blood lactate with HR providing additional measurement to verify the intensity. Yaicharoen et al. (In Press) further investigated the effect of WU intensity on sprint performance; the WU intensities were determined using physiological measurements of HR and lactate. Therefore the literature has demonstrated that HR or blood lactate can be used to accurately monitor intensity and consequently are commonly used by coaches and athletes to monitor intensity (Bishop, 2004).

Following the completion of the WU, participants rested for 20 minutes within a call room environment. This was in accordance with the guidance of the British Swimming protocol for a call room, produced in consultation with FINA and LEN technical swimming committee members. It was stated that the call room should be a contained and controlled area, with an entrance ideally in close proximity to, but not connected to the athlete area. The call room should also contain an exit with direct access to pool deck, whilst also containing seating for the athletes in a previously identified number of races (http:// www.swimwest.org/region/index.php?/news/educate/officials/britishswimmingprotocolforacallroom). The current study simulated these conditions, the call room was located off the pool deck but with the door leading immediately onto poolside and air temperature and humidity aimed to replicate competition conditions (air temperature was consistent with previously reported poolside air temperatures), despite no set conditions being specified within the British Swimming protocol. All participants were seated in this area within the 20 minute rest period, walking directly on to the pool deck behind the racing blocks to maintain consistency with protocols implemented during swimming competitions. During this time participants were exposed to two conditions; (1) a control trial incorporating clothes worn during rest at competitions (e.g. tracksuit bottoms, jumpers, socks and shoes) or (2) an experimental condition integrating a passive heat maintenance device (i.e. Blizzard Survival heat jackets). Blizzard Survival UK developed customised, full length heat jackets to be integrated into competition strategies to optimise WU preparation for British Winter sport athletes. The heat jackets were designed to improve performance by maintaining body temperature during recovery periods between WU and competitive racing. The jackets incorporated Reflexcell technology; reported to provide insulation due to the cellular construction of the material that traps warm air whilst also reducing heat loss through two primary mechanisms; convection and radiation (http://www.blizzardsurvival.com). The Reflexcell technology is manufactured to the same standard as verified by testing of the thermal properties completed within the laboratory. Blizzard conducts in-house tests and independent tests are also conducted by Leeds University. Thermal performance is measured in Togs, a unit of thermal resistance commonly used within textiles manufacturing, both in-house and independent tests identified 8-9 Togs worth of thermal resistance, identifying that the jackets can be re-used may times without loss of performance (http://www.blizzardsurvival.com). In addition, research completed with 20 rugby league players has identified that the Blizzard jackets maintained $T_{core}$ over a 15 minute rest period in all players compared to a control condition, demonstrating an average decrease in $T_{core}$ of 0.19±0.08°C in the passive heat maintenance condition versus 0.55±0.10°C within the control condition, respectively ($p<0.001$).

Further measurements were then taken prior to participants completing a maximal effort TT.

In total, physiological measurements (HR, RPE, blood lactate and $T_{core}$) were taken at five time points; pre-WU (baseline), immediately post WU, pre-TT following a 20 minute rest period, immediately post-TT and 3 minutes post-TT, a time course of events is illustrated in Figure 3.1.

**Table 3.1**: Physiological characteristics of the participants

| | Number of Participants | Age (yrs) | Mass (kg) | Height (cm) | Percentage of body fat (%) | Sum of skinfolds (mm) |
|---|---|---|---|---|---|---|
| Male | 8 | 20.88±2.75 | 78.28±5.86 | 184.28±6.09 | 5.42±1.02 | 44.7±3.90 |
| Female | 4 | 20.75±0.50 | 62.03±2.28 | 172.65±2.76 | 9.84±1.69 | 62.07±6.27 |

Data presented as Mean±SD

Sum of skinfolds – taken from 7 measurement sites (Appendix F); Percentage of body fat – calculated from the tricep, thigh and suprailliac measurement sites

**Table 3.2**: Standardised race specific warm-up protocol

| Warm up Protocol |
|---|
| 200 swim |
| 4 x 50m of 50s: Pull – Drill – Kick – FR Swim (PB + 5 ) |
| 4x 50m of 50s: Drill – Kick – FR swim (PB + 5)- pull |
| 2x (no1 stroke): |
| 15m race pace effort, 35m swim off 45s |
| 25m race pace effort, 25m swim off 45s |
| 35m race pace effort, 65m swim off 1:30 |
| 15m near max effort kick, 35m swim off 45s |
| 25m near max effort kick, 25m swim off 45s |
| 35m near max effort kick, 65m swim off 1:30 |
| Race pace: 3x50 des on 1:15, +5 +3 +1 (No 1 stroke) |
| 100 easy off 1:30 |
| Race pace: 3x50 des on 1:15, +5 +3 +1 (No 1 stroke) |
| 100 easy off 1:30 |
| Race pace: 3x50 des on 1:15, +5 +3 +1 (No 1 stroke) |
| 50 easy |

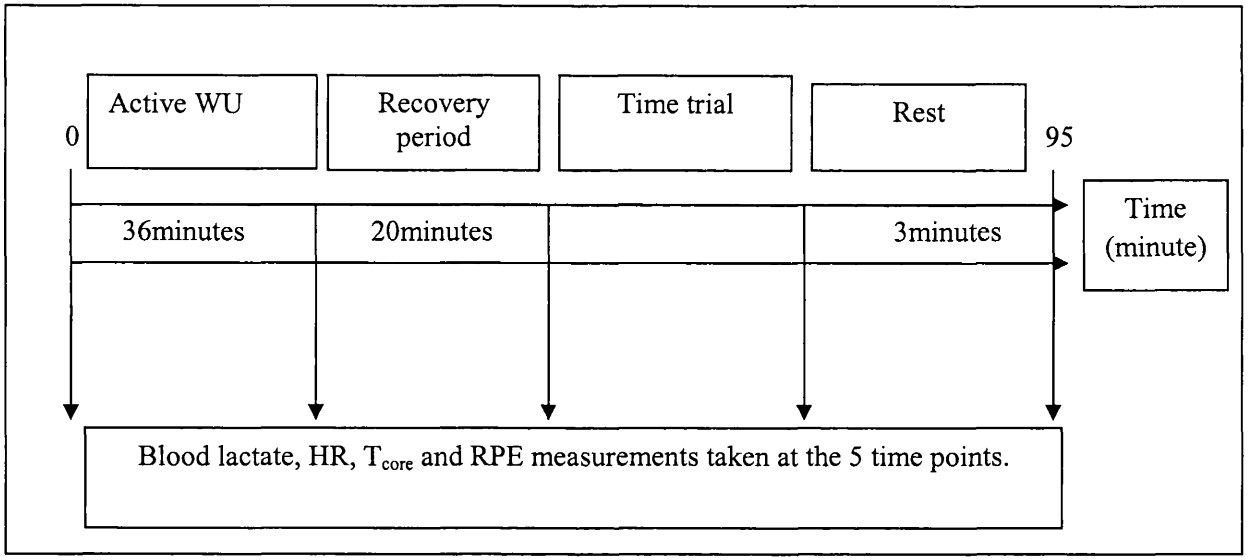

**Figure 3.1:** Overview of the experimental design

### 3.4 Body composition measurements

Prior to the main experimental trials commencing, anthropometric measurements consisting of height, weight and skinfold measurements were completed to determine participants' percentage of body fat and the sum of skinfolds. The skinfold measurements were taken at seven sites (triceps, biceps, subscapular, iliac crest, supraspinale, front thigh and medial calf – Appendix F), all of the measurements were completed by the same individual using the International Society for the Advancement of Kinanthropometry (ISAK) protocol. The Siri (1956) equation (Durnin & Womersley, 1974) was applied to calculate percentage of body fat:

Percentage body fat (%) = (495/D) - 450

Where D = body density ($g.cm^{-3}$) calculated using:

Men (18-60years) $D = 1.10938 - 0.0008267x + 0.0000016x^2 - 0.0002574y$

Women (18-55years) $D = 1.1099421 - 0.0009929x + 0.0000023x^2 - 0.0001392y$

Where y = age (years), x = sum (triceps, thigh and suprailiac skinfold in mm)

### 3.5 Physiological measurements

*Core Temperature measurement.* To measure $T_{core}$, participants swallowed an ingestible telemetric temperature sensor (CorTemp™ Ingestible core body temperature sensor; HQ Inc, USA) which transmitted a radio signal to an external monitor (CorTemp™ Data recorder; HQ Inc, USA). Participants were required to ingest the sensor 3 to 4 hours prior to testing to ensure transit beyond the stomach, preventing measurements being influenced by the ingestion of food, saliva or liquid (Edwards & Clark, 2006). To ensure $T_{core}$ was not affected by water consumption throughout the current study, participants were required to ingest water before the initial baseline measurement to confirm the pill was located in the intestine as opposed to the stomach.

Prior to data collection, the sensors were calibrated in a water bath at four different water temperatures against a mercury thermometer. Published research has verified precision and accuracy can be confirmed by comparing temperature against a calibrated thermometer across a physiologically valid range of water bath temperatures (Byrne & Lim, 2007).

The ingestible telemetric system provides valid results and an acceptable level of accuracy as a measure of $T_{core}$ without causing the discomfort caused by rectal ($T_{rectal}$) and oesophageal temperature ($T_{oes}$) measurements (Lim, Byrne & Lee, 2008). Existing literature highlights that the telemetry pill is accepted to be valid when $T_{core}$ is increased, decreased or at a steady state, accurate within ±0.1°C of the criterion standard (rectal temperature - $T_{rectal}$) (O'Brien, Hoyt & Buller, 1998). The telemetric pill has also proven to be reliable; the limits of agreement (LOA) analysis performed by Gant, Atkinson & Williams (2006) recognised no significant bias (-0.01°C; $p<0.05$) and 95% LOA of -0.24°C to +0.22°C, indicating an acceptable level of reliability.

*Blood Lactate measurement.* In order to obtain capillary blood samples, a small incision was performed on the fingertip using a single-use disposable lancet (Accu-check, Roche Diagnostics, GmbH). After applying gentle pressure to the finger a blood sample was collected in a capillary tube taking a volume of 20µl (Davison et al., 2000), this was immediately placed in a pre-filled reaction tube, mixed with a lysing stabilising agent in a safe-lock vial (Davison et al., 2000). The sealed vial was shaken and labelled for later analysis, as reports identify resting and maximal exercise blood samples remain stable for up to 20 hours, whether stored at room temperature in a sealed vial or exposed to the air (Davison et al., 2000). The blood sample was analysed for lactate using an automated lactate analyser (Biosen C-Line Sport, EFK-diagnostic GmgH, Barleben, germany). Prior to each testing session the analyser was calibrated with a standard known solution ($12 mmol \cdot L^{-1}$) before any analysis was carried out (Davison et al., 2000). Previous research has identified the Biosen as a valid and reliable analyser for a full range of blood lactate values ranging from $0.85 mmol \cdot L^{-1}$ (resting) to $16.37 mmol \cdot L^{-1}$ (maximal), with samples remaining stable when sealed in a vial for up to 18.8 hours (Davison et al., 2000).

*Heart rate and Rate of Perceived Exertion.* A polar HR monitor (Polar FT1; Polar Electro, Finland) was utilised to record HR during WU whilst participants remained in the water, allowing WU intensity to be monitored. The polar HR monitor is a wireless device, consisting of a transmitter and a receiver (Achten & Jeukendrup, 2003). For the remaining HR measurements participants remained on poolside whilst a polar HR monitor was placed on the chest to obtain a recording. At each measurement point HR was recorded for 1 minute, therefore taking four readings at 15 second intervals. A mean of the four readings was recorded.

Ratings of perceived exertion were recorded using the twelve point Borg scale (1982) (Appendix G). Participants were asked to rate the difficulty of work experienced on a scale of 6 to 20 extending from extremely light to maximal effort.

### 3.6 Performance measurement

Participants were required to complete a TT of their preferred swimming event at maximal effort. Of the eight male participants, all completed 200m, three swimming freestyle, two as backstroke, one as breaststroke, one as fly and one completed this on individual medley (IM). Of the four female participants, one swam 200m freestyle, one swam 200m fly, one swam 100m backstroke and one completed 200m IM.

Race conditions were simulated with participants beginning with a dive off the race blocks, when in position the participants were given the verbal command 'take your mark' and shortly after the starting signal was sounded. Performance time was recorded manually using a stopwatch, the same experienced individual carried out the timing to minimise human error. Performance time was verified using the video recording of the TT, the start system was visible on the camera, allowing the strobe light to be used for synchronising the timing. The video recording also allowed for stroke rate (SR) to be determined:

$$\text{Stroke rate} = \frac{(\text{Number of complete strokes over 25m x 60})}{(\text{Time of hand entry 1} - \text{time of hand entry 2})}$$

Where hand entry 1 is the first hand entry at the start of 25m and hand entry 2 is the hand entry at the end of 25m, recorded in seconds.

This was repeated for each 25m of the TT, the Mean±SD was then calculated for each 50m. To ensure acceptable reliability of the SR measurement, intra-observer tests were completed. The analyst viewed two randomly selected TT performances ten times over a two week period under the same conditions. The coefficient of variation (CV) was calculated to identify the measurement error, this resulted in a low, acceptable percentage of error (CV=0.002%).

### 3.7 Statistical analyses

Data were analysed to identify any significant differences between the control condition and passive heat maintenance condition using the Blizzard survival heat jackets. Prior to analysis, data were screened for errors and parametric suitability. Tests of assumptions were carried out to check for normality and homogeneity of variance. As assumptions were not violated a t-test compared the conditions against the time to complete the TT. Data were analysed for main effects using a repeated-measures analysis of variance on two factors (condition and time). Where appropriate, paired sample t-tests were performed with Bonferroni adjustments to establish the location of any significant effect. Statistical analysis was completed using SPSS software (version 19; SPSS Inc., Chicago, IL), with significance set at $p<0.05$. Values are presented as Mean±SD.

In addition, it has been suggested that null hypothesis testing has limitations for assessing clinical or practical importance (Hopkins et al., 2009). The reliability of competitive performance of athletes in a given sport can provide an estimate of the smallest worthwhile change in performance, which is crucial when testing athletes and when assessing factors that affect performance in sport (Paton & Hopkins, 2005). The smallest worthwhile enhancement in performance can be important, as it corresponds to the modifications that make meaningful differences to the probability of an athlete winning (Paton & Hopkins, 2005).

This has previously been investigated by Hopkins, Hawley & Burke (1999), who performed mathematical simulations to assess the impact of performance enhancement on gold-medal prospects. Ten thousand events were simulated, each with an independent draw of fifteen athletes and in each of which a particular athlete (e.g. true fourth place in an Olympic final) was given a particular enhancement (e.g. 1.5xcoefficient of variation - CV). The chance of the athlete winning was calculated as the percentage of events in which the athlete placed first (Hopkins et al., 1999). The worthwhile enhancement was found to range from 0.3 to 0.7% depending on the grade of the athletes in question; for a top athlete an enhancement of at least 0.3% would be worthwhile, however 0.5% would be a more realistic representation of the typical within athlete variation in performance between events (Stewart & Hopkins, 2000). This is supported by research written by Hopkins et al. (1999) and Pyne, Trewin & Hopkins (2004) in which they use 0.5% as the meaningful value within elite swimmers. In summary, enhancement needs to overcome the variability in performance. Therefore a measure of the variability is necessary, best expressed as a CV.

Within the present study, practical significance was calculated by using variation between competition performances. The measure was the typical race-to race variation of an athlete's time, derived as a CV. Official results were obtained from the British Swimming website from swimming competitions for the same subjects involved in the study. The four most recent competition performances were used; any results post-dating 2010 were discredited due to the ban imposed on race suits. One-half of the CV was then calculated to identify if performance improvements from the experimental trials had overcome the typical between race variations.

# Chapter 4 – Results

## 4.1 Time trial performance

Analysis of time trial (TT) performance revealed an average time of 125.6±20.8 seconds compared to 126.7±21.3 seconds for the passive heat maintenance versus the control condition, respectively. The participants were 1.1±1.3 seconds faster ($p=0.013$; Figure 4.1 A & B) after the passive heat maintenance condition, which equates to a 0.8±1.0% improvement in performance. From Cohen's (1992) criterion, a small effect size (ES = 0.054) was established in the TT performance. When examining the TT performance in quartiles, except for the first quartile, an improvement in performance was evident in the passive heat maintenance condition as reflected in the cumulative times after each 50m (Table 4.1).

When examining the smallest worthwhile enhancement in performance for each participant, the observed change in performance within the passive heat maintenance condition overcame one-half of the variation between previous competition performance times in seven out of twelve participants (Table 4.2).

A two way repeated-measures ANOVA revealed a significant condition ($p=0.005$; $d=1$; $F=12.704$) and time effect ($p<0.001$; $df=3$; $F=9.652$) for stroke rate (SR), but a condition*time interaction was not established ($p=0.778$; $df=1.837$; $F=0.230$). Post hoc analyses identified that SR was significantly different between conditions during the second ($p=0.005$) and third ($p=0.012$) quartiles; the average SR for each condition was 43.8±2.1 in the control condition as opposed to 44.6±2.1 within the passive heat maintenance condition. A medium ES of 0.560 was established according to Cohen's (1992) standards used to evaluate effect sizes, therefore the passive heat maintenance condition had a medium effect on SR. A significant time effect was also identified for stroke count (SC) ($p=0.014$; $df=1.096$; $F=8.312$), but significance was not established between conditions ($p=0.268$; $df=1$; $F=1.377$) (Table 4.3).

**Table 4.1**: Comparison of the cumulative quartile performance times completed in the control and the passive heat maintenance condition

| Cumulative Distance (m) | Control (seconds) | Passive heat maintenance (seconds) | N | P value |
|---|---|---|---|---|
| 50 | 30.2±1.7 | 30.2±1.6 | 12 | 0.978 |
| 100 | 64.3±3.7 | 63.7±3.6 | 12 | 0.032 |
| 150 | 99.4±7.0 | 98.3±6.9 | 11 | 0.008 |
| 200 | 132.4±8.9 | 131.1±8.6 | 11 | 0.013 |

Data presented as Mean±SD

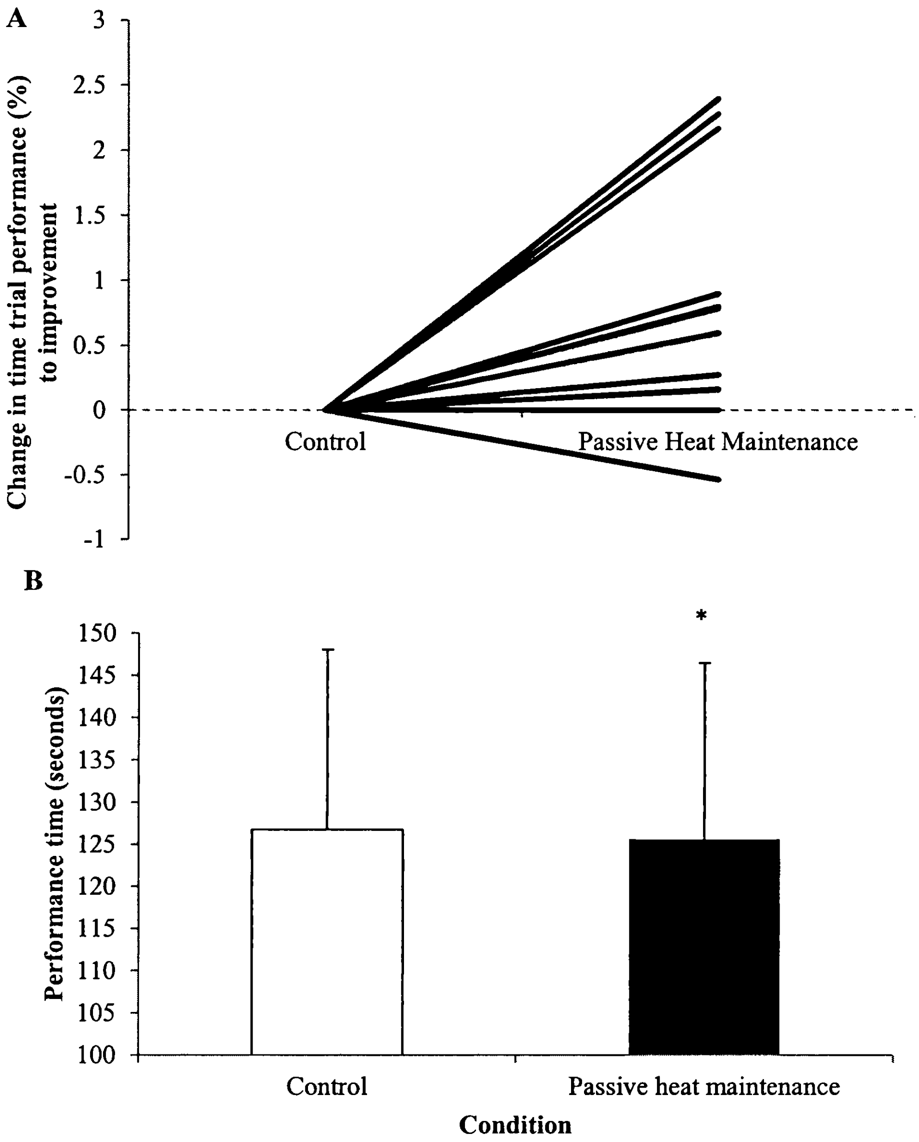

**Figure 4.1**: Change in TT performance (A) and the average performance in the swimming TT between a control and passive heat maintenance condition (B) * indicates significance between the control condition and the passive heat maintenance condition ($p<0.05$; n=12)

**Table 4.2:** The smallest worthwhile enhancement in performance required to overcome individual variation between previous competitions

| Subject | CV between competitions (%) | Smallest worthwhile enhancement (Hopkins et al., 1999) (%) | Change in performance (%) | Worthwhile enhancement |
|---|---|---|---|---|
| 1 | 1.74 | 0.87 | 0.00 | No |
| 2 | 1.30 | 0.65 | 0.78 | Yes |
| 3 | 0.65 | 0.33 | 0.16 | No |
| 4 | 0.21 | 0.11 | 0.16 | Yes |
| 5 | 1.46 | 0.73 | 2.40 | Yes |
| 6 | 0.78 | 0.39 | 0.59 | Yes |
| 7 | 1.00 | 0.5 | 0.27 | No |
| 8 | 0.71 | 0.36 | 2.28 | Yes |
| 9 | 1.57 | 0.78 | -0.54 | No |
| 10 | 1.28 | 0.64 | 2.17 | Yes |
| 11 | 3.98 | 1.99 | 0.80 | No |
| 12 | 1.18 | 0.59 | 0.90 | Yes |

CV; coefficient of variation

**Table 4.3:** The average SR and SC for each 50m of the performance TT

| | Condition | Stroke Rate | Stroke Count |
|---|---|---|---|
| 1st 50m | Experimental | 46.5±4.1 | 28.8±8.6 |
| | Control | 45.4±4.8 | 28.1±8.4 |
| 2nd 50m | Experimental | 42.6±5.4 * | 34.8±8.7 |
| | Control | 41.8±5.4 | 34.9±9.1 |
| 3rd 50m | Experimental | 42.9±5.9 * | 32.4±9.1 |
| | Control | 42.1±5.8 | 31.9±9.0 |
| 4th 50m | Experimental | 46.3±4.7 | 37.8±9.5 |
| | Control | 45.8±5.8 | 37.5±10.5 |

Data presented as Mean ±SD

### 4.2 Core temperature

Core temperature ($T_{core}$) responses are presented in Figure 4.2. Pre-WU (baseline) $T_{core}$ measurements were comparable between conditions (**Control** 37.13±0.43°C; **Passive heat maintenance** 37.28±0.37°C; p=0.188). Analysis of the data revealed a significant time effect for the $T_{core}$ response (p<0.001; df=4; F=8.191), but a condition*interaction effect was not established (p=0.900; df=4; F=0.263). The active warm-up (WU) produced a similar rise in $T_{core}$ in both conditions, increasing by Δ+0.87±0.43°C in the control condition and Δ+0.83±0.43°C within the passive heat maintenance condition (p=0.826). After 20 minutes (pre-TT), $T_{core}$ remained significantly elevated above baseline (**Control** 0.54±0.46°C; **Passive heat maintenance** 0.57±0.23°C; p<0.001), but a decline from post WU to pre TT under both conditions was observed (**Control** Δ-0.33±0.44°C; **Passive heat maintenance** Δ-0.25±0.38°C). Core temperature decreased further following the performance TT, before continuing to rise within the 3 minutes post TT (Figure 4.2).

### 4.3 Blood lactate

Measurement of blood lactate concentrations at pre-WU (baseline) identified similar results between conditions (**Control** 1.23±0.29mmol·L$^{-1}$; **Passive heat maintenance** 1.25±0.38mmol·L$^{-1}$; p=0.878). Temporal analysis indicated that blood lactate was significantly different across the five time points (p<0.001; df=1.495; F=250.832), however, there was no significant difference between the two conditions (p=0.287; df=1; F=1.252) (Figure 4.3). Blood lactate concentrations increased to a similar extent from baseline to post WU under both conditions (**Control** Δ+1.94±1.14mmol·L$^{-1}$; **Passive heat maintenance** Δ+1.86±1.14mmol·L$^{-1}$; p=0.671). Over the 20 minute rest period, a decline in blood lactate was observed (**Control** Δ-1.73±0.87mmol·L$^{-1}$; **Passive heat maintenance** Δ-1.61±0.89mmol·L$^{-1}$) before a significant increase post TT, remaining elevated after 3 minutes.

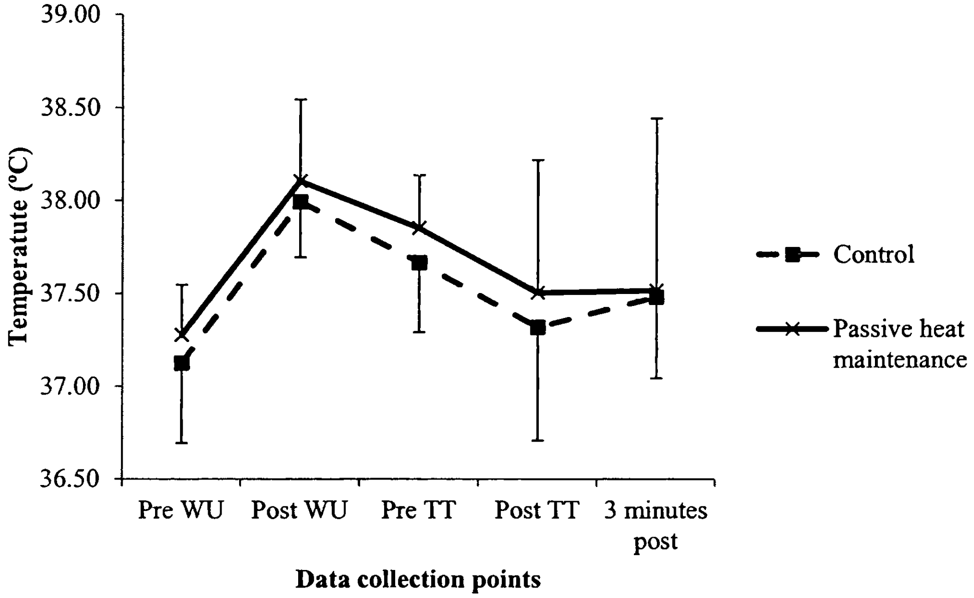

**Figure 4.2**: The $T_{core}$ response to the control and passive heat maintenance conditions (n=9)

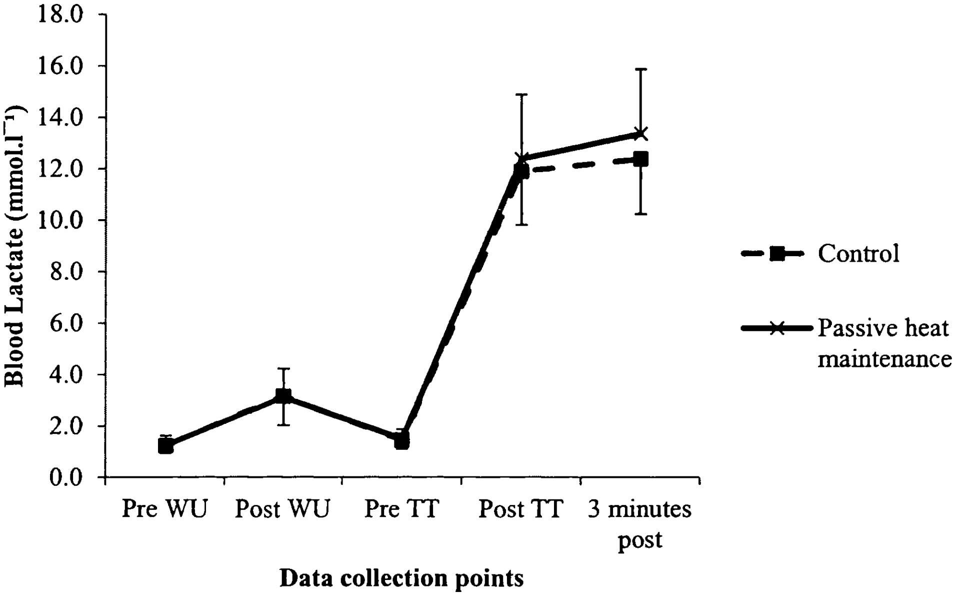

**Figure 4.3**: The Blood Lactate response to the control and passive heat maintenance conditions (n=12)

### 4.4 Heart rate

A significant time effect was established in relation to heart rate (HR) ($p<0.001$; df=4; F=252.376) with HR increasing across all time points compared to pre-WU (baseline) measurements ($p<0.001$) (Table 4.4). However, there was no significant difference between the two conditions ($p=0.996$; df=1; F<0.001). Heart rate displayed similar baseline values 83.1±12.9 versus 82.7±14.7beats·mins$^{-1}$ (Control versus experimental) ($p=0.916$) with WU causing elevations to 117.7±15.3 versus 119.0±11.1beats·min$^{-1}$ (control versus experimental) ($p=0.806$). A decrease in HR was observed over the 20 minute rest period to pre TT (**Control** 102.6±16.8beats·min$^{-1}$; **Passive heat maintenance** 95.8±11.3beats·min$^{-1}$; $p=0.078$), although HR was still elevated above baseline values ($p<0.001$). A significant increase was recorded following the performance TT, before declining over the 3 minute period that followed (Appendix I, Figure 1).

### 4.5 Rate of perceived exertion

Similar to the $T_{core}$, blood lactate and HR response, there were no significant differences in rate of perceived exertion (RPE) at baseline measurement between the control and the passive heat maintenance condition; 6.9±1.7 and 7.3±2.1 respectively ($p=0.457$). There was no condition effect on the measure of RPE ($p=0.559$; df=1; F=0.364), but a significant time effect was identified ($p<0.001$; df=4; F=180.159). Following an active WU, perceived effort had increased, remaining elevated above baseline at the cessation of the 20 minute rest period (**Control** 11.2±2.1; **Passive heat maintenance** 10.7±1.5; $p=0.455$). Perceived effort increased following the performance TT before declining at 3 minutes post TT (Table 4.4; Appendix I, Figure 2).

**Table 4.4**: Average HR and RPE results for the control and passive heat maintenance conditions

| | **Condition** | **Pre WU** | **Post WU** | **Pre TT** | **Post TT** | **3minutes Post** |
|---|---|---|---|---|---|---|
| **Heart rate ($beats{\cdot}min^{-1}$)** | Control | 83.1 ± 12.9 | 117.7 ± 15.3 | 102.6 ± 16.8 | 162.0 ± 12.9 | 111.7 ± 12.0 |
| | Experimental | 82.7 ± 14.7 | 119.0 ± 11.1 | 95.8 ± 11.3 | 166.5 ± 12.1 | 113.1 ± 9.1 |
| **Rate of Perceived Exertion** | Control | 6.9 ± 1.7 | 12.5 ± 1.1 | 11.2 ± 2.1 | 18.4 ± 1.4 | 14.6 ± 2.2 |
| | Experimental | 7.3 ± 2.1 | 13.3 ± 1.2 * | 10.7 ± 1.5 | 19.6 ± 3.6 | 14.6 ± 2.2 |

Data presented as Mean±SD * indicates statistically significant differences between the control and passive heat maintenance condition ($p<0.05$; n=12)

### 4.6 Correlation analysis

There was no significant relationship between the changes in performance and the change in temperature between post WU and pre TT in both the control (r=-0.289, p=0.451, n=9) and passive heat maintenance conditions (r=-0.122, p=0.755, n=9) (Appendix I, Figure 3). The sum of skinfolds data were also examined in relation to the changes in pre TT temperature between the two conditions; again, no significant correlation was observed (r=0.222, p=0.597, n=8). The sum of skinfolds was also correlated against the change in temperature from baseline to post WU within the control condition; no significant correlation was established (r=-0.473, p=0.237, n=8).

# Chapter 5 – Discussion

The main finding of the current study was a 1.1±1.3 second improvement in an elite swimming time trial (TT) performance when a passive device was implemented (versus control data) (Figure 4.1). Therefore, the results of the present study demonstrate that a passive heat maintenance device can improve elite swimming performance when implemented between WU and subsequent race performance. Comparable changes in core temperature ($T_{core}$), blood lactate and heart rate (HR) following WU demonstrate that the WU conducted in both conditions produced a similar physiological strain on the swimmers and consequently any differences in performance can be attributed to the manipulation of conditions within the 20 minute recovery period. As mentioned previously, in the present study there were no significant differences in $T_{core}$ between the control and passive heat maintenance conditions when measured at pre TT (Control 37.67±0.37°C; Passive heat maintenance 37.85±0.29°C) as the decline in temperature over the 20 minute rest period was not significantly different (Control Δ-0.33±0.44°C; Passive heat maintenance Δ-0.25±0.38°C) (Figure 4.2). Therefore, maintenance of $T_{core}$ is unlikely to be the primary, underlying mechanism responsible for the observed improvement in performance.

Although there is a degree of uncertainty regarding the primary mechanism responsible for the improvement in TT performance, the benefit of a 1.1±1.3 second enhancement in performance cannot be ignored within elite sport. This is further emphasized by research completed by Pyne, Trewin & Hopkins (2004), stating an additional enhancement of ~0.4%, determined by one-half of the typical within-swimmer random variation in performance at international events, can substantially increase a swimmers prospect of a medal. Thus the observed improvement of 0.8±1.0% in the TT results would appear to be of practical relevance within the elite swimming cohort recruited. When examining the smallest worthwhile enhancement in performance for each participant in the current study, the observed change in performance within the passive heat maintenance condition overcame one-half the variation between competition performance times in seven out of twelve participants (coefficient of variation; 0.21-3.98).

The primary aim of the current study was to implement a passive heat maintenance device (heat jacket incorporating Reflexcell technology), to alleviate possible decrements in elite swimming performance that may result from a decrease in temperature. To date, no previous research has investigated the effect of passive heat maintenance devices and/or strategies within elite sport. However, some support for this hypothesis can be obtained from medical literature, for example Bennett et al. (1994) investigated the use of passive heat maintenance devices in comparison to a control group during surgery to prevent hypothermia. The results identified a decrease in mean skin temperature ($T_{skin}$) and hand temperatures ($T_{hand}$) within the control group, whereas $T_{skin}$ and $T_{hand}$ remained unchanged within the passive group. Furthermore, Sessler & Schroeder (1993) reported that insulated blankets reduced heat loss by ~30% under similar conditions, preventing postoperative hyperthermia. Both of the reported studies utilised similar devices to the current study, based on a metallised plastic sheet that was able to insulate the skin from radiant and convective heat losses. When specifically examining the use of the passive heat maintenance device implemented in the current study, Allen et al. (2010) established that Blizzard survival blankets, incorporating Reflexcell technology, maintained $T_{core}$ effectively when compared to active heating devices. This was determined by warming an in-vitro torso (control) to 37°C prior to the commencement of the study, therefore preventing variation in baseline measurements. The decrement in $T_{core}$ was then measured every 5 minutes for 120 minutes to determine the rate of heat loss and/or heat maintenance as a consequence of the implemented active heating or passive maintenance devices.

Despite medical literature highlighting the efficacy of passive heat maintenance devices for maintaining temperature, currently there is an absence of literature detailing the subsequent effect of passive heat maintenance on performance in elite sport. This is unexpected considering the reported influential effect of an elevated temperature on subsequent performance. For example, West et al. (In Press) compared the effect of a 45 and a 20 minute rest period on elite swimming performance. The swimmers demonstrated a 1.5±1.1% improvement in performance under 20 minutes compared to 45 minutes, attributed to a smaller decline in $T_{core}$. Nonetheless, a decrease in $T_{core}$ was still observed within the 20 minute trial. Consequently, the rationale behind the implementation of a passive heat maintenance device was to maintain $T_{core}$ within the 20 minute rest period within swimming. Further support for this hypothesis is evident in the extensive research that highlights the performance improvements associated with an elevated $T_{core}$. For example, within preseason football matches, Duffield, Coutts & Quinn (2009) identified significant positive correlations between $T_{core}$ and high intensity running velocity (r=0.72) and moderate intensity activity (r=0.68). Supplementary evidence to support the positive effect of an increased temperature on performance is provided by Stewart & Sleivert (1998), observing an increase in $T_{core}$ of 0.7-1.0°C resulted in a 10-13% improvement in supramaximal performance. Furthermore, Mandengue et al. (2005) illustrated that a 0.67±0.18°C increase in $T_{core}$ improved cycle time to exhaustion from 324±69.3 seconds to 440±121.5 seconds.

Although the outlined research has highlighted the positive benefit of $T_{core}$ on sporting performance, in the current study, significance was not established between conditions regarding $T_{core}$ maintenance. Consequently, no differences in $T_{core}$ were identified between conditions to explain the improvement observed in the current study. As an alternative explanation, it is important to explore the difference in $T_{muscle}$ response in comparison to $T_{core}$ and the resultant effect of the two measurements on performance. Detailed work comparing $T_{muscle}$ and $T_{core}$ (rectal and oesophageal) at rest, during exercise and recovery has been completed by Saltin & Hermansen (1966) and more recently by Kenny et al. (2003). Observations have demonstrated that $T_{core}$ decreases rapidly (-0.04°C·min$^{-1}$) during the initial minutes following the cessation of exercise, declining to 0.35°C above recorded baseline values within 5 minutes. However, after 60 minutes, $T_{core}$ had only decreased an additional

0.05°C (Kenny et al., 2003). Within the present study, the rate of decrease in $T_{core}$ was -0.03°C·min$^{-1}$ after 10 minutes, resulting in a similar decrease of 0.33±0.67°C in the control trial. Whereas in the passive heat maintenance condition a rate of decrease of -0.01°C·min$^{-1}$ was observed, resulting in a 0.14±0.35°C decrease in $T_{core}$, approximately half of the reported decrease in the control. Unlike the response in $T_{core}$, when examining $T_{muscle}$, a continuous decrease during the initial 30 minutes of recovery was observed (Kenny et al., 2003). A potential explanation becomes apparent when considering the dissipation of heat from the core to the muscle tissue. This is particularly relevant in elite athletes who potentially possess efficient thermoregulatory systems, resulting in an improved exchange of generated heat and the prevention of hyperthermia induced fatigue (Bishop, 2003a). This is further supported by the thermoregulatory mechanisms wherein $T_{core}$ is endothermic and carefully regulated by the brain at 36.8°C (Lim et al., 2008). This is demonstrated in the current study; $T_{core}$ was 0.33±0.67°C and 0.14±0.35°C after 10 minutes of rest, displaying a difference in heat loss when a heat jacket was implemented. However, by 20 minutes the decline in the control condition had not decreased any further, whereas $T_{core}$ had been regulated to 0.25±0.38°C above baseline values within the passive heat maintenance condition i.e. a return to an acceptable level of controlled deviation. Conversely, the 'shell' temperature (skin, subcutaneous tissue and muscle) is ectothermic, therefore blood flow to the skin and environmental conditions have a greater influence on $T_{muscle}$ (Lim et al., 2008). If restricted by the conditions and/or implemented strategies, the heat generated in the muscle will exhibit limited dissipation to the environment, thereby maintaining an elevated $T_{muscle}$ whilst $T_{core}$ returns to near baseline values due to confined limits of regulation. Therefore, despite similar $T_{core}$ measurements between the two conditions, in the presence of a passive heat maintenance device it is possible that the rate of dissipation may have differed from the control condition and thus impacted on performance.

Furthermore, $T_{muscle}$ may have been significantly elevated in comparison to $T_{core}$. For example, Saltin & Hermansen (1966) highlighted a substantial increase in $T_{muscle}$ (2.92°C) compared to an increase of 1.94°C in $T_{core}$. These results are reinforced by more recent research, demonstrating variable $T_{muscle}$ and $T_{core}$ responses with different WU intensities (Yaicharoen et al., In press). From the temperature changes identified in Table 2.3, $T_{muscle}$ elevations varied from 0.8-2.8°C (dependent on intensity), whereas $T_{core}$ only ranged from 0.1-0.4°C. Additionally, Cochrane et al. (2008) identified an increase of 0.1°C in $T_{core}$, contrasted to an increase of 1.6°C in $T_{muscle}$, attributable to an increase in peak power output. In conjunction with these findings, Saltin & Hermansen (1966) highlighted that a difference of 0.7°C was detectable between $T_{core}$ and $T_{muscle}$ measurements at various testing stages. Based on this theory, it is attainable that $T_{muscle}$ was elevated to ~1°C within the current study. This is especially relevant, as previously outlined, due to the effect of the environment on $T_{muscle}$ in comparison to $T_{core}$ which is tightly controlled by the thermoregulatory mechanisms, causing increased difficulty in detecting significant changes. Therefore, the larger change in $T_{muscle}$ may have been a significant factor involved in the enhancement in swimming performance.

In light of the above, extensive research is available to confirm the beneficial effect of $T_{muscle}$ on performance. For example, Mohr et al. (2004) highlighted that a reduction of 2.4±0.3% in sprint performance correlated to a decrease of ~2.0°C in $T_{muscle}$ despite both $T_{core}$ and $T_{muscle}$ being measured. Furthermore, with the inclusion of an active re-WU this effect was reversed, maintaining $T_{muscle}$ and preventing the resultant decrease in sprint performance. Sargeant (1987) also identified the importance of $T_{muscle}$ on performance, reporting a 1°C increase in $T_{muscle}$ resulted in a concomitant 4% improvement in cycling performance. A primary mechanism has been proposed in which an elevated $T_{muscle}$ can have a positive effect on both the force/velocity and power/velocity relationships of the muscle (Gray et al., 2006). Reports have suggested that the temperature-dependent contractile properties are a function of myofibrilar ATPase activity, which as with other enzymatic processes is temperature dependent (He et al., 2000). Practically, warming up the muscle can improve muscle function and performance (Bishop, 2003a); improving maximal shortening velocity and promoting related changes in the force velocity relationship (Racinais & Oksa, 2010). Nonetheless, $T_{muscle}$ was not measured in the present study due to practicality and also due to ethical issues surrounding $T_{muscle}$ measurement within elite athletes, thus discussed mechanisms can only be hypothesized based on previous findings.

In the absence of $T_{muscle}$ measurement, blood lactate results may provide indirect support to the proposed theory of $T_{muscle}$ presenting as a potential underlying mechanism influencing swimming performance. Within the current study, blood lactate concentrations were higher at 3 minutes post TT under the passive heat maintenance compared to the control condition (difference of 1.0±1.9mmol.$l^{-1}$; $p=0.10$; Figure 4.3). This is reinforced by research completed by Gray et al. (2006) in which lactate was 22.0±4.1mmol·$kg^{-1}$ post exercise under normal $T_{muscle}$, whereas elevated $T_{muscle}$ resulted in a subsequent increase to 24.9±5.1mmol·$kg^{-1}$ ($p<0.05$). The greater blood lactate concentrations are a potential result of increased glycolytic flux, a consequence of an elevation in $T_{muscle}$ (Febbraio et al., 1996). Although speculative, an elevation in $T_{muscle}$ may increase the activity of key enzymes involved in ATP breakdown. Accordingly, this would enhance adenine nucleotide degradation and subsequent allosteric activation of key glycolytic enzymes (West et al.,In Press). Greater activity of these enzymes would increase the glycolytic flux and subsequent lactate formation; thus the activation of this pathway may be a contributing factor to improved performance observed in the passive heat maintenance condition (Bishop, 2003a; Febbraio et al., 1996).

An improvement in performance with passive heating has also been attributed to an increase in cross bridge cycling rate coupled with an improved capacity for ATP resynthesis (Febbraio et al., 1996). It has been recognised that this mechanism was responsible for the enhancement in power output during high intensity activity. This suggestion was substantiated by the conduction of research, in which a high power output (990±245W versus 1057±260W) was associated with a higher pedal cadence during heating (116±9

$rev \cdot min^{-1}$ versus 122±9 $rev \cdot min^{-1}$); the function of a rightward shift in the power velocity characteristics of the muscle (Linnane et al., 2004). Although $T_{muscle}$ and indeed muscle contractile properties or ATP resynthesis were not measured within the current study, a higher stroke rate (SR) within the passive heat maintenance condition was identified in comparison to the control condition (44.6±2.1 versus 43.8±2.1, respectively). Therefore, this suggests that SR frequency was a key mechanical factor influencing the difference observed in performance. A higher SR is an equivalent of pedal cadence within cycling, both of which are freely chosen; thus the results of Linanne et al's. (2004) study provides weight to the speculative attribution of improved SR and performance within the current study. This is increasingly prominent in elite swimmers as a consequence of the specific SR training and implementation of race strategies. Further supporting research is detailed in the work completed by Ball, Burrows & Sargeant (1999). A greater peak power output was achieved in a hot versus control environment, mirrored by an initial difference and subsequent change in mean pedal frequency. Overall, pedal frequency was higher when exercise was performed in the heat, thus improvement in performance was attributed to mechanical changes in human movements.

Another potential mechanism contributing to the improvement in performance in the current study may be attained through the exploration of psychological perspectives. For example psychological factors encompassing self-efficacy or athlete expectations can also influence how well a participant adheres to or responds to an exercise intervention programme (Fradkin, Zazryn & Smoliga, 2010). The placebo effect provides explanation of this occurrence, referring to a positive outcome resulting from the belief that a beneficial treatment has been received (Trojian & Beedie, 2008). For example, a study by Beedie, Coleman & Foad (2007) administered a hypothetical ergogenic aid in sport to determine how the placebo effect manipulates performance, in this instance performance involved 3x30m sprint trials. Group1 was provided with positive information of the likely effects, whereas Group2 received negative information concerning the same substance. A significant linear trend of greater speed with successive experimental trials suggested a positive belief creates a positive effect on performance. Whereas a negative belief resulted in Group2 running 1.57% slower than baseline values, suggesting a negative belief can create a negative effect on performance. Further findings suggest that psychological variables such as motivation, expectancy and conditioning, and the interaction with physiological variables might be significant factors in driving both positive and negative responses to an experimental trial (Trojian & Beedie, 2008). This effect may have occurred within the current study due to the nature and implementation of heat jackets, as it was not possible to blind participants to the different treatments.

Finally, gender differences may also impact on thermal responses and heat loss due to variation in anthropometric characteristics, subsequently effecting sporting performance. Although unable to fully explore the different responses in the current study due to limited female and male participants, consideration of this factor is important when collecting and analysing results in relation to passive heat maintenance. For instance, female participants differ from males in thermal responses to heat load and loss, because they typically have a higher ratio of body surface to body mass, a greater subcutaneous fat content and lower exercise capacity (Kaciuba-Uscilko & Grucza, 2001). This is supported by research stating that body fat percentage and the surface to mass ratio had the greatest influence of all the measured individual parameters on variance in heat storage capacity (Havenith & Middendorp, 1990). When specifically examining percentage of body fat on heat loss/maintenance, females in the current study had a greater percentage of body fat (9.84±1.69%) in comparison to the male participants (5.42±1.02%). Chudecka & Lubkowska (2010) reported a statistically significant relationship was established between estimated body fat percentage values and the rate of temperature loss after exercise. Individuals with higher estimated percentage of body fat values cooled significantly slower than those with lower levels of body fat. Therefore, it may be suggested that the use of passive heat maintenance has a more prominent use within male athletes; however, this requires further investigation due to the limited sample of accessible elite athletes within the current study.

## Limitations

When examining the limitations of the current study, one predominant factor to consider is the measurement of $T_{core}$ versus $T_{muscle}$. Within the literature, $T_{muscle}$ has been identified to have a greater impact on performance compared to $T_{core}$ (e.g. Mohr et al., 2004). However, $T_{muscle}$ could not be measured within the current study due to the practical restraints of measuring $T_{muscle}$ both before and after entering the water in addition to the ethical issues associated with $T_{muscle}$ measurement in swimming. Testing conducted within the laboratory would allow for the measurement of $T_{muscle}$, however the ecological validity and practical application of the study would be reduced.

The sample size is another identified limitation of the study; twelve elite swimmers were exposed to the experimental condition, potentially reducing the power of the results. However, difficulties arise when accessing elite athletes, considering the small size of this population; consequently this has resulted in a small sample size within the current study. Increasing the sample size would have prevented an elite cohort of swimmers being tested, rather the sample would have included a range of swimming abilities.

Furthermore, Fradkin et al. (2010) has previously reported that a limitation of literature relating to WU is the absence of a genuine control condition within the study design. For example, Bishop et al. (2001) incorporated an actual WU procedure as the baseline value and compared variations in the WU with this baseline. Although this allowed for improvements in performance to be determined, it did not reflect a true increase in performance as a control should ideally consist of no prior activity; however the impact on athletes would have been too great a risk. Similarly, within the current study a genuine control was not included, instead, conditions replicated those of a competition environment requiring swimmers to wear tracksuit bottoms, trainers and t-shirt. The study aimed to identify the additional improvement that a passive heat maintenance device could have on a swimming TT performance compared to the conditions of a normal swimming competition.

## Conclusion

In conclusion, this study highlights the effect of a passive heat maintenance device (Blizzard survival heat jacket) within a group of elite swimmers. An improvement in swimming performance under TT conditions has been highlighted when a passive device is utilised within the 20 minute marshalling call room (rest period) that follows WU. Although there is a degree of speculation regarding the underlying mechanisms responsible for the improvement in TT performance, the benefit of 1.1±1.3 seconds enhancement in performance cannot be ignored within elite sport.

## Practical application

From a practical perspective, the improvement in swimming performance in the passive heat maintenance condition has highlighted several areas that may contribute to elite sporting performance. First, the wearing of a heat jacket can be successfully utilised and implemented in a swimming environment (e.g. within a marshalled call room) as a non-invasive performance aid, despite limited access to elite athletes in the current study and the potential reduction in power of the results due to a limited sample size. Additionally, within the present study the change in performance following passive heat maintenance ranged from -0.54% to +2.4%. This has identified that participants respond differently to the strategy implemented and thus highlighting the need to individualise passive treatments to optimise performance gains in swimming. The wearing of a heat jacket may also provide similar or perhaps even greater benefits for sporting performance for those athletes competing in extreme cold or outdoor environments (e.g. Open water competitions). Second, as based on previous research, the temporal effect on the dynamics of the cross bridge cycling rate, as a result of an elevated $T_{muscle}$, appears to cause a rightward shift in the power/velocity characteristics of the muscle. Equally an elevated $T_{muscle}$ may improve the capacity for ATP resynthesis and muscle glycogenesis and glycolysis, thus enhancing performance. Although not measured in the current study due to practical and ethical issues, for future research it appears important that $T_{muscle}$ is measured when investigating the effect of temperature on performance, as extensive research indicates the greater impact $T_{muscle}$ has on performance in comparison to $T_{core}$. Third, this work has highlighted the possibility of other important areas of research, including gender differences arising from heat dissipation due to the differences in anthropometric characteristics. Therefore, non-invasive performance aids to enhance performance through temperature maintenance and/or elevation warrant further investigation due to the smallest marginal gains influencing medal prospects within elite sport.

### Future recommendations

An important area, warranting further investigation is the difference in heat dissipation and maintenance between genders due to variation in anthropometric characteristics. The literature has identified a greater rate of heat dissipation in individuals with a lower percentage of body fat (Chudecka & Lubkowska, 2010) with female participants' displaying differences in thermal responses to heat load and loss compared to male participants as they typically have a greater subcutaneous fat content (Kaciuba-Uscilko & Grucza, 2001). Genders need to be divided, investigating the influence of passive heat maintenance devices in males and females. To enable a comprehensive understanding of the mechanism(s) influencing performance, it may be beneficial to identify how the participants felt after each trial, potentially allowing any placebo effect to be identified.

Following research identifying that an elevated $T_{muscle}$ improves power output during a 20 second maximal sprint (Sargeant, 1987), it may be beneficial to measure swim time to 15- and/or 25m to identify the effect of an elevated temperature consequence of a passive heat maintenance device on explosive movements. Furthermore, the combined measurement of $T_{core}$ and $T_{skin}$ may allow improved identification of heat maintenance and/or heat dissipation;

as $T_{core}$ is tightly regulated by the hypothalamus, $T_{skin}$ may provide additional information on the effect of the environment on temperature.

Alternative non-temperature related mechanisms should also be investigated to identify potential benefits within swimming performance. For example, completing a land based WU within the marshalled 20 minute call room, for the first 10-15 minutes, may allow competition to begin with an elevated $VO_2$. This may also produce associated temperature related responses. Additionally the influence of post activation in conjunction with temperature maintenance should be explored; however logistics of completing this within a contained call room would have to be considered to maintain practical application.

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# Appendices

## Appendix A: Weekly training regime

**Table 1:** Training regime completed by participants throughout the testing period

| | Pool based training | Land based training |
|---|---|---|
| Monday | *Am* – Long course, 6000m total, 500-1500m race pace swimming<br>*Pm* – Long course, 6000m total, 500-1500m race pace swimming | Core session |
| Tuesday | *Am* – Long course, 6000m total, 500-1500m race pace swimming<br>*Pm* – Short course, 6000m total, 500-1500m race pace swimming | Shoulder mobility/ stability and gym |
| Wednesday | No training<br>*Pm* – Long course, 6000m total, 500-1500m race pace swimming | No training |
| Thursday | *Am* - Long course, 6000m total, 500-1500m race pace swimming<br>*Pm* - Pm – Short course, 6000m total, 500-1500m race pace swimming | Shoulder mobility/ stability and gym |
| Friday | *Am* - Long course, 6000m total, 500-1500m race pace swimming<br>*Pm* – Long course, 6000m total, 500-1500m race pace swimming | Core session |
| Saturday | *Am* - Long course, 6000m total, 500-1500m race pace swimming<br>No training | Gym/ Circuit training |
| Sunday | No training<br>No training | No training |

Main focus of gym sessions: Tuesday – strength, Thursday – strength/power, Friday – strength endurance. Total distance and race pace swimming is an average as it varied between the individuals

## Appendix B: Ethical approval form

SPORT AND EXERCISE SCIENCE
COLLEGE OF ENGINEERING, SWANSEA UNIVERSITY
ETHICAL ADVISORY COMMITTEE

### APPLICATION FOR ETHICAL COMMITTEE APPROVAL OF A RESEARCH PROJECT

In accordance with Departmental Safety Policy, all research undertaken in the department must be approved by the Departmental Ethics Advisory Committee **prior to data collection. Applications for approval should be typewritten on this form using the template available in the Public Folders.** The researcher(s) should complete the form in consultation with the project supervisor. Where appropriate, the application must include the following appendices:

(A) subject information sheet;
(B) subject consent form;
(C) subject health questionnaire.

**After completing sections 1-12 of the form, 1 copy of the form should be handed-in to the Department Administrator who will then submit copies of the application for consideration by the Departmental Ethics Advisory Committee. The applicant(s) will be informed of the decision of the Committee in due course.**

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### 1. DRAFT TITLE OF PROJECT

The effects of pre-conditioning strategies on swimming performance in international swimmers

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### 2. NAMES AND STATUS OF RESEARCH TEAM

Natalie Williams (Postgraduate Masters student, Swansea University)

Dr Liam Kilduff (Supervisor, Swansea University)
Bernie Dietzig (British Swimming Performance Scientist)

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### 3. RATIONALE

Warm up (WU) has previously shown to enhance performance, for example a recent meta-analysis reported WU improved performance in 79% of the 32 studies reviewed (Fradkin et al., 2010). The majority of the effects of WU have been attributed to temperature-related mechanisms (Bishop, 2003a). It has been suggested that a rise in muscle temperature is a key contributing factor to improve performance (Bishop, 2003a) and that a higher temperature in a working organism facilitates work done (Seto, 2005). A rise is muscle temperature has shown to result in both physiological and metabolic changes, including increased anaerobic metabolism (Febbraio et al., 1996), a speeding of rate limiting reactions (Koga et al., 1997) and decreased resistance of muscles through a reduction in the internal viscosity (Zochowski et al., 2007). In addition, elevating muscle temperature can increase the speed of muscle contraction and can decrease both the time to peak tension and half relaxation time (Davies & Young, 1983) which may be crucial during fast and intense contractions (Febbraio et al., 1996). There are several factors (e.g. intensity, duration and recovery following WU) that can influence the benefit observed from the pre-event WU. When specifically investigating the recovery time between WU and the event, previous research within swimming has reported a 10minute rest period resulted in ~4% improvement in a 200m time trial in comparison to a 45minute recovery (Zochowski et al., 2007). However, within swimming, athletes must report to the call room 20minutes before racing, therefore 10minutes recovery is not applicable to improve race time. A more recent study has investigated the effect of a 20minute vs. a 45minute post WU recovery on swimming performance (West et al., under review). A 1.5±1.1% improvement in performance was identified when preceded by a 20minute recovery as opposed to a 45minute recovery period (West et al., under review). However, despite a faster performance in the 20minute condition, a decrease in body temperature of 0.3±0.1°C was observed during this time. It has been reported that muscle temperature rises rapidly within the first 3-5minutes of exercise and reaches plateau after 10-20minutes, however muscle temperature is likely to drop significantly following a 15-20minute of the cessation of exercise (Saltin et al., 1968). Mohr et al. (2004) reported the decrease in muscle temperature at half time from 39.4±0.1°C to 38.0±0.2 and 37.7±0.1°C ($p<0.05$) after 10 and 15minutes of recovery, respectively. This correlated to the reduction in sprint performance during half time ($r=0.60$, $p<0.05$, $n=16$), identifying a decrease in performance of 2.4±0.3% ($p<0.05$) before the second half, compared with before the match. When players performed a period of moderate intensity exercise prior to the second half, body temperatures were maintained and sprint performance did not deteriorate (Mohr et al., 2004). Due to the compulsory 20minute rest period between WU and competition within swimming and the restrictions of the call room preventing an active WU being performed, an alternative method needs to be implemented to maintain core temperature elevation whilst in the call room. Passive heat maintenance allows for an increase or maintenance in core temperature, without depleting energy substrates (Bishop, 2003a). Previous research has reported the positive impact passive heating can have on performance, for example Linnane et al. (2004) heated subjects in a water bath (43°C) for 16minutes prior to entering an environmental chamber for 30.7minutes and identified a 6% improvement in power output.

In addition to the above, Postactivation Potentiation (PAP) has consistently been shown to improve lower body muscle power (Kilduff et al., 2011; Kilduff et al., 2007; Young et al., 1998). Postactivation potentiation has been defined as an acute enhancement of muscle function after a preload stimulus; it is therefore possible that active WU including maximum voluntary contractions (MVCs) may improve certain types of performance by increasing muscle contractile performance (Bishop, 2003). For example Bevan et al. (2010) included a pre load stimulus of 1 set of 3 repetitions of a back squat at 91% of 1 repetition max (RM). An improvement in performance of 5.0±1.0 and 8.0±1.0% over 5 and 10m respectively was observed. It was concluded PAP can be harnessed to enhance sprinting performance (Bevan et al., 2010). However, to date the majority of studies have used heavy resistance training to induce PAP (eg. Gourgoulis et al., 2003 & Sale, 2004), but this is not practical within a call room at swimming competitions. Therefore it still needs to be investigated if high velocity, low force movements can improve performance through PAP. One study has recently investigated the use of a low load, high velocity protocol to induce PAP to increase upper body peak power output (PPO) as this has increased practical application for athletes to use as part of WU prior to competition (West et al., Under Review). It was established that performance of a ballistic bench press throw using a load of 30% 1RM provided an effective method of inducing the PAP effect by increasing PPO (West et al., Under Review). Upper body PPO increased by approximately 4.1 and 4.9% under an 8minute recovery period condition and an individualised and optimal recovery time condition. However, this still needs to be established to have the same impact on the lower body as this would be transferable to increase power produced during a swimming dive.

The aim of the study is therefore to implement a passive heat maintenance method to maintain core body temperature during the 20minute recovery period and to introduce low load, high velocity exercises into the period to induce PAP prior to competition with the overall aim of improving performance.

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## 5. AIMS AND OBJECTIVES

The study aims to maintain core body temperature using a passive method following a standardised swimming warm up to improve performance of a 200m elite swimming performance.
The second aim is to incorporate low load, high velocity exericses 12minutes into the 20minute rest period to induce Post-activation Potentiation (PAP) in each individual.

The objectives of the study are:

- To use Blizzard jackets to maintain an elevated core temperature in comparison to a control trial with the absence of blizzard jackets.
- To monitor core (intestinal) temperature every 5minutes over the 20minute rest period
- To measure heart rate, core temperature (intestinal) and blood lactate to monitor the physiological responses of both active warm up and passive heat maintenance.
- To incorporate countermovement jump (CMJ) exercises, to activate PAP, into the rest period that will be suitable to be performed in the call room at competitions

## 6. METHODOLOGY

### 6.1 Study Design

Following an active warm up, Blizzard jackets will be used to passively maintain core body temperature. The time to complete a 200m maximal swim will be measured. This will be compared against a control trial in which passive heat maintenance will not be present, thus enabling the effect on performance to be established. A third condition will involve counter movement jumps (CMJ) to induce Post-activation Potentiation (PAP) within the swimmers whilst wearing the blizzard jackets.

The study group will consist of 10 elite swimmers aged 18-25 years and include males and females. The subjects will be middle distance swimmers from the British Swimming Intensive training centre in Swansea. All subjects will read the subject information sheet and sign a consent form prior to testing (refer to appendix A & B). Subjects will complete an American College of Sports Medicine pre-participation screening questionnaire (AHA/ACSM, 1998) (Appendix C). Any health issues that become apparent from the questionnaire will exclude the subject from further participation. Subjects will be required to attend Wales National Pool Swansea (Olympic standard 50m pool) for their normal training sessions on three occasions to carry out the experimental trials. This will be a repeated measures design with all subjects acting as their own control. All subjects have previously been involved in research and are familiar with test procedures.

### 6.2 Experimental Procedures

All field measurements will be carried out at the swimming pool and will take approximately 2 hours over eight sessions, all of which will be within the swimmers training sessions. Wales National Pool have no objections to taking blood samples on pool side, blood samples are routinely taken on poolside as part of the British Swimming ITC high performance centre testing. All items containing blood will be will disposed of appropriately as detailed in section 6.4.

To begin, all swimmers will perform a standard individualized warm up. Lactate, heart rate and core temperature will all be monitored. Swimmers will then have a rest period of 20minutes prior to completing a maximal effort 200m time trial.

### 6.2.1 Experimental conditions

Within the 20minute rest period, in condition 1 swimmers will wear Blizzard Jackets and core body temperature will be measured every 5minutes. Within the same training cycle, the swimmers will perform the same warm up and race, however they will not wear the blizzard jackets (condition 2). The third condition will involve wearing the blizzard jackets and performing three sets of three CMJ 12minutes into the 20minute recovery period with the addition of weight vests. In total, subjects will complete three conditions and three maximal time trials. Recovery between the warm up and time trial will remain the same.

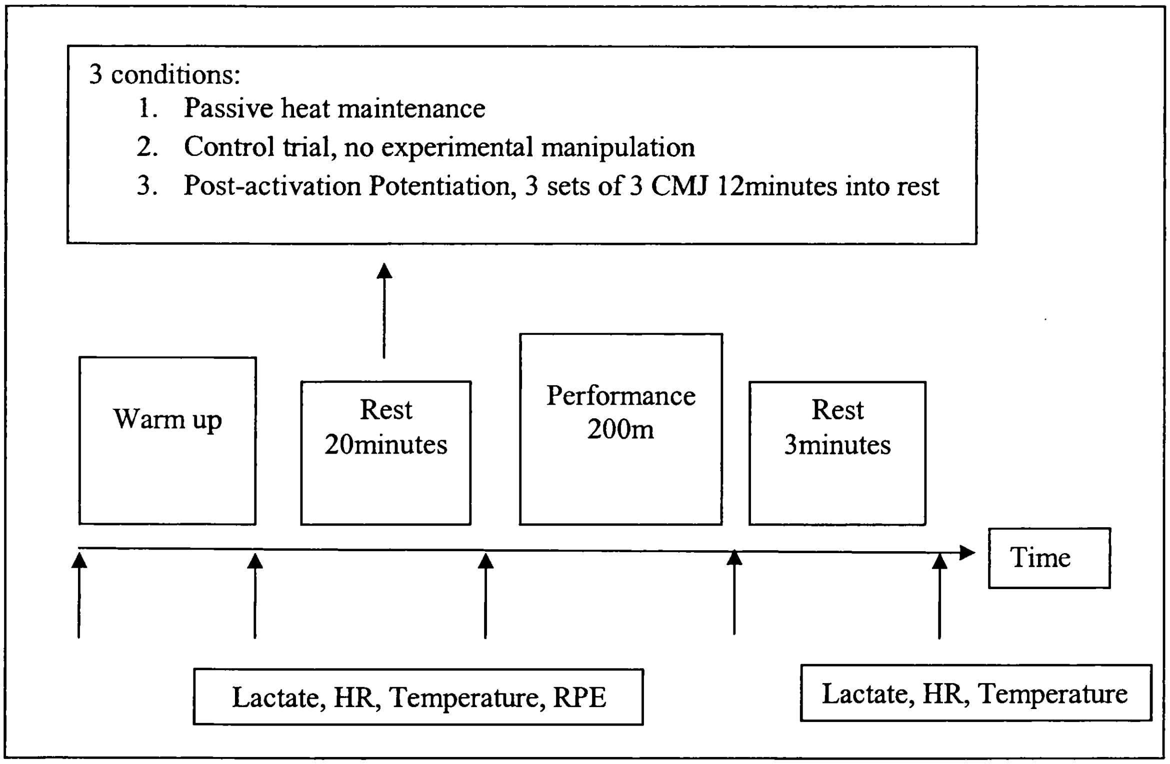

**Figure 1:** Overview of the experimental design

### 6.2.2 Physiological measurements

Heart rate, lactate levels, core body temperature and rate of perceived exertion (RPE) will be taken and recorded at rest, post warm up, pre-time trial and post-time trial. Heart rate will be recorded using a Polar heart rate monitor. The subjects will be on poolside during this. To record blood lactate levels, capillary blood samples will be taken from the finger whilst subjects are on poolside and analysed using an automated lactate analyser for blood lactate (Biosen C-line Sport, EKF – diagnostic GmgH, Barleben, Germany). Davison et al., (2000) has previously reported that the Biosen Lactate Analyser can provide valid, fast and reliable measures of blood lactate. To record core temperature, an ingestible core temperature sensor will be used (CorTemp Ingestible core body temperature sensor, HQ Inc) which sends a radio signal to an external sensor (CorTemp Data recorder, HQ Inc). Subjects will be required to ingest the core temperature sensor 3 hours prior to testing to ensure transit beyond the stomach before testing begins (Byrne & Lim, 2007). The sensor will then transmit the core body temperature of the swimmers' as wireless signals for the external detector to pick up and convert into a digital format. All measurements will be taken whilst the subjects are in the water, therefore 5minutes before warm up swimmers will enter the water and remain stationary to enable a baseline measurement to be taken. The ingestible core temperature pill has previously been accepted to provide valid results of core temperature when compared against other measurements (Byrne & Lim, 2007). There will be additional temperature measurements during the 20minute rest period, taking a reading every 5minutes to track the effect of passive heat maintenance on the subjects. Finally RPE will be measured using the Borg scale (1982). Subjects will indicate how hard they think they are working by rating it on a scale of 6-20 from extremely light to maximal effort. Within the 200m time trial video analysis will be used to record stroke rate and stroke count and time to complete 200m, this will also be recorded manually.

Subjects will also be required to attend an additional session to take skinfold measurement's to determine percentage of body fat. The individual carrying out the measurements will be ISAK trained.

### 6.3 Data Analysis Techniques

The data will be analysed to identify any significant differences between the experimental passive heat maintenance trial, the control trial and the PAP condition. All data will be presented as the mean ± standard deviation unless otherwise indicated. Before carrying out analysis the data will be screened for errors and parametric suitability. Tests of assumptions will be carried out to check for normality and homogeneity of variance. Analysis of the means of the time trial, core temperature, blood lactate and heart rate will also be carried out using repeated measures ANOVA. Post hoc comparisons will be made where appropriate. All statistical analysis will be carried out using SPSS (version 16.0, SPSS, Chicago, IL) with significance being accepted at the 95% confidence limit. Estimation of progression and variability in swimming performance to characterize the practical (clinical) significance of observations, rather than simple interpretation of statistical significance (Stewart & Hopkins, 2000 a,b) will also be carried out.

### 6.4 Storage and Disposal of Data and Samples

Biological samples (blood samples) and subject information will be stored and disposed of according to the Exercise Physiology laboratory guidelines. At the end of the study, data will be disposed of in line with the Exercise Physiology guidelines.

All data will be stored on a password protected computer. Data relating to subjects in the study will be kept in a digital format to avoid identification of subjects.

Access to data generated during the study will be limited to the research team as stated in section 2.

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## 7. LOCATION OF THE PREMISES WHERE THE RESEARCH WILL BE CONDUCTED

Research will be conducted at Wales National Pool Swansea. Liam Kilduff and Bernie Dietzig will be at all sessions to supervise, both being trained first aid members of staff.

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## 8. SUBJECT RISKS AND DISCOMFORTS

There are potential risks of the study. Blood samples will be taken from the subjects. Procedures of how blood will be taken will be explained to subjects prior to taking the samples and will have the right to withdraw at any time; subjects will also be asked of any phobias of needles or blood. A first aider will always be supervising the study due to potential health risks, all researchers will wear gloves when conducting the tests and any items that have blood on will be disposed of accordingly. Likewise any sharp items will be disposed of appropriately. The ingestible core temperature pill could cause discomfort to take therefore subjects will be given the option not to participate if they are uncomfortable. Strenuous exercise could also be a risk if any underlying health issues are present. Therefore all subjects will fill in a consent form and a health/fitness screening questionnaire to identify any health risks maximal exercise could cause before testing begins. Due to subjects being required to wear blizzard jackets this may cause some discomfort, especially when performing exercise within these jackets. However, the subjects will be informed they can withdraw from testing at any stage.

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## 9. INFORMATION SHEET AND INFORMED CONSENT

Have you included a Subject Information Sheet for the participants of the study ?
YES
Have you included a Subject Consent Form for the participants of the study?
YES

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## 10. COMPUTER

Are computers to be used to store data? YES
If so, is the data registered under the Data Protection Act? YES

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## 11. STUDENT DECLARATION

Please read the following declarations carefully and provide details below of any ways in which your project deviates from them. Having done this, each student listed in section 2 is required to sign where indicated.

1. I have ensured that there will be no active deception of participants.
2. I have ensured that no data will be personally identifiable.
3. I have ensured that no participant should suffer any undue physical or psychological discomfort
4. I certify that there will be no administration of potentially harmful drugs, medicines or foodstuffs.
5. I will obtain written permission from an appropriate authority before recruiting members of any outside institution as participants.
6. I certify that the participants will not experience any potentially unpleasant stimulation or deprivation.
7. I certify that any ethical considerations raised by this proposal have been discussed in detail with my supervisor.
8. I certify that the above statements are true with the following exception(s):

Student signature:

Date:

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## 12. SUPERVISOR'S DECLARATION

In the supervisor's opinion, this project (delete those that do not apply):

- Does not raise any significant issues.
- Raises some ethical issues, but I consider that appropriate steps and precautions have been taken and I have approved the proposal.

- Raises ethical issues that need to be considered by the Departmental Ethics Committee.
- Raises ethical issues such that it should not be allowed to proceed in its current form.

Supervisor's signature: Date:

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## 13. ETHICS COMMITTEE DECISION (COMMITTEE USE ONLY)

ETHICAL APPROVAL: GRANTED REJECTED (delete as appropriate)

The ethical issues raised by this project have been considered by members of the Departmental Ethical Approval Committee who made the following comments:

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Please ensure that you take account of these comments and prepare a revised submission that should be shown to your supervisor/ resubmitted to the Department Ethical Approval Committee (delete as appropriate).

Signed: Date:

(Chair, Departmental Ethics Advisory Committee)

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**Appendix C: Subject information sheet**

## DEPARTMENT OF SPORTS SCIENCE

## SUBJECT INFORMATION SHEET

**Date :**

**Contact Details:**
Natalie Williams; 07902169696, 520869@swansea.ac.uk

### 1. Study title

The effects of pre-conditioning strategies on swimming performance in international swimmers

### 2. Invitation paragraph

We would like to invite you to volunteer for this study that aims to identify if the use of blizzard jackets will help maintain core body temperature during your rest period between warm up and racing whilst also incorporating jumps to be completed 12minutes into your recovery that will be transferable to be used within a call room that will aid performance. The study will be beneficial to you, aiming to improve race time specifically of a 200m swim on your number one stroke that can be transferred to competitions. We would like to thank you for taking time to read this information sheet and very much hope you decide to take part in what is a very beneficial study.

### 3. What is the purpose of this study?

The purpose of the study is to identify if the use of blizzard jackets are effective in maintaining core body temperature whilst also incorporating low weight, high velocity exercises (counter movement jumps) into your recovery period to establish if this has a benefit on your swimming performance.

### 4. Why have I been chosen?

You have been chosen based upon the level of swimming you compete at, having already been accepted to swim at Swansea Performance Centre. You will have the right to withdraw from the study at any time, without having to provide reasoning.

### 5. What will happen to me if I take part?

You will be required to attend three sessions at Wales National Pool Swansea during your normal training sessions. The sessions will require you to perform three conditions. All conditions will require you to complete a standard individualized warm up with a 20minute rest period before completing a 200m maximal swim on your number one stroke. All experimental manipulation will occur within the 20minute rest period. Within one condition you will be required to wear a blizzard jacket with the aim of maintaining your core body temperature. Within the second condition you will be required to wear the clothes normally worn at a swimming competition. Within the third condition you will be required to complete 3 sets of 3 countermovement jumps whilst wearing the blizzard jacket. You will be expected to give maximum effort within the time trial and therefore participating in strenuous exercise. After each warm up you will have your heart rate measured using a heart rate monitor strap and watch, blood samples taken from the finger and temperature recorded. Three hours before each session you will be required to swallow a core temperature pill to allow for core temperature to be monitored.

### 6. What are the possible disadvantages of taking part?

There are possible risks of the study. Firstly, blood samples will be taken. Procedures of how blood will be taken will be explained to you prior to taking the blood and you will have the right to withdraw. You will also be expected to participate in strenuous exercise, completing three 200m time trials. The ingestible core temperature pill could also be a discomfort to take therefore you will be given the option to not participate if you are not comfortable. The blizzard jackets may cause discomfort, making you feel hot as they aim to maintain an elevated body temperature achieved during your swimming warm up. All procedures will be the same as you normally carry out during testing sessions.

### 7. What are the possible benefits of taking part?

As a result of participating, you will gain valuable information on how to maintain core body temperature that can be used prior to racing and exercises to be completed in the call room which could be beneficial to your performance at a competition.

### 8. Will my taking part in the study be kept confidential?

All data will be kept confidential and results will not be accessible to anyone else, only the research team will have access to the information. At the end of the study all data will be disposed of according to set guidelines.

**Appendix D: Consent form**

## DEPARTMENT OF SPORTS SCIENCE
## SUBJECT CONSENT FORM

**Contact Details: Natalie Williams 07902169696, 520869@swansea.ac.uk**

**Project Title:** The effects of pre-conditioning strategies on swimming performance in international swimmers

**Please initial box**

1. I confirm that I have read and understood the information sheet dated ....../....../...... (version number ........................) for the above study and have had the opportunity to ask questions. ☐
2. I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason, without my medical care or legal rights being affected. ☐
3. I understand that sections of any of data obtained may be looked at by responsible individuals from the University of Wales Swansea or from regulatory authorities where it is relevant to my taking part in research. I give permission for these individuals to have access to these records. ☐
4. I agree to take part in the above study.

| | | |
|---|---|---|
| ______________________ | ____________ | ______________ |
| Name of Subject | Date | Signature |
| ______________________ | ____________ | ______________ |
| Name of Person taking consent | Date | Signature |
| ______________________ | ____________ | ______________ |
| Researcher | Date | Signature |

## Appendix E: Health screening questionnaire

### AHA/ACSM Health/Fitness Facility Preparticipation Screening Questionnaire.

**Name** ______________________________
**Address** ______________________________
**Phone number** home ____________ work ____________
**Emergency contact** name ____________________ phone ____________
**Date of birth** ____________

**History** *Assess your health needs by marking all true statements.*

You have had:
☐ a heart attack
☐ heart surgery
☐ cardiac catheterization
☐ coronary angioplasty (PTCA)
☐ pacemaker/implantable cardiac defibrillator/rhythm disturbance
☐ heart valve disease
☐ heart failure
☐ heart transplantation
☐ congenital heart disease

*If you marked any of the statements in this section, consult you a health provider before engaging in exercise. You may need to use a facility with a medically qualified staff.*

**Symptoms and other health issues:**
☐ You experience chest discomfort with exertion.
☐ You experience unreasonable breathlessness.
☐ You experience dizziness, fainting, blackouts.
☐ You take heart medications.
☐ You take prescription medication(s).
☐ You have musculoskeletal problems.
☐ You have concerns about the safety of exercise.
☐ You are pregnant.

**Cardiovascular risk factors**
☐ You are a man older than 45 years.
☐ You are a woman older than 55 years or you have had a hysterectomy or you are postmenopausal.
☐ You smoke.
☐ Your blood pressure is greater than 140/90.
☐ You don't know your blood pressure.
☐ You take blood pressure medication.
☐ Your blood cholesterol level is >240 mg/dL.
☐ You don't know your cholesterol level.
☐ You have a blood relative who had a heart attack before age 55 (father or brother) or age 65 (mother or sister).
☐ You are diabetic or take medicine to control your blood sugar
☐ You are physically inactive (i.e., you get less than 30 minutes of physical activity on at least 3 days per week).
☐ You are more than 20 pounds overweight.

*If you marked two or more of the statements in this section, you should consult your healthcare provider before engaging in exercise. You might benefit by using a faciltiy with professionally qualified exercise staff to guide your exercise program.*

☐ **None of the above is true.**
*You should be able to exercise safely without consulting your healthcare provider in almost any facility that meets your exercise programme needs.*

AHA/ACSM indicates American Heart Association/American College of Sports Medicine.

## Appendix F: Location and measurement of skinfold sites

**Triceps skinfold**
The site is located at the mid-position between the acromiale and radiale landmarks on the posterior aspect of the arm when the forearm is supinated
The subject stands with the arms hanging relaxed with the right forearm supinated. The subjects elbow may be bent to help locate the site
A vertical fold is lifted so that the landmark is midway between the lower edges of the left thumb and index finger
The caliper jaws are applied 1 cm below the marked site, to a similar depth on the fold as the left thumb and index finger

**Biceps skinfold**
The site is located at the mid position between the acromiale and radiale landmarks but at the most anterior aspect of the arm when the forearm is supinated
The subject stands with the arms hanging relaxed with the right forearm supinated. The subjects elbow may be bent to help locate the site
A vertical fold is lifted so that the landmark is midway between the lower edges of the left thumb and index finger
The caliper jaws are applied 1 cm below the marked site, to a similar depth on the fold as the left thumb and index finger

**Subscapular skinfold**
The site is marked at the inferior angle of the scapula when the subject is standing erect with the arms by the sides. For obese individuals, gently placing the right arm behind the back helps in locating the site. The left index finger is placed on the mark and the thumb a sufficient distance inferior to this point so as to lift an oblique (diagonal fold) infero-laterally, approximately 45 degrees to the horizontal.
The caliper is applied 1 cm lateral to the left index finger and thumb perpendicular to the line of the fold.

**Supraspinale skinfold**
To locate this site, project an imaginary line from the iliospinale landmark to the right anterior axillary (armpit) border.
Mark a point on this imaginary line at a level that is horizontal to the iliac crest (~7 cm above the iliospinale for adults)
Lift an oblique fold (infero-medially, approximately 45 degrees to the horizontal) at this site and apply the caliper 1 cm medial to the left index finger.

**Abdominal skinfold**
This point is 5 cm to the right side of and at the level of the omphalion (mid-point of the navel). The subject stands and relaxes the abdominal wall musculature as much as possible and breathes normally.
A vertical fold is lifted at the site and the caliper is applied 1 cm inferiorly to this point.

**Medial calf skinfold**
The site is located on the medial aspect of the leg at the level of the greatest girth
The subject may raise the right leg and rest it on the stool or bench to assist the tester
A vertical fold is lifted at the site and the caliper is applied 1 cm distal to the left index finger and thumb.

**Front thigh skinfold**
With the subject seated, the site for this skinfold is located on the anterior thigh, at the midpoint between the inguinal crease and the proximal border of the patella.
The subject flexes the hip to assist location of the inguinal crease. A fold lifted parallel to the shaft of the femur at the site and the caliper is applied `1 cm distal to the index finger and thumb
Where the fold is difficult to obtain, the subject is asked to support the hamstring musculature to relieve tension from the skin.

## Appendix G: Borg scale

### Rate of Perceived Exertion (RPE)

| Rating | Perception |
|---|---|
| 6 | |
| 7 | Very, very light |
| 8 | |
| 9 | Very light |
| 10 | |
| 11 | Fairly light |
| 12 | |
| 13 | Somewhat hard |
| 14 | |
| 15 | Hard |
| 16 | |
| 17 | Very hard |
| 18 | |
| 19 | Very, very hard |
| 20 | |

## Appendix H: Tables

**Table 1:** Split times for each 50m of the time trial performance

| Subject | T50 | T100 | T150 | T200 |
|---|---|---|---|---|
| 1 | 32.02 | 64.80 | | 64.80 |
| 2 | 30.67 | 65.20 | 99.50 | 134.25 |
| 3 | 30.05 | 62.84 | 95.80 | 127.70 |
| 4 | 29.70 | 61.21 | 94.40 | 125.22 |
| 5 | 27.33 | 64.10 | 99.20 | 133.60 |
| 6 | 27.90 | 57.87 | 88.20 | 117.70 |
| 7 | 32.58 | 70.00 | 108.40 | 147.10 |
| 8 | 32.13 | 70.73 | 111.13 | 145.26 |
| 9 | 30.83 | 63.70 | 97.50 | 130.30 |
| 10 | 31.70 | 65.64 | 100.40 | 133.80 |
| 11 | 28.82 | 65.10 | 106.60 | 138.20 |
| 12 | 28.82 | 60.00 | 92.00 | 122.80 |
| Average | 30.21 | 64.27 | 99.38 | 126.73 |
| SD | 1.74 | 3.68 | 7.02 | 21.30 |

| Subject | T50 | T100 | T150 | T200 |
|---|---|---|---|---|
| 1 | 31.5 | 64.80 | | 64.80 |
| 2 | 30.58 | 64.60 | 98.31 | 133.20 |
| 3 | 30.58 | 63.10 | 96.03 | 127.50 |
| 4 | 29.07 | 61.10 | 93.15 | 125.02 |
| 5 | 29.27 | 62.60 | 96.61 | 130.40 |
| 6 | 27.56 | 57.34 | 87.40 | 117.00 |
| 7 | 32.69 | 70.10 | 109.00 | 146.70 |
| 8 | 31.49 | 68.60 | 108.60 | 141.95 |
| 9 | 31.16 | 64.20 | 97.93 | 131.00 |
| 10 | 31.70 | 65.10 | 98.90 | 130.90 |
| 11 | 28.74 | 64.20 | 104.90 | 137.10 |
| 12 | 28.14 | 58.95 | 90.30 | 121.70 |
| Average | 30.21 | 63.72 | 98.28 | 125.61 |
| SD | 1.61 | 3.58 | 6.94 | 20.83 |

**Table 2:** Stroke rate for both conditions

Control

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Seg 1 | 50.63 | 49.88 | 49.02 | 45.92 | 51.55 | 52.94 | 43.73 | 40.32 | 38.5 | 44.40 | 45.90 | 51.90 |
| Seg 2 | 48.21 | 40.78 | 48.47 | 41.38 | 50.75 | 46.79 | 42.00 | 36.97 | 34.20 | 42.00 | 43.20 | 49.80 |
| Average first 50 | 49.42 | 45.33 | 48.75 | 43.65 | 51.15 | 49.87 | 42.87 | 38.65 | 36.35 | 43.20 | 44.55 | 50.85 |
| Seg 3 | 48.70 | 45.45 | 47.51 | 39.70 | 48.26 | 44.69 | 42.77 | 35.86 | 34.40 | 40.20 | 39.70 | 35.50 |
| Seg 4 | 52.08 | 43.83 | 47.62 | 40.27 | 49.59 | 41.86 | 42.25 | 35.53 | 33.70 | 39.40 | 38.90 | 35.20 |
| Average second 50 | 50.39 | 44.64 | 47.57 | 39.98 | 48.92 | 43.28 | 42.51 | 35.69 | 34.05 | 39.80 | 39.30 | 35.35 |
| Seg 5 | | 46.23 | 48.78 | 40.82 | 49.53 | 50.08 | 44.53 | 34.94 | 34.50 | 40.50 | 37.10 | 36.70 |
| Seg 6 | | 44.63 | 48.74 | 41.24 | 49.02 | 50.56 | 44.44 | 35.78 | 34.50 | 39.70 | 37.70 | 37.10 |
| Average third 50 | | 45.43 | 48.76 | 41.03 | 49.27 | 50.32 | 44.49 | 35.36 | 34.50 | 40.10 | 37.40 | 36.90 |
| Seg 7 | | 46.79 | 57.20 | 48.56 | 56.49 | 46.00 | 52.53 | 39.18 | 36.40 | 41.20 | 38.70 | 44.70 |
| Seg 8 | | 47.62 | 50.00 | 44.70 | 50.00 | 51.72 | 46.51 | 38.24 | 37.20 | 41.30 | 41.40 | 50.90 |
| Average fourth 50 | | 47.21 | 53.60 | 46.63 | 53.24 | 48.86 | 49.52 | 38.71 | 36.80 | 41.25 | 40.05 | 47.80 |
| | 49.91 | 45.65 | 49.67 | 42.82 | 50.65 | 48.08 | 44.85 | 37.10 | 35.43 | 41.09 | 40.33 | 42.73 |

Jacket

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Seg 1 | 52.40 | 50.36 | 50.00 | 44.51 | 51.37 | 51.87 | 45.18 | 40.65 | 49.60 | 43.60 | 44.90 | 52.00 |
| Seg 2 | 50.00 | 46.88 | 50.08 | 44.36 | 49.91 | 46.15 | 44.21 | 37.23 | 36.70 | 41.40 | 42.50 | 50.20 |
| Average first 50 | 51.20 | 48.62 | 50.04 | 44.44 | 50.64 | 49.01 | 44.70 | 38.94 | 43.15 | 42.50 | 43.70 | 51.10 |
| Seg 3 | 49.18 | 46.15 | 50.00 | 41.81 | 50.00 | 44.28 | 44.21 | 36.14 | 34.60 | 39.50 | 39.30 | 37.70 |
| Seg 4 | 50.17 | 44.63 | 49.34 | 42.11 | 49.72 | 41.99 | 44.20 | 36.75 | 34.70 | 39.70 | 39.20 | 36.30 |
| Average second 50 | 49.67 | 45.39 | 49.67 | 41.96 | 49.86 | 43.14 | 44.20 | 36.45 | 34.65 | 39.60 | 39.25 | 37.00 |
| Seg 5 | | 46.71 | 51.06 | 43.24 | 50.31 | 49.59 | 45.45 | 35.84 | 35.60 | 40.40 | 39.60 | 37.30 |
| Seg 6 | | 45.76 | 50.68 | 42.03 | 49.92 | 49.93 | 44.86 | 34.78 | 34.40 | 39.30 | 38.80 | 37.90 |
| Average third 50 | | 46.24 | 50.87 | 42.64 | 50.12 | 49.76 | 45.16 | 35.31 | 35.00 | 39.85 | 39.20 | 37.60 |
| Seg 7 | | 48.47 | 51.33 | 48.74 | 51.92 | 48.47 | 52.84 | 46.23 | 35.90 | 41.50 | 41.70 | 49.10 |
| Seg 8 | | 48.39 | 50.76 | 45.08 | 51.81 | 47.04 | 46.15 | 42.93 | 36.60 | 41.40 | 43.40 | 49.30 |
| Average fourth 50 | | 48.43 | 51.05 | 46.91 | 51.87 | 47.76 | 49.50 | 44.58 | 36.25 | 41.45 | 42.55 | 49.20 |
| | 50.44 | 47.17 | 50.41 | 43.98 | 50.62 | 47.42 | 45.89 | 38.82 | 37.26 | 40.85 | 41.18 | 43.73 |

**Table 3:** Stroke count for both conditions

Control

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1st 50 | 38 | 41 | 20 | 35 | 20 | 21 | 33 | 17 | 28 | 33 | 34 | 19 |
| 2nd 50 | 43 | 45 | 23 | 39 | 22 | 46 | 39 | 19 | 32 | 37 | 36 | 38 |
| 3rd 50 | | 46 | 23 | 40 | 23 | 30 | 41 | 20 | 32 | 39 | 35 | 22 |
| 4th 50 | | 48 | 24 | 43 | 23 | 52 | 42 | 22 | 35 | 40 | 36 | 47 |
| Total | 81 | 180 | 90 | 157 | 88 | 149 | 155 | 78 | 127 | 149 | 141 | 126 |
| | 40.5 | 45 | 22.5 | 39.25 | 22 | 37.25 | 38.75 | 19.5 | 31.75 | 37.25 | 35.25 | 31.5 |

Jacket

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1st 50 | 38 | 42 | 20 | 36 | 20 | 20 | 34 | 18 | 30 | 33 | 35 | 20 |
| 2nd 50 | 42 | 45 | 23 | 41 | 22 | 44 | 39 | 20 | 32 | 37 | 35 | 37 |
| 3rd 50 | | 47 | 24 | 41 | 24 | 29 | 41 | 20 | 33 | 38 | 37 | 22 |
| 4th 50 | | 48 | 25 | 44 | 25 | 47 | 42 | 23 | 35 | 40 | 39 | 48 |
| Total | 80 | 182 | 92 | 162 | 91 | 140 | 156 | 81 | 130 | 148 | 146 | 127 |
| | 40 | 45.5 | 23 | 40.5 | 22.75 | 35 | 39 | 20.25 | 32.5 | 37 | 36.5 | 31.75 |

**Table 4:** Paired samples t-test for time trial performance

| | | Paired Differences | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | 95% Confidence Interval of the Difference | | | | |
| | | Mean | Std. Deviation | Std. Error Mean | Lower | Upper | t | df | Sig. (2-tailed) |
| Pair 1 | C50 - J50 | .00583 | .72829 | .21024 | -.45690 | .46857 | .028 | 11 | .978 |
| Pair 2 | C100 - J100 | .54167 | .76579 | .22106 | .05511 | 1.02823 | 2.450 | 11 | .032 |
| Pair 3 | C150 - J150 | 1.09091 | 1.10745 | .33391 | .34691 | 1.83491 | 3.267 | 10 | .008 |
| Pair 4 | C200 - J200 | 1.22273 | 1.33555 | .40268 | .32550 | 2.11996 | 3.036 | 10 | .013 |

**Table 5:** Two way repeated measures ANOVA for SR

| Source | | Type III Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|---|
| Condition | Sphericity Assumed | 14.589 | 1 | 14.589 | 12.704 | .005 |
| | Greenhouse-Geisser | 14.589 | 1.000 | 14.589 | 12.704 | .005 |
| | Huynh-Feldt | 14.589 | 1.000 | 14.589 | 12.704 | .005 |
| | Lower-bound | 14.589 | 1.000 | 14.589 | 12.704 | .005 |
| Error(Condition) | Sphericity Assumed | 11.483 | 10 | 1.148 | | |
| | Greenhouse-Geisser | 11.483 | 10.000 | 1.148 | | |
| | Huynh-Feldt | 11.483 | 10.000 | 1.148 | | |
| | Lower-bound | 11.483 | 10.000 | 1.148 | | |
| Time | Sphericity Assumed | 327.237 | 3 | 109.079 | 9.652 | .000 |
| | Greenhouse-Geisser | 327.237 | 2.001 | 163.513 | 9.652 | .001 |
| | Huynh-Feldt | 327.237 | 2.502 | 130.781 | 9.652 | .000 |
| | Lower-bound | 327.237 | 1.000 | 327.237 | 9.652 | .011 |
| Error(Time) | Sphericity Assumed | 339.037 | 30 | 11.301 | | |
| | Greenhouse-Geisser | 339.037 | 20.013 | 16.941 | | |
| | Huynh-Feldt | 339.037 | 25.022 | 13.550 | | |
| | Lower-bound | 339.037 | 10.000 | 33.904 | | |
| Condition * Time | Sphericity Assumed | 1.147 | 3 | .382 | .230 | .874 |
| | Greenhouse-Geisser | 1.147 | 1.837 | .624 | .230 | .778 |
| | Huynh-Feldt | 1.147 | 2.231 | .514 | .230 | .819 |
| | Lower-bound | 1.147 | 1.000 | 1.147 | .230 | .642 |
| Error(Condition *Time) | Sphericity Assumed | 49.789 | 30 | 1.660 | | |
| | Greenhouse-Geisser | 49.789 | 18.372 | 2.710 | | |
| | Huynh-Feldt | 49.789 | 22.307 | 2.232 | | |
| | Lower-bound | 49.789 | 10.000 | 4.979 | | |

**Table 6:** Paired samples t-test for SR

| | | Paired Differences | | | | | t | df | Sig. (2-tailed) |
|---|---|---|---|---|---|---|---|---|---|
| | | Mean | Std. Deviation | Std. Error Mean | 95% Confidence Interval of the Difference | | | | |
| | | | | | Lower | Upper | | | |
| Pair 1 | Control50 - PassiveH50 | -1.05636 | 2.29750 | .69272 | -2.59985 | .48712 | -1.525 | 10 | .158 |
| Pair 2 | Control100 - PassiveH100 | -.91636 | .84367 | .25438 | -1.48315 | -.34958 | -3.602 | 10 | .005 |
| Pair 3 | Control150 - PassiveH150 | -.84273 | .91764 | .27668 | -1.45921 | -.22625 | -3.046 | 10 | .012 |
| Pair 4 | Control200 - PassiveH200 | -.44182 | 2.32854 | .70208 | -2.00616 | 1.12252 | -.629 | 10 | .543 |

**Table 7:** Two way repeated measures ANOVA for SC

| Source | | Type III Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|---|
| Condition | Sphericity Assumed | 2.557 | 1 | 2.557 | 1.377 | .268 |
| | Greenhouse-Geisser | 2.557 | 1.000 | 2.557 | 1.377 | .268 |
| | Huynh-Feldt | 2.557 | 1.000 | 2.557 | 1.377 | .268 |
| | Lower-bound | 2.557 | 1.000 | 2.557 | 1.377 | .268 |
| Error(Condition) | Sphericity Assumed | 18.568 | 10 | 1.857 | | |
| | Greenhouse-Geisser | 18.568 | 10.000 | 1.857 | | |
| | Huynh-Feldt | 18.568 | 10.000 | 1.857 | | |
| | Lower-bound | 18.568 | 10.000 | 1.857 | | |
| Time | Sphericity Assumed | 1139.034 | 3 | 379.678 | 8.312 | .000 |
| | Greenhouse-Geisser | 1139.034 | 1.096 | 1039.371 | 8.312 | .014 |
| | Huynh-Feldt | 1139.034 | 1.129 | 1008.684 | 8.312 | .013 |
| | Lower-bound | 1139.034 | 1.000 | 1139.034 | 8.312 | .016 |
| Error(Time) | Sphericity Assumed | 1370.341 | 30 | 45.678 | | |
| | Greenhouse-Geisser | 1370.341 | 10.959 | 125.044 | | |
| | Huynh-Feldt | 1370.341 | 11.292 | 121.352 | | |
| | Lower-bound | 1370.341 | 10.000 | 137.034 | | |
| Condition * Time | Sphericity Assumed | 1.580 | 3 | .527 | 1.068 | .378 |
| | Greenhouse-Geisser | 1.580 | 1.997 | .791 | 1.068 | .363 |
| | Huynh-Feldt | 1.580 | 2.495 | .633 | 1.068 | .371 |
| | Lower-bound | 1.580 | 1.000 | 1.580 | 1.068 | .326 |
| Error(Condition*Time) | Sphericity Assumed | 14.795 | 30 | .493 | | |
| | Greenhouse-Geisser | 14.795 | 19.971 | .741 | | |
| | Huynh-Feldt | 14.795 | 24.952 | .593 | | |
| | Lower-bound | 14.795 | 10.000 | 1.480 | | |

**Table 8:** Two way repeated measures ANOVA for $T_{core}$

| Source | | Type III Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|---|
| Condition | Sphericity Assumed | .424 | 1 | .424 | .644 | .446 |
| | Greenhouse-Geisser | .424 | 1.000 | .424 | .644 | .446 |
| | Huynh-Feldt | .424 | 1.000 | .424 | .644 | .446 |
| | Lower-bound | .424 | 1.000 | .424 | .644 | .446 |
| Error(Condition) | Sphericity Assumed | 5.275 | 8 | .659 | | |
| | Greenhouse-Geisser | 5.275 | 8.000 | .659 | | |
| | Huynh-Feldt | 5.275 | 8.000 | .659 | | |
| | Lower-bound | 5.275 | 8.000 | .659 | | |
| Time | Sphericity Assumed | 7.803 | 4 | 1.951 | 8.191 | .000 |
| | Greenhouse-Geisser | 7.803 | 2.669 | 2.923 | 8.191 | .001 |
| | Huynh-Feldt | 7.803 | 4.000 | 1.951 | 8.191 | .000 |
| | Lower-bound | 7.803 | 1.000 | 7.803 | 8.191 | .021 |
| Error(Time) | Sphericity Assumed | 7.621 | 32 | .238 | | |
| | Greenhouse-Geisser | 7.621 | 21.352 | .357 | | |
| | Huynh-Feldt | 7.621 | 32.000 | .238 | | |
| | Lower-bound | 7.621 | 8.000 | .953 | | |
| Condition * Time | Sphericity Assumed | .082 | 4 | .021 | .263 | .900 |
| | Greenhouse-Geisser | .082 | 2.605 | .032 | .263 | .825 |
| | Huynh-Feldt | .082 | 3.975 | .021 | .263 | .899 |
| | Lower-bound | .082 | 1.000 | .082 | .263 | .622 |
| Error(Condition*Time) | Sphericity Assumed | 2.506 | 32 | .078 | | |
| | Greenhouse-Geisser | 2.506 | 20.840 | .120 | | |
| | Huynh-Feldt | 2.506 | 31.801 | .079 | | |
| | Lower-bound | 2.506 | 8.000 | .313 | | |

**Table 9**: Two way repeated measures ANOVA for Blood Lactate

| Source | | Type III Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|---|
| Condition | Sphericity Assumed | 2.628 | 1 | 2.628 | 1.252 | .287 |
| | Greenhouse-Geisser | 2.628 | 1.000 | 2.628 | 1.252 | .287 |
| | Huynh-Feldt | 2.628 | 1.000 | 2.628 | 1.252 | .287 |
| | Lower-bound | 2.628 | 1.000 | 2.628 | 1.252 | .287 |
| Error(Condition) | Sphericity Assumed | 23.098 | 11 | 2.100 | | |
| | Greenhouse-Geisser | 23.098 | 11.000 | 2.100 | | |
| | Huynh-Feldt | 23.098 | 11.000 | 2.100 | | |
| | Lower-bound | 23.098 | 11.000 | 2.100 | | |
| Time | Sphericity Assumed | 3266.890 | 4 | 816.723 | 250.832 | .000 |
| | Greenhouse-Geisser | 3266.890 | 1.495 | 2185.181 | 250.832 | .000 |
| | Huynh-Feldt | 3266.890 | 1.677 | 1948.008 | 250.832 | .000 |
| | Lower-bound | 3266.890 | 1.000 | 3266.890 | 250.832 | .000 |
| Error(Time) | Sphericity Assumed | 143.266 | 44 | 3.256 | | |
| | Greenhouse-Geisser | 143.266 | 16.445 | 8.712 | | |
| | Huynh-Feldt | 143.266 | 18.447 | 7.766 | | |
| | Lower-bound | 143.266 | 11.000 | 13.024 | | |
| Condition * Time | Sphericity Assumed | 4.483 | 4 | 1.121 | 2.146 | .091 |
| | Greenhouse-Geisser | 4.483 | 1.893 | 2.369 | 2.146 | .144 |
| | Huynh-Feldt | 4.483 | 2.274 | 1.971 | 2.146 | .133 |
| | Lower-bound | 4.483 | 1.000 | 4.483 | 2.146 | .171 |
| Error(Condition*Time) | Sphericity Assumed | 22.981 | 44 | .522 | | |
| | Greenhouse-Geisser | 22.981 | 20.819 | 1.104 | | |
| | Huynh-Feldt | 22.981 | 25.016 | .919 | | |
| | Lower-bound | 22.981 | 11.000 | 2.089 | | |

**Table 10:** Two way repeated measures ANOVA for heart rate

| Source | | Type III Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|---|
| Condition | Sphericity Assumed | .008 | 1 | .008 | .000 | .996 |
| | Greenhouse-Geisser | .008 | 1.000 | .008 | .000 | .996 |
| | Huynh-Feldt | .008 | 1.000 | .008 | .000 | .996 |
| | Lower-bound | .008 | 1.000 | .008 | .000 | .996 |
| Error(Condition) | Sphericity Assumed | 3402.092 | 11 | 309.281 | | |
| | Greenhouse-Geisser | 3402.092 | 11.000 | 309.281 | | |
| | Huynh-Feldt | 3402.092 | 11.000 | 309.281 | | |
| | Lower-bound | 3402.092 | 11.000 | 309.281 | | |
| Time | Sphericity Assumed | 89378.950 | 4 | 22344.738 | 252.376 | .000 |
| | Greenhouse-Geisser | 89378.950 | 2.610 | 34250.502 | 252.376 | .000 |
| | Huynh-Feldt | 89378.950 | 3.494 | 25581.901 | 252.376 | .000 |
| | Lower-bound | 89378.950 | 1.000 | 89378.950 | 252.376 | .000 |
| Error(Time) | Sphericity Assumed | 3895.650 | 44 | 88.538 | | |
| | Greenhouse-Geisser | 3895.650 | 28.705 | 135.712 | | |
| | Huynh-Feldt | 3895.650 | 38.432 | 101.364 | | |
| | Lower-bound | 3895.650 | 11.000 | 354.150 | | |
| Condition * Time | Sphericity Assumed | 418.617 | 4 | 104.654 | 1.499 | .219 |
| | Greenhouse-Geisser | 418.617 | 3.322 | 126.021 | 1.499 | .229 |
| | Huynh-Feldt | 418.617 | 4.000 | 104.654 | 1.499 | .219 |
| | Lower-bound | 418.617 | 1.000 | 418.617 | 1.499 | .246 |
| Error(Condition*Time) | Sphericity Assumed | 3072.783 | 44 | 69.836 | | |
| | Greenhouse-Geisser | 3072.783 | 36.540 | 84.094 | | |
| | Huynh-Feldt | 3072.783 | 44.000 | 69.836 | | |
| | Lower-bound | 3072.783 | 11.000 | 279.344 | | |

**Table 11**: Two way repeated measures ANOVA for RPE

| Source | | Type III Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|---|
| Condition | Sphericity Assumed | 1.008 | 1 | 1.008 | .364 | .559 |
| | Greenhouse-Geisser | 1.008 | 1.000 | 1.008 | .364 | .559 |
| | Huynh-Feldt | 1.008 | 1.000 | 1.008 | .364 | .559 |
| | Lower-bound | 1.008 | 1.000 | 1.008 | .364 | .559 |
| Error(Condition) | Sphericity Assumed | 30.492 | 11 | 2.772 | | |
| | Greenhouse-Geisser | 30.492 | 11.000 | 2.772 | | |
| | Huynh-Feldt | 30.492 | 11.000 | 2.772 | | |
| | Lower-bound | 30.492 | 11.000 | 2.772 | | |
| Time | Sphericity Assumed | 1748.633 | 4 | 437.158 | 180.159 | .000 |
| | Greenhouse-Geisser | 1748.633 | 2.682 | 652.102 | 180.159 | .000 |
| | Huynh-Feldt | 1748.633 | 3.628 | 481.999 | 180.159 | .000 |
| | Lower-bound | 1748.633 | 1.000 | 1748.633 | 180.159 | .000 |
| Error(Time) | Sphericity Assumed | 106.767 | 44 | 2.427 | | |
| | Greenhouse-Geisser | 106.767 | 29.497 | 3.620 | | |
| | Huynh-Feldt | 106.767 | 39.907 | 2.675 | | |
| | Lower-bound | 106.767 | 11.000 | 9.706 | | |
| Condition * Time | Sphericity Assumed | 5.200 | 4 | 1.300 | 1.692 | .169 |
| | Greenhouse-Geisser | 5.200 | 2.541 | 2.046 | 1.692 | .197 |
| | Huynh-Feldt | 5.200 | 3.368 | 1.544 | 1.692 | .181 |
| | Lower-bound | 5.200 | 1.000 | 5.200 | 1.692 | .220 |
| Error(Condition*Time) | Sphericity Assumed | 33.800 | 44 | .768 | | |
| | Greenhouse-Geisser | 33.800 | 27.952 | 1.209 | | |
| | Huynh-Feldt | 33.800 | 37.052 | .912 | | |
| | Lower-bound | 33.800 | 11.000 | 3.073 | | |

**Table 12:** Paired samples t-test for $T_{core}$

| | | Paired Differences | | | | | t | df | Sig. (2-tailed) |
|---|---|---|---|---|---|---|---|---|---|
| | | Mean | Std. Deviation | Std. Error Mean | 95% Confidence Interval of the Difference | | | | |
| | | | | | Lower | Upper | | | |
| Pair 1 | Temp1C - Temp1J | -.15111 | .31478 | .10493 | -.39307 | .09085 | -1.440 | 8 | .188 |
| Pair 2 | Temp2C - Temp2J | -.11111 | .49494 | .16498 | -.49155 | .26933 | -.673 | 8 | .520 |
| Pair 3 | Temp3C - Temp3J | -.20444 | .54955 | .18318 | -.62686 | .21798 | -1.116 | 8 | .297 |
| Pair 4 | Temp4C - Temp4J | -.18556 | .67086 | .22362 | -.70122 | .33011 | -.830 | 8 | .431 |
| Pair 5 | Temp5C - Temp5J | -.03444 | .92143 | .30714 | -.74272 | .67383 | -.112 | 8 | .913 |

**Table 13:** Paired samples t-test for Blood Lactate

| | | Paired Differences | | | | | t | df | Sig. (2-tailed) |
|---|---|---|---|---|---|---|---|---|---|
| | | Mean | Std. Deviation | Std. Error Mean | 95% Confidence Interval of the Difference | | | | |
| | | | | | Lower | Upper | | | |
| Pair 1 | Lactate1C - Lactate1J | -.01917 | .42382 | .12235 | -.28845 | .25012 | -.157 | 11 | .878 |
| Pair 2 | Lactate2C - Lactate2J | .05750 | .73263 | .21149 | -.40799 | .52299 | .272 | 11 | .791 |
| Pair 3 | Lactate3C - Lactate3J | -.06250 | .33537 | .09681 | -.27559 | .15059 | -.646 | 11 | .532 |
| Pair 4 | Lactate4C - Lactate4J | -.48500 | 2.00338 | .57833 | -1.75789 | .78789 | -.839 | 11 | .420 |
| Pair 5 | Lactate5C - Lactate5J | -.97083 | 1.88034 | .54281 | -2.16554 | .22388 | -1.789 | 11 | .101 |

**Table 14**: Paired samples t-test for Heart rate

| | | Paired Differences | | | | | t | df | Sig. (2-tailed) |
|---|---|---|---|---|---|---|---|---|---|
| | | Mean | Std. Deviation | Std. Error Mean | 95% Confidence Interval of the Difference | | | | |
| | | | | | Lower | Upper | | | |
| Pair 1 | HR1C - HR1J | .41667 | 13.43982 | 3.87974 | -8.12259 | 8.95592 | .107 | 11 | .916 |
| Pair 2 | HR2C - HR2J | -1.33333 | 18.32204 | 5.28912 | -12.97460 | 10.30793 | -.252 | 11 | .806 |
| Pair 3 | HR3C - HR3J | 6.75000 | 12.01609 | 3.46875 | -.88466 | 14.38466 | 1.946 | 11 | .078 |
| Pair 4 | HR4C - HR4J | -4.50000 | 17.93676 | 5.17790 | -15.89647 | 6.89647 | -.869 | 11 | .403 |
| Pair 5 | HR5C - HR5J | -1.41667 | 13.95746 | 4.02917 | -10.28481 | 7.45148 | -.352 | 11 | .732 |

**Table 15**: Paired samples t-test for RPE

| | | Paired Differences | | | | | t | df | Sig. (2-tailed) |
|---|---|---|---|---|---|---|---|---|---|
| | | Mean | Std. Deviation | Std. Error Mean | 95% Confidence Interval of the Difference | | | | |
| | | | | | Lower | Upper | | | |
| Pair 1 | RPE1C - RPE1J | -.33333 | 1.49747 | .43228 | -1.28478 | .61812 | -.771 | 11 | .457 |
| Pair 2 | RPE2C - RPE2J | -.75000 | .62158 | .17944 | -1.14493 | -.35507 | -4.180 | 11 | .002 |
| Pair 3 | RPE3C - RPE3J | .50000 | 2.23607 | .64550 | -.92073 | 1.92073 | .775 | 11 | .455 |
| Pair 4 | RPE4C - RPE4J | -.33333 | 1.30268 | .37605 | -1.16102 | .49435 | -.886 | 11 | .394 |
| Pair 5 | RPE5C - RPE5J | .00000 | 1.53741 | .44381 | -.97683 | .97683 | .000 | 11 | 1.000 |

**Table 16:** Correlation between change in performance and change in temperature during the passive heat maintenance condition

| | | PassiveTemp | ChangePerformance |
|---|---|---|---|
| PassiveTemp | Pearson Correlation | 1 | -.122 |
| | Sig. (2-tailed) | | .755 |
| | N | 9 | 9 |
| ChangePerformance | Pearson Correlation | -.122 | 1 |
| | Sig. (2-tailed) | .755 | |
| | N | 9 | 9 |

**Table 17:** Correlation between change in performance and change in temperature during the control condition

| | | ControlTemp | ChangePerform |
|---|---|---|---|
| ControlTemp | Pearson Correlation | 1 | -.289 |
| | Sig. (2-tailed) | | .451 |
| | N | 9 | 9 |
| ChangePerform | Pearson Correlation | -.289 | 1 |
| | Sig. (2-tailed) | .451 | |
| | N | 9 | 9 |

**Table 18**: Correlation between sum of skinfold data in relation to changes in pre TT temperatures between conditions

| | | VAR00001 | VAR00002 |
|---|---|---|---|
| VAR00001 | Pearson Correlation | 1 | .222 |
| | Sig. (2-tailed) | | .597 |
| | N | 8 | 8 |
| VAR00002 | Pearson Correlation | .222 | 1 |
| | Sig. (2-tailed) | .597 | |
| | N | 8 | 8 |

**Table 19**: Correlation between sum of skinfold and change in temperature from baseline to post WU in the control condition

| | | Temperature | SumSkinfold |
|---|---|---|---|
| Temperature | Pearson Correlation | 1 | -.473 |
| | Sig. (2-tailed) | | .237 |
| | N | 8 | 8 |
| SumSkinfold | Pearson Correlation | -.473 | 1 |
| | Sig. (2-tailed) | .237 | |
| | N | 8 | 8 |

## Appendix I: Figures

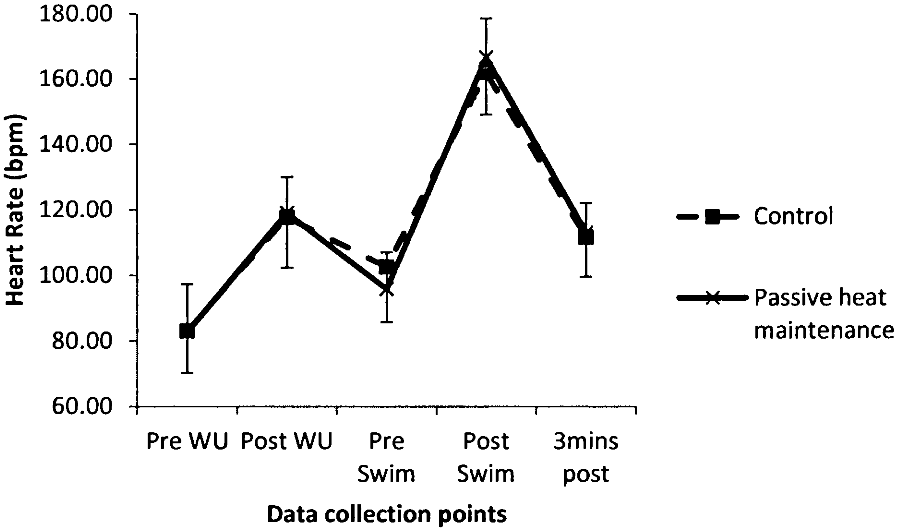

**Figure 1:** The heart rate response to the control and passive heat maintenance conditions (n=12)

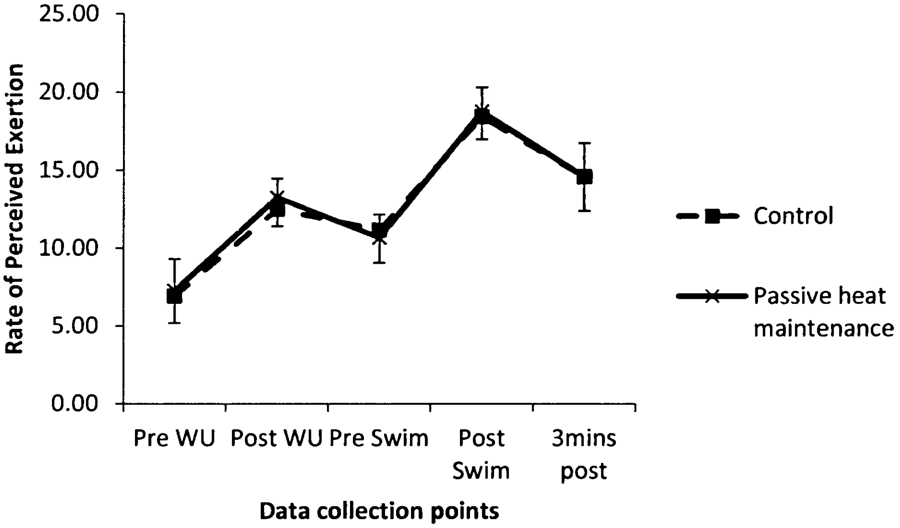

**Figure 2:** The RPE response to the control and passive heat maintenance conditions

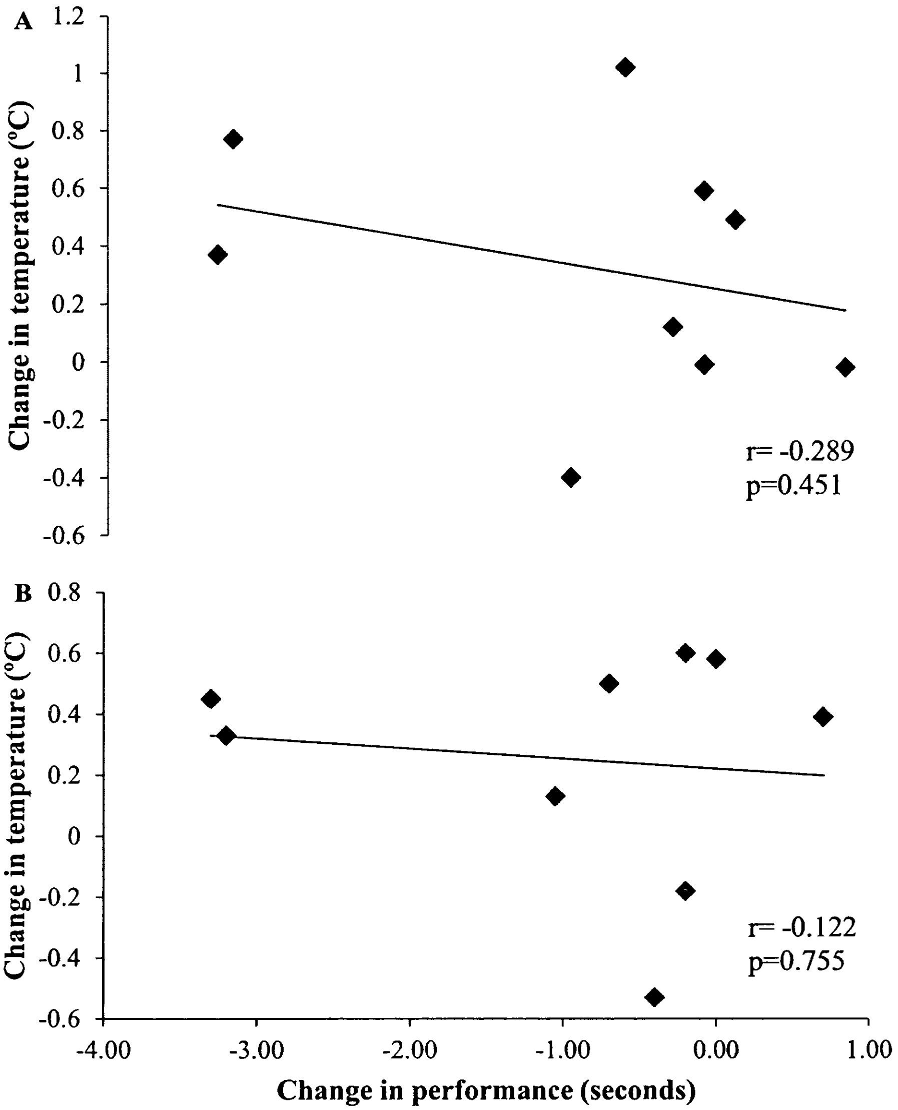

**Figure 3:** Change in performance correlated against the change in temperature in the control (A) and passive heat maintenance conditions (B)

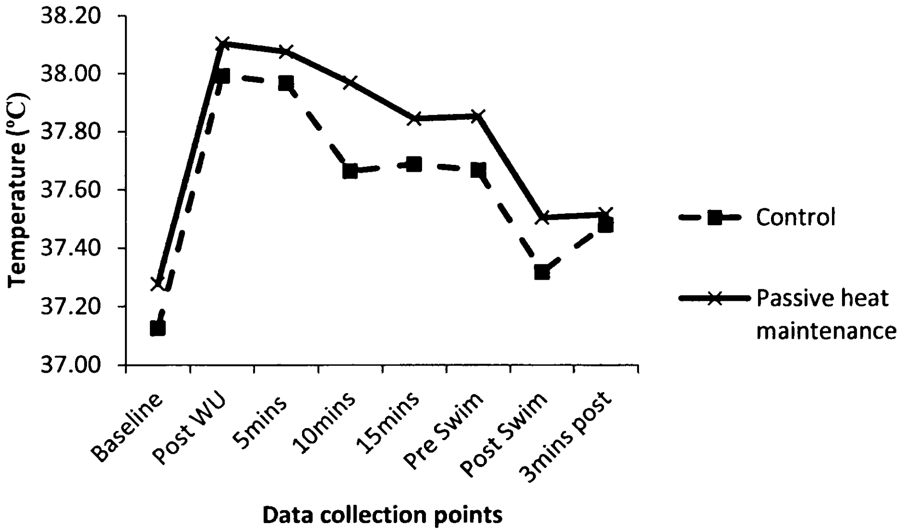

**Figure 4**: The $T_{core}$ response including data collection within the 15 minute rest period