Competition day preparation strategies to enhance performance in swimmers

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Dedication

This thesis is dedicated to Forbes and Ursula Carlile - pioneers of applied swimming research.
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• 2015 Recipient of the Sports Medicine Australia (ACT Branch) Best Young Investigator Award

• 2015 University of Canberra Department of Sport and Exercise Science Higher Degree Research Student of the Year

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Abstract

In the lead up to major competitions, swimming coaches and sport scientists spend many hours ensuring their athlete’s training and recovery strategies are appropriate to elicit optimal performance. However, on competition day itself there are additional opportunities in which event performance might be improved by utilising various preconditioning strategies, the most common being the pre-competition warm-up. Both passive and active warm-ups can enhance swimming performance, though the competition warm-up practices of elite swimming coaches are presently unknown or have been poorly documented. In addition, competitive swimmers typically experience a delay between the pool warm-up and race start (transition phase). Transition phases of > 20 min are not uncommon which is problematic given that muscle temperature declines immediately following exercise, with appreciable reductions occurring after ~15-20 min. Additional warm-up strategies within the transition phase may therefore be required to optimise performance. Recent research has also demonstrated that completion of an exercise bout several hours prior to a competitive event may provide a priming effect to improve performance later that same day. The studies contained within this thesis aimed to investigate how altering the content of these two preconditioning strategies would affect subsequent sprint swimming performance.

Study 1: An initial survey was conducted to determine the current pre-competition warm-up practices and contemporary issues faced by elite swimming coaches (n = 46) during competition. The combination of dryland-based activation exercises followed by pool-based warm-up routines appears to be the preferred approach taken by elite swimming coaches when preparing their athletes for racing. Elite swimming coaches believe the pool warm-up affords athletes the opportunity to gain a tactile “feel” for the water and surrounding pool environment. Coaches stated that transition phases were unnecessarily lengthened due to extended marshalling periods (> 15-20 min), delays in the competition schedule and the lengthy time required to don race swimsuits (~10 min). Therefore, a number of experimental studies were undertaken to address the issue of lengthy transition phases.

Study 2: In the first of these investigations, 16 national junior swimmers completed a standardised pool warm-up followed by a 30 min transition phase and a 100 m freestyle time-trial. Within the transition phase, swimmers wore a conventional tracksuit and remained
seated (Control), wore a tracksuit jacket with integrated heating elements (Passive), performed a dryland-based exercise routine (Dryland) or a combination of Passive and Dryland (Combo). Faster overall junior time-trial performances were recorded in Combo (1.1% ± 0.3%; mean ± 90% confidence limits, p < 0.01) and Dryland (0.7% ± 0.3%, p = 0.02), with start times (to 15 m) also faster for Combo (0.4% ± 0.1%, p < 0.01) compared to Control. Core temperature declined less during the transition phase in Combo (-0.1 ± 0.3°C, p = 0.01, effect size, ES, -1.18) compared to Control (-0.6 ± 0.2°C), with a smaller reduction in core temperature related to better time-trial performance (R² = 0.91, p = 0.04). Elite swimmers are more consistent performers (~0.8% typical variation in performance between competitions) than their less experienced counterparts (versus ~1.1%) and may not respond to the same degree to particular interventions. Therefore, the influence of the Combo additional warm-up strategy on elite swimming performance was investigated.

Studies 3 and 4: Elite sprint freestyle (n = 25) and breaststroke (n = 10; heated tracksuit pants were used) performance was examined following completion of the Control and Combo warm-up strategies. Faster start (1.5% ± 1.0%; mean ± 90% confidence limits, p = 0.02) and 100 m freestyle time-trial (0.8% ± 0.4%, p < 0.01) performances were yielded with Combo compared to Control. Core temperature again declined less during transition (-0.2°C ± 0.1°C versus -0.5°C ± 0.1°C, p = 0.02, ES, 0.78) within Combo compared to Control in freestyle swimmers. Total local (trapezius) haemoglobin concentration immediately prior to the 100 m freestyle time-trial was greater within Combo compared to Control (81µM ± 25µM; mean ± standard deviation, versus 30µM ± 18µM, p < 0.01, ES 1.45). Pre time-trial skin temperature was also higher in Combo (30.6 ± 1.0°C, p < 0.01, ES, 1.10) compared to Control (29.1 ± 1.2°C). Combo did not enhance elite sprint breaststroke performance (p = 0.55) despite significantly higher Tskin values recorded immediately prior to the 100 m time-trial in Combo (30.1 ± 0.9°C; mean ± standard deviation, p = 0.01, ES, 0.70) compared to Control (29.1 ± 1.3°C). It was unclear if the decline in core temperature during the transition phase was less in Combo (-0.1 ± 0.2°C; mean ± 90% confidence limits, p = 0.36, ES, 0.65) in comparison with Control (-0.3 ± 0.2°C) in elite breaststroke swimmers. Completion of additional warm-up strategies during the transition phase can enhance elite senior sprint freestyle, but not breaststroke performance.

Study 5: Completion of a morning (07:30-08:30) exercise priming bout consisting of swimming exercise (SwimOnly), swimming and dryland-based resistance exercise (SwimDry)
or no exercise (NoEx) was investigated to ascertain the effect upon afternoon swimming performance (n = 13). Following a six hour break, afternoon (14:30-16:00) time-trial performance was faster in SwimOnly (1.6 ± 0.6%; mean ± 90% confidence limits, p < 0.01) and SwimDry (1.7 ± 0.7%, p < 0.01). First 50 m stroke rate was higher in SwimOnly (0.70 ± 0.21 Hz; mean ± standard deviation, p = 0.03) and SwimDry (0.69 ± 0.18 Hz, p = 0.05) compared to NoEx (0.64 ± 0.16 Hz). Before the afternoon session, core (0.2°C ± 0.1°C; mean ± 90% confidence limits, p = 0.04, ES, 1.03), body (0.2°C ± 0.1°C, p = 0.02, ES, 1.74) and skin (0.3°C ± 0.3°C, p = 0.02, ES, 0.78) temperatures were higher in SwimDry compared to NoEx. Completion of a morning swimming exercise bout alone or in combination with resistance exercises can enhance afternoon sprint swimming performance.

Swimming coaches are concerned that lengthy marshalling periods may compromise the retention of beneficial effects induced by pre-competition warm-ups. Coaches can be advised that a combination of heated jackets and dryland-based activation exercises employed within lengthy transitions can yield benefits to sprint freestyle performance in the range of 0.8% (seniors) to 1.1% (juniors). Attenuation in the decline of core temperature and augmented total local haemoglobin concentration appear as likely mechanisms. Tracksuit pants integrated with heating elements covering a greater surface area may be required to enhance core temperature maintenance during lengthy transition phases and subsequently, elite sprint breaststroke performance. Preliminary evidence suggests that afternoon sprint swimming performance is enhanced following the completion of a morning exercise bout consisting of swimming exercise alone or in combination with resistance exercises. In summary, utilising additional warm-up strategies during the transition phase between pool warm-up end and race start and completion of a morning exercise bout prior to afternoon racing was shown to significantly enhance sprint swimming performance.
List of Abbreviations

ATP – adenosine triphosphate
cm – centimetres
CMJ – countermovement jump
FINA – Fédération internationale de natation
Hb – haemoglobin
Hb\textsubscript{diff} – haemoglobin difference (where Hb\textsubscript{diff} = oxyhaemoglobin – deoxyhaemoglobin concentration)
HR – heart rate
hr – hour
Kg – kilograms
La\textsuperscript{−} – capillary blood lactate
m – metres
MFCV – muscle fibre conduction velocity
min – minutes
mmol – millimolar units
O\textsubscript{2} – oxygen
O\textsubscript{2}Hb – oxyhaemoglobin
PAP – postactivation potentiation
PCr – creatinine phosphate
RM – repetition maximum
Rpm – revolutions per minute
sec – seconds (s in chapter 2 and 4)
T\textsubscript{core} – core temperature
tHb – total haemoglobin
T\textsubscript{muscle} – muscle temperature
T\textsubscript{skin} – skin temperature
µM – micromolar units
VO\textsubscript{2} – oxygen uptake
VO\textsubscript{2max} – maximal oxygen uptake
VO\textsubscript{2peak} – peak oxygen uptake
yr – year (y in chapter 4)
CHAPTER 1: Introduction

Swimming is a popular sport contested at both Olympic and World Championship level in pool and open water settings. In the lead up to major competitions, swimming coaches and sport scientists spend many hours ensuring their athlete’s training and recovery strategies are appropriate to elicit optimal performance. However, on competition day itself there are additional opportunities in which event performance might be improved by utilising various preconditioning strategies, the most common being the pre-competition warm-up.

Completion of a warm-up prior to a competitive exercise bout is a widely accepted practice within modern sport; with athletes and coaches alike believing that warming-up is essential for attaining optimal performance. Both passive and active warm-up strategies can enhance subsequent exercise performance, with one of the main purported benefits being an increase in body temperature. Initially, passive elevation of body temperature was achieved via external heating methods such as hot showers/baths. Hot showers (~47°C) lasting 8–10 min or 15-18 min hot baths (~40 °C), prompted an increase in muscle temperature ($T_{\text{muscle}}$), and were linked with improvements in the total work completed in a subsequent exercise bout and swimming performances over 36.6 m, 50 m and 400 m. More recently, hot (43°C) water-perfused tracksuit pants have been shown to attenuate the decline in $T_{\text{muscle}}$ for up to 30 min following an active cycle ergometer warm-up. However, while effective, the practicality of completing these types of passive warm-up strategies within the competition environment is often impractical. Therefore, an active warm-up has traditionally been the most commonly utilised form of warm-up. Furthermore, completion of an active warm-up has been reported to induce greater metabolic changes than that of a passive warm-up, enhancing preparedness for a subsequent exercise task.

The effectiveness of an active warm-up strategy is determined largely by its composition, including the intensity and duration of the physical elements, as well as the time between the end of the warm-up and the start of the subsequent exercise bout, here termed the transition phase. In swimming, both pool- and dryland-based active warm-ups are typically employed. Pool-based warm-ups can elicit improvements and similar subsequent swimming performances in comparison to when no warm-up is performed (Appendix 1). Dryland-based warm-ups completed separately can also produce comparable improvements
In performances\textsuperscript{26,28,29} to that of a pool-based warm-up, though two studies have reported inferior performances\textsuperscript{19,30}.

In a recent review article, a pool warm-up of 1000-1500 m was considered optimal, with the inclusion of technical stroke drills along with a set of race-pace efforts recommended to improve swimming efficiency and permit swimmers to gain a feel for racing pace.\textsuperscript{31} A dryland-based warm-up completed at high-intensity, involving all body segments and strength exercises such as back squats, was also recommended if swimmers are unable to access a swimming pool.\textsuperscript{31} Interestingly, the authors noted that the transition phase in swimming is lengthy in duration (> 20 min) and this may in turn mitigate the benefits of the previous active warm-ups (pool- or dryland-based).\textsuperscript{31} Lengthy transition phases of 30-45 min have also been reported by other research groups investigating swimming.\textsuperscript{20,36}

It is well established that $T_{\text{muscle}}$ begins to decline immediately following exercise, with appreciable reductions occurring after 15-20 min\textsuperscript{16} and thus, there is a greater risk of a significant decline in body temperature with longer transitions. In addition, high velocity movements (e.g. sprinting) are more temperature-dependent\textsuperscript{32} than low velocity movements with the rate of deterioration in muscle performance strongly associated with reductions in $T_{\text{muscle}}$.\textsuperscript{33} Reducing the duration of the transition phase can yield faster swimming performance,\textsuperscript{15,34} possibly due to core temperature ($T_{\text{core}}$) remaining elevated during shorter transitions.\textsuperscript{34} However, while this knowledge is useful, it would be difficult to alter swimming competition schedules by such large (> 25 min) margins. It has been suggested that passive warming or completion of a dryland-based warm-up within the transition phase may offset the inducement of any negative temperature-related effects.\textsuperscript{31} However, until recently, the feasibility of combining these two warm-up strategies was limited, with the notion of athletes bathing in a hot bath in the last 10–20 min before competition often impractical. The emergence of new passive warming methods, such as heated athletic garments and blizzard survival jackets, may provide practical alternatives.

Combining an athlete’s sport-specific active warm-up with the wearing of heated tracksuit pants\textsuperscript{35,36} or blizzard survival jackets\textsuperscript{37-39} during the transition phase can increase tympanic temperature\textsuperscript{37} and enhance $T_{\text{core}}$\textsuperscript{38,39} and $T_{\text{muscle}}$ maintenance\textsuperscript{35,36} within transition. As a result, subsequent cycling power output\textsuperscript{35,36}, 20 m sled sprinting,\textsuperscript{37} and repeat-sprint performance\textsuperscript{39,40}...
are enhanced. It is likely then that additional passive heating provided via heated athletic
garments or blizzard survival jackets could plausibly enhance body temperature maintenance
during the lengthy transitions typically experienced by competitive swimmers.

In addition to increasing body temperature, completion of an active warm-up is associated
with improvements in neuromuscular function, typically via the inducement of a
postactivation potentiation (PAP) response. The phenomenon known as PAP is where
muscular performance is acutely enhanced when preceded by maximal or near-maximal
neuromuscular activation exercises. To date, swimming performance has been shown to
be faster following a PAP stimulus of lunges and YoYo squats, similar following a back
squat stimuli, and slower when a combination of pull-ups and countermovement jumps
(CMJ) were completed, in comparison to performances recorded following a pool-based
warm-up.

When seeking to induce a PAP response, it is important to consider the timing of PAP stimuli
completion. While potentiation of muscle twitch is greatest immediately following a PAP
stimulus, PCr resynthesis requires ~4-8 min following completion of a preloading
activity. Resynthesis rate is dependent upon tissue oxygen supply and removal of
metabolites including blood lactate (La⁻) and hydrogen ions (H⁺). Transition phases of 7–
10 min are deemed optimal for eliciting improvements in peak power output in experienced
individuals. For competitive swimmers, completion of a dryland-based PAP stimulus
towards the end of a lengthy transition phase may assist in offsetting potential declines in
neuromuscular function.

In competitive swimming, it is common for swimmers to compete in morning heats and then
semi-finals in the afternoon/evening of the same day. At the Olympics and World
Championships, coaches of swimmers qualifying for the final in 50, 100 and 200 m events
are faced with the question of whether to prescribe a morning exercise bout prior to racing
later that day or to simply rest. In addition, the majority of high-level competitive swimmers
complete two training sessions on a typical training day, one in the early morning (e.g. 6:00-
8:00) and one in the afternoon (16:00-18:00), with benchmark time-trials generally completed
in the afternoon session. An exercise bout consisting of sport-specific and non-specific
resistance or sprint activities can enhance performance for up to six hours. A movement-
specific priming effect is also likely given that completion of the morning sprint session
substantially enhanced afternoon sprint, but not strength performance. It is possible that an intra-day priming effect might be advantageous to competitive swimmers. One mechanism through which these improvements occur could be the manipulation of body temperature and/or changes to circadian rhythms.

The influence of circadian rhythms on exercise performance has been well documented, with alterations in anaerobic physical performance (e.g. force and power) reported at different times across the day. Physiological markers including $T_{core}$ and heart rate (HR) are known to exhibit circadian rhythmicity, with an early morning nadir and a subsequent peak in the late afternoon. It appears pertinent then to investigate if completion of a morning exercise bout can influence swimming performance completed later that same day, for example, benchmark time-trials in training or competitive racing.

1.1 Thesis Aims and Research Questions

The primary aim of this thesis was to determine the effectiveness of competition day preconditioning strategy use on sprint swimming performance by addressing the following key questions:

1. What are the current competition warm-up practices and contemporary issues faced by elite swimming coaches and their athletes?
2. To what extent can additional warm-up strategies utilised within the transition phase mediate the adverse physiological and physical responses which result from swimmers enduring lengthy transition phases?
3. Can completion of a same-day morning priming exercise bout enhance afternoon sprint swimming performance?
1.2 Research Objectives

**Study 1: Current warm-up practices and contemporary issues faced by elite swimming coaches**

1. Determine the structure (i.e. intensity, duration, recovery) of the pool and dryland-based warm-up strategies currently prescribed by elite swimming coaches within the competition environment.
2. Ascertain the issues and challenges faced by athletes and coaches during the final stages of event preparation.

**Study 2: Heated jackets and dryland-based activation exercises used as additional warm-ups during transition enhance sprint swimming performance**

1. Determine whether the application of additional passive heat and/or the completion of dryland-based activation exercises within the transition phase can enhance sprint freestyle swimming performance in junior athletes.
2. Examine if any observed differences in the maintenance of $T_{\text{core}}$ during the transition phase are associated with improvements in overall swimming time-trial performance.

**Study 3: Elite competitor sprint swimming performance is enhanced by completion of additional warm-up activities**

1. Determine whether the application of additional passive heat, and completion of dryland-based activation exercises within the transition phase, can enhance sprint freestyle swimming performance in elite senior athletes.
2. Determine if this particular additional warm-up strategy enhances $T_{\text{core}}$ maintenance during the transition phase in elite senior athletes.
3. Investigate if this additional warm-up strategy can improve lower-body power output and subsequently elite senior freestyle start time (to 15 m) performance.
4. Quantify measures of near-infra-red-related (NIRS) local tissue oxygenation during completion of this additional warm-up strategy.
**Study 4: Additional warm-up strategies do not enhance elite sprint breaststroke performance**

1. Determine whether the application of additional passive heat, and completion of dryland-based activation exercises within the transition phase, can enhance sprint breaststroke swimming performance in elite senior athletes.
2. Determine if this particular additional warm-up strategy enhances $T_{\text{core}}$ maintenance during the transition phase in elite senior athletes.
3. Investigate if this combination additional warm-up strategy can improve lower-body power output and subsequently elite senior breaststroke start time (to 15 m) performance.

**Study 5: Morning exercise enhances afternoon sprint swimming performance**

1. Determine if completion of a morning exercise bout consisting of swimming exercise alone, or in combination with dryland-based exercises, enhances afternoon sprint swimming performance later that same day.
2. Quantify the influence of a morning exercise bout on physiological variables such as body temperature, heart rate and stroke characteristics including swimming stroke rate and length.
DECLARATION OF CO-AUTHORED PUBLICATION

CHAPTER 2

Declaration by candidate

In the case of Chapter 2, the nature and extent of my contribution to the work was the following:

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<thead>
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<th>Nature of contribution</th>
<th>Extent of contribution (%)</th>
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<tr>
<td>Developing the research question and research design, data collection and analysis, write-up and editing the manuscript</td>
<td>80%</td>
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The following co-authors contributed to the work.

<table>
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<tr>
<th>Name</th>
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<th>Contributor is also a student at UC Y/N</th>
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<tr>
<td>Dr Ben Rattray</td>
<td>Research design, editing the manuscript</td>
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<td>N</td>
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<tr>
<td>Prof David Pyne</td>
<td>Research design, editing the manuscript</td>
<td>7%</td>
<td>N</td>
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<tr>
<td>Prof Kevin Thompson</td>
<td>Research design, editing the manuscript</td>
<td>5%</td>
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Candidate's Signature  
11/02/2016

Declaration by co-authors

The undersigned hereby certify that:

1. the above declaration correctly reflects the nature and extent of the candidate’s contribution to this work, and the nature of the contribution of each of the co-authors.
2. they meet the criteria for authorship in that they have participated in the conception, execution, or interpretation, of at least that part of the publication in their field of expertise;
3. they take public responsibility for their part of the publication, except for the responsible author who accepts overall responsibility for the publication;
4. there are no other authors of the publication according to these criteria;
(5) potential conflicts of interest have been disclosed to (a) granting bodies, (b) the editor or publisher of journals or other publications, and (c) the head of the responsible academic unit; and
(6) the original data are stored at the following location(s) and will be held for at least five years from the date indicated below:

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<th>Location(s)</th>
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[Please note that the location(s) must be institutional in nature, and should be indicated here as a department, centre or institute, with specific campus identification where relevant.]

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CHAPTER 2: Literature Review - Warm-Up Strategies for Sport and Exercise: Mechanisms and Applications

The manuscript contained within this chapter has been accepted for publication: McGowan CJ, Pyne DB, Thompson KG & Rattray B. Warm-Up Strategies for Sport and Exercise: Mechanisms and Applications. Sports Medicine. 2015: 45 (11) 1523-1546.

2.1 Abstract

It is widely accepted that warming-up prior to exercise is vital for the attainment of optimum performance. Both passive and active warm-up can evoke temperature, metabolic, neural and psychology-related effects, including increased anaerobic metabolism, elevated oxygen uptake kinetics and post-activation potentiation. Passive warm-up can increase body temperature without depleting energy substrate stores, as occurs during the physical activity associated with active warm-up. While the use of passive warm-up alone is not commonplace, the idea of utilizing passive warming techniques to maintain elevated core and muscle temperature throughout the transition phase (the period between completion of the warm-up and the start of the event) is gaining in popularity. Active warm-up induces greater metabolic changes, leading to increased preparedness for a subsequent exercise task. Until recently, only modest scientific evidence was available supporting the effectiveness of pre-competition warm-ups, with early studies often containing relatively few participants and focusing mostly on physiological rather than performance-related changes. External issues faced by athletes pre-competition, including access to equipment and the length of the transition/marshalling phase, have also frequently been overlooked. Consequently, warm-up strategies have continued to develop largely on a trial-and-error basis, utilizing coach and athlete experiences rather than scientific evidence. However, over the past decade or so, new research has emerged, providing greater insight into how and why warm-up influences subsequent performance. This review identifies potential physiological mechanisms underpinning warm-ups and how they can affect subsequent exercise performance, and provides recommendations for warm-up strategy design for specific individual and team sports.
2.1.1 Key Points

- Passive and active warm-ups markedly influence subsequent exercise performance via increases in adenosine triphosphate turnover, muscle cross-bridge cycling rate and oxygen uptake kinetics, which enhance muscular function.
- An active warm-up, consisting of a brief (< 15 min) aerobic portion and completion of 4–5 activation sprints/race-pace efforts, post-activation potentiation exercises or small-sided games, elicits improvements in performance.
- Passive heat maintenance techniques can preserve the beneficial temperature effects induced via active warm-up during lengthy transition phases.

2.2 Introduction

Warming-up prior to a competitive exercise bout is a widely accepted practice in the modern sporting environment, with athletes and coaches alike believing that warming-up is essential for attaining optimal performance. However, until quite recently, this belief was not well supported by empirical evidence, with coaches often resorting to a trial-and-error approach to design their athletes’ warm-up strategies. In light of this, extensive research has been conducted over the past decade to determine the key warm-up elements for specific exercise tasks. A large number of physiological and neural mechanisms have been examined to ascertain their contributions to performance and responses to different warm-up strategies. Purported mechanisms include increased muscle metabolism, elevated oxygen uptake (VO2) kinetics and post-activation potentiation (PAP). Technological advances over the past decade have also facilitated the emergence of new types of warm-up strategies. With the last major review published over 10 years ago, prior to several of these advances, it is timely to provide an update on recent developments in the area.

Compiling this review involved identifying articles via systematic searches (search completed 30 April 2014) of the EBSCO, Medline and SPORTDiscus databases, as well as inspection of the reference lists of the selected articles. Studies that examined passive and active warm-up strategies specifically are discussed, but we have excluded those investigating stretching-only strategies (see Smith 64). For the final section of this review, studies regarding sport-specific
strategies were sourced from publications between 2003 and 2014. Studies investigating tasks common to the competitive environment (e.g. a 100 m swimming time-trial) and those with a well-defined endpoint (e.g. a 4 min cycling time-trial) were included, but studies using ‘time to exhaustion’ tasks were not. From this analysis, recommendations are provided for warm-up strategies across several individual and team-based sports, taking into consideration the differences in competition structure and environment.

2.2.1 Mechanisms of Warm-Up

One of the main outcomes associated with warming-up is an increase in body temperature. Increases in muscle temperature (T\textsubscript{muscle}) are reportedly accompanied by increases in muscle metabolism\textsuperscript{3} and muscle fibre conduction velocity (MFCV).\textsuperscript{65} Elevation of VO\textsubscript{2} kinetics\textsuperscript{66} and increases in muscle contractile performance following prior contractile activity\textsuperscript{62} have also been reported. In addition, visualisation and preparatory arousal techniques have been shown to enhance subsequent exercise performance.\textsuperscript{67} For ease of reference, we have defined short-term/sprint performance as < 1 min in duration, sustained high-intensity performance as > 1–5 min in duration and long-term (endurance) performance as > 5 min in duration.

2.3 Temperature Mechanisms

Performance improvements in exercise tasks preceded by a warm-up are generally attributed to temperature-related mechanisms. The early pioneers of warm-up research, Asmussen and Bøje,\textsuperscript{8} determined that ‘organisms facilitate work more effectively at higher temperatures’. More recently, a strong association between power output and T\textsubscript{muscle} has been established, with a 1ºC increase in T\textsubscript{muscle} being shown to enhance subsequent exercise performance by 2–5%, depending on the type and velocity of contraction(s),\textsuperscript{33,68,69} with the magnitude of the T\textsubscript{muscle} response being positively related to movement velocity.\textsuperscript{69} In addition, changes in T\textsubscript{muscle} are directly related to changes in the relative work rate, with T\textsubscript{muscle} rising rapidly from baseline (~35–37ºC) at the onset of moderate-intensity exercise, before reaching a relative equilibrium after ~10–20 min.\textsuperscript{70,71}
2.3.1 Increased Muscle Metabolism

Accelerated muscle glycogen degradation at higher ambient temperatures was first shown in the early 1970s. The passive elevation of T_{muscle} (e.g. via water-perfused cuffs) has been linked with faster adenosine triphosphate (ATP) turnover, primarily via augmentation in the rate of creatinine phosphate (PCr) utilisation and H⁺ accumulation, as well as increases in anaerobic glycolysis and muscle glycogenolysis. Increases in subsequent exercise power production are considered the primary outcome of these changes. Specifically, passive warming of T_{muscle} can increase anaerobic ATP turnover within the first 2 min of heavy exercise, with no further changes in turnover rate after this period. However, several studies investigating this shift towards greater anaerobic metabolism have yielded variable results, partly due to researchers failing to take muscle biopsy samples during the initial phase of the exercise task (< 2 min) and instead procuring samples only upon exercise completion some 4+ min later. An increase in the muscle cross-bridge cycling rate is one possible explanation for this higher reported turnover rate, with a temperature-dependent relationship existing between muscle fibre cross-bridge cycling and the force produced during the power stroke in cycling. Given that passive elevation of T_{muscle} can increase muscle glycogen availability in the short term (~2 min), it is likely that both sprint and sustained high-intensity events could benefit from this intervention.

2.3.2 Increased Muscle Fibre Performance

There is much debate about which muscle fibre types are most affected by changes in temperature. Greater PCr utilisation in type I fibres has been shown during low-cadence cycle exercise [≤ 60 revolutions per minute (rpm)] but not in type II fibres following prior passive warming. However, at these low velocities, type II fibres are likely operating towards the lower part of the power–velocity curve, where a rightward shift would have a minimal effect on their power production capabilities. At a high cadence (~160–180 rpm), however, elevating T_{muscle} results in greater PCr and ATP utilisation and maximal power outputs in type II, but not in other fibre types. It seems that the function of both type I and type II muscle fibres is affected by elevations in T_{muscle} if contraction frequency is taken into account, with a velocity-dependent effect reported, i.e. type II fibres are more likely to benefit from increased
When the contraction frequency of the exercise task is high, and vice versa for type I fibres.

### 2.3.3 Increased Muscle Fibre Conduction Velocity

Elevations in $T_{\text{muscle}}$ can positively alter the force–velocity relationship and concomitantly the power–velocity relationship,\textsuperscript{78-80} leading to higher power outputs in exercise tasks,\textsuperscript{78} with a $\sim 3^\circ$C augmentation in $T_{\text{muscle}}$ being reported to elicit a measurable increase in both MFCV and power.\textsuperscript{2} Following passive muscle warming, evidence for an improvement in MFCV has been observed, via a reduction in the time to reach peak twitch and an increase in the rate of force development.\textsuperscript{2,4} The MFCV in muscles both actively and passively involved in the warm-up has also been reported to increase (~5% in the hand and ~8.5% in the leg) following a moderate-intensity running-based warm-up.\textsuperscript{65} Similarly, different types of active warm-up modalities, running- or back squat-based, produced ~12% increases in MFCV.\textsuperscript{81} Release of calcium from the sarcoplasmic reticulum during fibre membrane depolarisation,\textsuperscript{82} membrane hyperpolarisation as a result of increased Na$^+$/potassium (K$^+$) Pumping activity,\textsuperscript{83} muscle fibre swelling\textsuperscript{84} and/or faster activation of muscle fibres\textsuperscript{2} are all plausible explanations for MFCV enhancement. Thus, post-warm-up improvements in neuromuscular performance can, in part, be attributed to alterations in muscle fibre conduction properties. In addition, strength- and power-demanding sports, such as sprinting and jumping, typically require a fast rate of force development to attain the highest possible peak power output within a short timeframe.\textsuperscript{85,86} It is also evident that during rapid cyclical movements, muscles must relax quickly. The muscle relaxation rate depends on the force level recorded from the time when a muscle starts to relax; thus, this is the chosen point of reference.\textsuperscript{79} The speed of muscle relaxation can decrease at lower temperatures (22–25$^\circ$C). It has been established that maximal rates of force development (peak power) and relaxation have a temperature-dependent relationship with peak power output and peak relaxation rate reported at higher temperatures (25–37$^\circ$C).\textsuperscript{79} Temperature dependency is likely related to one of the underlying processes of muscle relaxation, such as calcium removal from the myoplasm, calcium dissociation from troponin and/or the cross-bridge detachment rate.\textsuperscript{78,79,87}
2.3.4 Temperature Mechanisms Summary

In summary, passively or actively elevating $T_{\text{muscle}}$ can markedly influence exercise performance. Increases in ATP turnover and cross-bridge cycling rate, as well as improvements in muscle fibre functionality and MFCV, appear as likely mechanisms. Athletes competing in sprint and sustained high-intensity events seem the most likely beneficiaries of elevations in body temperature due to increases in muscle glycogen availability and the rate of force development. However, caution should be exercised under conditions of high heat and/or humidity, as it is conceivable that prescribed warm-ups that are overly intense or prolonged might adversely affect thermal tolerance. Pre- and within-exercise cooling methods, such as cold water immersion, cooling vests, ice slurry ingestion or a combination of different strategies, might be introduced in these settings.

2.4 Metabolic Mechanisms

While elevating body temperature via either passive or active warm-up can improve subsequent exercise performance, such elevations are not the sole determinant of energy metabolism changes during exercise. Active warm-up, in particular, can stimulate changes in the mechanisms underlying both anaerobic and aerobic metabolism. In a landmark study, Gerbino and colleagues showed that 6 min of heavy-intensity (> lactate threshold, < critical power) but not moderate-intensity (< lactate threshold) exercise increased $\text{VO}_2$ kinetics during a subsequent heavy exercise bout. Importantly, this was one of the first studies to definitively show a ‘speeding’ of $\text{VO}_2$ kinetics following an exercise-based intervention. In addition, the elevated $\text{VO}_2$ and associated aerobic metabolism might spare finite anaerobic stores during the initial stages of a subsequent exercise bout, thus preserving this energy for subsequent use.

2.4.1 Elevation of Oxygen Uptake Kinetics

Oxidative metabolism is the principal means by which humans generate energy for physical activity, the exception being sprint-based activities. It is well established that a bout of heavy-
intensity priming exercise affects the time course of the pulmonary VO₂ response within a subsequent heavy-intensity exercise bout by speeding overall VO₂ kinetics.\(^{98,100-103}\) Initially it was believed that this speeding of VO₂ kinetics occurred via an enhancement of the primary VO₂ response to exercise.\(^{98,104}\) However, it has now been revealed that completion of a priming exercise bout elicits an increase in the amplitude of the primary VO₂ response and a reduction in the VO₂ slow component.\(^{101,105,106}\) Together, these changes in metabolic function can improve exercise tolerance\(^{100,107}\) and mean power output.\(^{105}\) However, there are other reports that priming exercise bout completion may impair\(^{108}\) or have no influence\(^{109}\) on subsequent exercise performance. Explanations for the large variation between studies include differences in the intensities of the priming and criterion bouts, and the length of time between the priming and criterion exercise bouts (here termed the ‘transition phase’).

Moderate-intensity (below the lactate threshold) priming bouts have a limited effect on the subsequent VO₂ response,\(^{106}\) yet priming bouts performed at a heavy intensity (from the lactate threshold up to critical power) can enhance subsequent exercise performance.\(^{98,100-103}\) Severe-intensity priming exercise (above critical power) has been linked to improved\(^{105-107}\) as well as impaired subsequent performance,\(^{110}\) with impairments most likely attributable to the transition phase being too short, such that the blood lactate concentration (La⁻) at the onset of the subsequent bout was > 3 mmol/L.\(^{106}\) Therefore, it is necessary to strike a balance between the potential benefits of priming exercise on VO₂ kinetics and the depletion of anaerobic stores, as well as the associated metabolic acidosis. This challenge was addressed in a comprehensive study conducted by Bailey and colleagues,\(^{106}\) in which both the intensity of the priming exercise bout and the duration of the transition phase were manipulated. A severe-intensity priming bout increased the time to exhaustion (15–30\%) when the transition phase was ≥ 9 min. This particular combination of priming bout intensity and transition phase duration appears to have optimised the balance between preserving the beneficial effects of the priming bout on VO₂ kinetics while still providing sufficient time for muscle homeostasis (e.g. muscle phosphocreatine and H⁺ concentrations) to be restored.

Another study reported that a 6 min priming bout completed at a constant work rate of ~80\% of peak oxygen uptake (VO₂peak), followed by a 10 min transition phase, produced a mean La⁻ concentration of ~2.6 mmol/L.\(^{100}\) Taking into consideration these findings, as well as others,\(^{106}\) it appears that a bout of priming exercise which elicits a degree of lactic acidosis (< 3 mmol/L at the onset of the criterion bout) is capable of positively altering VO₂ kinetics.
Furthermore, an individual’s baseline VO\textsubscript{2} response may be elevated following completion of a priming exercise bout.\textsuperscript{99} This outcome may lead to the initial sparing of an individual’s finite anaerobic energy stores, preserving this energy for subsequent use (e.g. the final sprint to the line). However, this elevated baseline VO\textsubscript{2} returns to baseline if the transition duration exceeds 10 min,\textsuperscript{101} so the duration of the transition phase is important to consider.

The precise physiological mechanism(s) responsible for the effects of priming exercise on VO\textsubscript{2} kinetics are unclear. Altered O\textsubscript{2} delivery and extraction,\textsuperscript{98,111-113} increased motor unit recruitment,\textsuperscript{101,104,106,114} shifts in the oxyhaemoglobin curve,\textsuperscript{98} oxidative enzyme activity,\textsuperscript{115,116} residual acidosis\textsuperscript{100,105,117} or a combination of these mechanisms\textsuperscript{118-120} have all been implicated in altering the VO\textsubscript{2} kinetic response. Overall, it appears that completion of a bout of heavy-intensity priming exercise can increase the amplitude of the primary VO\textsubscript{2} response and reduce the VO\textsubscript{2} slow component. Collectively, these effects may enhance subsequent exercise performance via increases in oxidative enzyme activity and/or motor unit recruitment, such that the ‘strain’ placed on each individual muscle fibre is reduced.

2.5 Neural Mechanisms

It has been postulated that following a pre-loading stimulus (i.e. active warm-up), fatigue and muscle potentiation coexist within skeletal muscle,\textsuperscript{42,121} with the subsequent force that a muscle is capable of generating ultimately being dependent upon the net balance between these factors.\textsuperscript{121} Although fatigue will impair performance, inclusion of muscle ‘potentiation’ exercises within an active warm-up might improve subsequent performance. At present, tasks that require maximum power output over a relatively short (< 1 min) timespan,\textsuperscript{41,43} such as jumping\textsuperscript{122,123} and sprinting,\textsuperscript{50,124} can benefit following completion of a pre-loading stimulus.

2.5.1 Postactivation Potentiation

The recent activity of skeletal muscle is known to have a significant effect upon a muscle’s ability to generate subsequent force.\textsuperscript{41,43,125} PAP is a phenomenon where muscular performance is acutely enhanced when preceded by maximal or near-maximal neuromuscular
activation exercises.\textsuperscript{41-43} It has been proposed that PAP may increase the rate of acceleration attained with loads between zero and peak isometric force, thus shifting the load (force)–velocity relationship upward and to the right (making it less concave).\textsuperscript{62} For example, 1 min after inducement of PAP (via a 6 s maximal voluntary contraction) the load-velocity relationship shifted significantly upward and the maximal power of the muscle (adductor pollicis) was increased.\textsuperscript{126} Mechanisms through which PAP may improve subsequent physical performance include enhanced central output to motor neurons,\textsuperscript{42} increased reflex electrical activity in the spinal cord\textsuperscript{127} and phosphorylation of myosin regulatory light chains,\textsuperscript{128,129} which increase Ca\textsuperscript{2+} sensitivity of the myofilaments.\textsuperscript{129} PAP may also increase the concentration of sarcoplasmic Ca\textsuperscript{2+}, which, in turn, can increase actin–myosin cross-bridge cycling\textsuperscript{130} Completion of PAP-inducing pre-loading can enhance performance in short-duration tasks, such as jumping\textsuperscript{50,123,131,132} and sprinting,\textsuperscript{7,124,133} with heavy-resistance exercises [\textgt\textasciitilde \textasciitilde 85\% of 1 repetition maximum (1RM)], such as bench presses,\textsuperscript{134} back squats\textsuperscript{124,135,136} and Olympic lifts,\textsuperscript{137} traditionally used to induce the PAP response. However, the practicality of completing such exercises in a competition setting is limited. In more recent times, increases in power output of 2–5\% have been elicited via completion of more practical, ballistic-style, pre-loading activities, such as drop jumps\textsuperscript{138,139} and weighted jumps.\textsuperscript{140-142}

The success of a pre-loading exercise in generating a PAP response depends on the balance between fatigue and potentiation.\textsuperscript{42} This balance is affected by numerous factors, including training experience,\textsuperscript{50} the transition phase duration\textsuperscript{143} and the intensity of the pre-loading activity.\textsuperscript{62} The load to be moved in a pre-loading exercise bout is important to consider, with higher loads associated with a greater PAP response.\textsuperscript{144-146} Henneman’s size principle\textsuperscript{147,148} likewise suggests that higher rather than lower loading should more effectively increase activation of the motor units in type II muscle fibres, which has been confirmed in in vitro studies.\textsuperscript{149,150} However, higher loads are associated with a greater concomitant increase in fatigue, which may eliminate the potential for performance enhancement if a sufficient transition phase is not observed. According to a recent meta-analysis,\textsuperscript{51} exercises of moderate intensity (60–84\% 1RM) are ideal for eliciting a PAP response, in comparison with very high-intensity exercises (\textgt\textasciitilde 85\% 1RM), independent of an athlete’s training experience,\textsuperscript{151} perhaps due to increased contractile activity leading to increased muscle damage. However, athletes with > 3 years of resistance training experience, where training adaptation may protect against muscle damage, appear more likely to respond optimally to pre-loading
activities. In addition, muscle fibre type has been reported to influence the level of PAP response, with persons possessing a higher percentage of type II postulated to achieve a greater PAP response. In support of this, a positive correlation ($R = 0.63$, $p = 0.01$) between muscular strength (absolute and relative) and counter-movement jump (CMJ) peak potentiation has been reported 12 min after completion of a 3 repetition maximum (3RM) back squat stimulus. The transition duration is also important to consider, because while potentiation of a muscle twitch is greatest immediately following a PAP stimulus, the same cannot be said for subsequent performance. Improvements in power output can occur after 5 min transitions, 8–12 min transitions and even 18.5 min transitions, with a transition duration of 7–10 min deemed optimal for eliciting peak power outputs in experienced individuals. Individual responses can vary, though; thus, coaches should determine each individual athlete’s optimal transition duration to maximise their power-generating capabilities in a subsequent exercise task. Finally, although some researchers have reported no improvement or a negative impact on performance following PAP, this outcome may be partially explained by methodological differences between studies.

In summary, several factors need to be considered when designing a PAP-inducing, pre-loading exercise bout, including an individual’s training experience and the intensity at which the bout is completed. Exercises such as drop jumps completed as part of a pre-loading bout appear to induce a PAP response and yield substantial improvements in subsequent exercise tasks in which maximal power production is a key determinant.

2.6 Psychological Mechanisms

The warm-up period is recognised as an opportunity to mentally prepare for an upcoming event by providing time for athletes to concentrate on the task ahead. It is well recognised that many athletes complete some form of mental preparation prior to competition tasks. Typical strategies include visualisation, saying of cue words, attentional focus and preparatory arousal (‘psyching-up’). These strategies are designed to narrow an individual’s attention and build their self-confidence. Athletes competing in various sports, such as water polo, football and tennis, have shown improvements in task execution following use of prior mental rehearsal techniques. Bench press force production can also be
enhanced by psyching-up.\textsuperscript{156} It is known that elite athletes often use mental preparation tasks more regularly in both training and competition than recreational and novice athletes,\textsuperscript{160} with the use of mental performance strategies prior to competition deemed a distinguishing characteristic of successful Olympians.\textsuperscript{161} Although the focus of this review is primarily on the physiological and performance aspects of warm-up, the information highlighted in this section is an important consideration for the real-world implications of effective warm-up strategies. Psychological feedback, including the athlete’s and their coach’s comfort with warm-up routines for future use, should be evaluated alongside physiological measures in future studies.

### 2.7 Passive Warm-Up Strategies and Exercise Performance

An increase in $T_{\text{muscle}}$ of 1°C can enhance subsequent exercise performance by 2–5%.\textsuperscript{33} Unlike active warm-up, passive warming permits an increase in core temperature ($T_{\text{core}}$) and/or $T_{\text{muscle}}$ without depletion of energetic substrates. Much of the early research in this area has been laboratory based, with increases in body temperature achieved via external heating methods, such as hot showers/baths. These types of passive warm-ups are, however, not often practical in the field. However further investigations of passive warm-up strategies have been prompted, given that (1) $T_{\text{muscle}}$ begins to decline immediately following exercise cessation; (2) appreciable declines occur as early as \textasciitilde15–20 min post-exercise;\textsuperscript{16,34} and (3) there is often a lengthy period between the end of the warm-up and the start of competition (the transition phase).

#### 2.7.1 Hot Showers, Baths, Heated Garments and Blizzard Survival Jackets

Passive elevation of $T_{\text{muscle}}$ was first achieved via the use of hot showers (~47°C), lasting 8–10 min, and/or baths, both of which were linked with improvements in the total work completed in a subsequent exercise bout\textsuperscript{8} and swimming performances over 50, 200 and 400 m distances.\textsuperscript{10,23} Hot water immersion (~42.8°C), combined with electric blankets applied to the lower body, also increased power output (by ~22%) in a 6 s maximal cycle sprint task.\textsuperscript{2} Recently, however, the way in which passive warm-up strategies are employed has changed,
largely because of the timing constraints incurred during competition.\textsuperscript{34,35} It is not uncommon for competitive athletes to complete their active warm-up and then have to wait 10–40 min in a changing room, call room or marshalling area before their event begins.\textsuperscript{15,34,35,162,163} This delay may reduce the beneficial effects of the pre-competition warm-up, given that $T_{\text{muscle}}$ begins to decline immediately following exercise cessation, with a significant reduction occurring $\sim$15–20 min after exercise termination.\textsuperscript{16,34} While it has been shown on several occasions that reducing the transition duration from $\sim$40 to $\sim$10 min improves subsequent performance,\textsuperscript{15,34,37} it is usually not possible to alter a competition schedule by such a large margin. In light of this, it has been postulated that the decline in body temperature during the transition phase could be offset by combining an athlete’s sport-specific active warm-up with passive warming techniques. However, until recently, the feasibility of combining these two warm-up strategies was limited, with the notion of athletes showering in the last 10–20 min before competition often being impractical. The emergence of new methods of passive heat maintenance, such as heated athletic garments (e.g. Adidas Clima365, AG, Germany) and blizzard survival jackets (e.g. those produced by Blizzard Protection Systems Ltd, Bangor, UK), provide practical passive warming alternatives.

Heated athletic garments have battery-powered heat filaments sewn into the fabric fibres, allowing them to be used across a wide range of athletic activities. Combining an active cycle ergometer warm-up with application of additional passive heat maintenance via heated tracksuit pants worn during a 30 min transition phase yielded a substantial improvement in $T_{\text{muscle}}$ maintenance (heated garment use resulted in a 1°C higher $T_{\text{muscle}}$ at a depth of 0.01 m and a 0.4°C higher $T_{\text{muscle}}$ at 0.03 m than when no additional heated was applied) within the transition, and $\sim$9% enhancement in both peak and relative power output during a sprint cycling task.\textsuperscript{35} In another study conducted by the same group, $T_{\text{muscle}}$ remained elevated during the transition and was greater immediately prior to the start of a sprint cycling task when heated tracksuit pants were worn during the transition phase (36.9 ± 0.3°C) and during the active warm-up (37.0 ± 0.2°C) compared to control (36.6 ± 0.3°C).\textsuperscript{36} However, wearing heated tracksuit pants during the active warm-up as well as during the transition phase did not provide additional performance benefit.\textsuperscript{36} The wearing of blizzard survival jackets has also been shown to elicit a 65% increase in tympanic temperature and improve performance in a 20 m sled sprinting task.\textsuperscript{37} Furthermore, an active warm-up followed by application of a blizzard survival jacket during a 15 min transition phase produced faster repeat-sprint performance (6.96 ± 0.14 s versus control 7.01 ± 0.16 s) in elite rugby players.\textsuperscript{38} The
reduction in $T_{\text{core}}$ during the transition was minimised when the blizzard jackets were worn (-0.19 ± 0.08°C) versus control (-0.55 ± 0.10°C). As a result, participants began the subsequent criterion testing bout with an elevated $T_{\text{core}}$.

In summary, although the use of passive warm-up alone is not commonplace, the idea of using it to maintain an elevated body temperature throughout the transition phase is gaining traction. Passive heat maintenance via the wearing of heated tracksuit pants or blizzard survival jackets appears to be an effective method for attenuating the decline in $T_{\text{muscle}}$ and/or $T_{\text{core}}$ during lengthy transition phases, and subsequently improving exercise performance. Furthermore, it is likely that passive warming techniques may be applied to other situations in which it is difficult to maintain $T_{\text{core}}$ via metabolic heat production alone, such as between repeated exercise bouts (e.g. multiple races within a swimming meet) separated by periods of low to moderate activity. Further research is required to determine the optimum use of such devices, including garment temperature, the length of time for which the garment(s) should be worn, when in the competition timeline the garment(s) should be used, and the specific placement of the passive heat source on the body for individual sports.

2.8 Active Warm-Up Strategies and Exercise Performance

Active warm-up is the most widely chosen warm-up strategy for pre-competition preparation. The effectiveness of an active warm-up strategy is determined largely by its composition, including the intensity and duration of the physical tasks completed, as well as the length of the transition phase. For each of the three individual sports we reviewed, we have confined our discussion to the effects of active warm-up on single exercise tasks (e.g. an 800 m running time-trial). For team sports, we have focused on reviewing studies that examined the effects of active warm-up on actual game play, simulated game play or relevant sport-specific performance tests (e.g. repeat-sprint tasks for team sports).
2.8.1 Running

Competitive runners competing across all distances ranging from sprint events (100–400 m) to middle-distance (800–1500 m) and long-distance (> 1500 m) events typically complete some form of active warm-up prior to competition. For the current review, ten papers met the selection criteria, of which eight demonstrated improved running performance following an active warm-up (Table 1). Only one study investigated if active warm-up induced biomechanical changes, with shoulder lean, hip flexion and forward lean deemed to have improved. However, in the same study, performance times for 36.6 m sprint sled pulls did not improve following an active warm-up involving sled pulls with different mass loadings. In another study, a set of 5 x 40 m efforts completed at near-race-pace intensity (90–95% VO₂max) resulted in faster 50–60 m split times in a subsequent 60 m sprint than when only a single near-race-pace effort was completed. All of the studies utilised a sprint-oriented (< 400 m) test, except for one study in which 800 m running performance was investigated. In that study, athletes completed an active warm-up involving ‘jogging’, mobility drills and strides with or without a 200 m effort at 800 m race pace, prior to a 20 min transition period. Subsequent performance in an 800 m time-trial was ~1% faster when a race-pace effort was included, with pacing differences in the latter part of the effort. It appears that completion of at least one race-pace effort (of at least 25% of the distance to be raced) is necessary to sufficiently prime runners for a middle-distance event, while completion of multiple near-race-pace efforts can improve sprint performance.

The most common active warm-up strategy we investigated involved completion of several repetitions of a back squat. One study reported similar performance times following no warm-up or a warm-up of 3 x 3 back squats (90/100% 1RM), while the remaining four studies required participants to complete one set at between 60% and 90% 1RM, resulting in superior sprint performance over 20, 30 and 40 m distances in comparison to when no back squats were completed. Another popular active warm-up strategy involves the use of drop jumps. A brief active warm-up entailing 5 min of ‘jogging’, dynamic stretches and three drop jumps improved (by 5%) 20 m sprint performance in comparison to when no drop jumps were completed. These findings were confirmed by another study, where completion of 2 x 5 drop jumps from a height of 0.75 m elicited faster 50 m sprint times (by ~2%). In addition, these researchers investigated the optimal transition duration after
### Table 1. Performance, physiological and biomechanical changes following active warm-up in running.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Participants</th>
<th>Warm-up</th>
<th>Post warm-up measures</th>
<th>Performance results</th>
<th>Physiological Results</th>
<th>Biomechanical Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Byrne et al. 2014</td>
<td>29T (M)</td>
<td>WU&lt;sub&gt;1&lt;/sub&gt;: 5 min</td>
<td>“Jog”</td>
<td>NS</td>
<td>Overall time: WU&lt;sub&gt;2&lt;/sub&gt; (2.2%)&lt;WU&lt;sub&gt;1&lt;/sub&gt;; WU&lt;sub&gt;3&lt;/sub&gt; (5%)&lt;WU&lt;sub&gt;1&lt;/sub&gt;; WU&lt;sub&gt;3&lt;/sub&gt; (2.9%)&lt;WU&lt;sub&gt;2&lt;/sub&gt;; WU&lt;sub&gt;4&lt;/sub&gt; &gt; WU&lt;sub&gt;1&lt;/sub&gt;; WU&lt;sub&gt;4&lt;/sub&gt; &gt; WU&lt;sub&gt;3&lt;/sub&gt;; Hip flexion: WU&lt;sub&gt;1&lt;/sub&gt; + WU&lt;sub&gt;3&lt;/sub&gt; &gt; WU&lt;sub&gt;2&lt;/sub&gt; + WU&lt;sub&gt;1&lt;/sub&gt;; Forward lean: WU&lt;sub&gt;4&lt;/sub&gt; + WU&lt;sub&gt;3&lt;/sub&gt; &gt; WU&lt;sub&gt;1&lt;/sub&gt;*</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>WU&lt;sub&gt;2&lt;/sub&gt;: same as WU&lt;sub&gt;1&lt;/sub&gt; + 10 dynamic stretches</td>
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<tr>
<td></td>
<td></td>
<td>WU&lt;sub&gt;3&lt;/sub&gt;: same as WU&lt;sub&gt;2&lt;/sub&gt; + 3 drop jumps</td>
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<tr>
<td>Smith et al. 2014</td>
<td>24T: 12 M, 12 F</td>
<td>WU&lt;sub&gt;1&lt;/sub&gt;: 4 min cycle</td>
<td>50-70%HR&lt;sub&gt;max&lt;/sub&gt;</td>
<td>4 (“slow” walk)</td>
<td>Overall time: similar</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>36.6 m</td>
<td>Max sprint</td>
<td></td>
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<td></td>
<td></td>
<td>18.3 m</td>
<td>Max sprint</td>
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<tr>
<td></td>
<td></td>
<td>WU&lt;sub&gt;2&lt;/sub&gt;: same as WU&lt;sub&gt;1&lt;/sub&gt; + 18.3 m</td>
<td>Sled sprint 10%BM</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>WU&lt;sub&gt;3&lt;/sub&gt;: same as WU&lt;sub&gt;1&lt;/sub&gt; + 18.3 m</td>
<td>Sled sprint 20%BM</td>
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<td></td>
<td></td>
<td>WU&lt;sub&gt;4&lt;/sub&gt;: same as WU&lt;sub&gt;1&lt;/sub&gt; + 18.3 m</td>
<td>Sled sprint 30%BM</td>
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<tr>
<td>Ingham et al. 2013</td>
<td>11T: 7M, 4F National/international level</td>
<td>WU&lt;sub&gt;1&lt;/sub&gt;: 10 min Mobility drills 6 x 50 m strides</td>
<td>“Jog”</td>
<td>La'&lt;sub&gt;1&lt;/sub&gt;: WU&lt;sub&gt;2&lt;/sub&gt; &lt; WU&lt;sub&gt;1&lt;/sub&gt;*</td>
<td>Overall time: WU&lt;sub&gt;2&lt;/sub&gt; &lt; WU&lt;sub&gt;1&lt;/sub&gt;; Split time (400-500; 700-800): WU&lt;sub&gt;2&lt;/sub&gt; &lt; WU&lt;sub&gt;1&lt;/sub&gt;; Peak VO&lt;sub&gt;2&lt;/sub&gt;: WU&lt;sub&gt;2&lt;/sub&gt; &lt; WU&lt;sub&gt;1&lt;/sub&gt;; Mean VO&lt;sub&gt;2&lt;/sub&gt; response time: similar</td>
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<td>WU&lt;sub&gt;2&lt;/sub&gt;: 10 min Mobility drills 2 x 50 m strides 200 m</td>
<td>“Jog”</td>
<td>RP</td>
<td>La': similar</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>WU&lt;sub&gt;3&lt;/sub&gt;: 10 min Mobility drills 2 x 50 m strides 200 m</td>
<td>“Jog”</td>
<td>RP</td>
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<tr>
<td></td>
<td></td>
<td>WU&lt;sub&gt;4&lt;/sub&gt;: 10 min Mobility drills 2 x 50 m strides 200 m</td>
<td>“Jog”</td>
<td>RP</td>
<td></td>
<td></td>
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<tr>
<td>Lim et al. 2013</td>
<td>12T (M)</td>
<td>WU&lt;sub&gt;1&lt;/sub&gt;: 0</td>
<td>2 min rest/sets</td>
<td>NS</td>
<td>Overall time: similar</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>WU&lt;sub&gt;2&lt;/sub&gt;: 3 (3 x 3sec) IKE</td>
<td>100% 1RM</td>
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<tr>
<td></td>
<td></td>
<td>WU&lt;sub&gt;3&lt;/sub&gt;: 3 (3 x 3sec) IS</td>
<td>90% 1 RM</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>WU&lt;sub&gt;4&lt;/sub&gt;: 3 (3 x 3sec) IS</td>
<td>90-95% VO&lt;sub&gt;2&lt;/sub&gt;max</td>
<td></td>
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<tr>
<td>Watterdale 2013</td>
<td>5T (M)</td>
<td>WU&lt;sub&gt;1&lt;/sub&gt;: 0</td>
<td>90-95% VO&lt;sub&gt;2&lt;/sub&gt;max</td>
<td>NS</td>
<td>Overall time: similar</td>
<td>-</td>
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<tr>
<td></td>
<td></td>
<td>WU&lt;sub&gt;2&lt;/sub&gt;: 10min 7 min 5 x 40-50 m</td>
<td>Mobility drills</td>
<td>“Jog”</td>
<td>Final 10 m: WU&lt;sub&gt;1&lt;/sub&gt; &lt; WU&lt;sub&gt;2&lt;/sub&gt;</td>
<td>-</td>
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<tr>
<td></td>
<td></td>
<td>WU&lt;sub&gt;3&lt;/sub&gt;: 10 min 1 x 40-50 m</td>
<td>“Jog”</td>
<td>“Jog”</td>
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</table>

Note: NS = not specified.
<table>
<thead>
<tr>
<th>Reference</th>
<th>Participants</th>
<th>Warm-up Volume</th>
<th>Intensity</th>
<th>Changes</th>
<th>Transition (min)</th>
<th>Criterion test</th>
<th>Performance results</th>
<th>Physiological Results</th>
<th>Biomechanical results</th>
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<tbody>
<tr>
<td>Bomfim</td>
<td>10T (M)</td>
<td>WU1: 0</td>
<td></td>
<td>NS</td>
<td>T ≥ 5</td>
<td>50 m</td>
<td>Overall time: WU₂</td>
<td>-</td>
<td>-</td>
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<tr>
<td></td>
<td></td>
<td>WU2: 2 x 5 drop jumps (0.75m)</td>
<td>15 sec rest/jumps</td>
<td>T ≥ 10</td>
<td>T ≥ 15</td>
<td></td>
<td></td>
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<tr>
<td>Lima et al. 2011</td>
<td>9T (M)</td>
<td>WU₁: 7 min 3-4 x 40 m</td>
<td></td>
<td>“Jogging”</td>
<td>“Submaximal”</td>
<td>40 m</td>
<td>Overall time:</td>
<td>WU₃&lt;WU₁⁺; WU₁⁺</td>
<td></td>
</tr>
<tr>
<td>&amp; Ellefsen 2011</td>
<td></td>
<td>15 x BhS</td>
<td></td>
<td>BW</td>
<td></td>
<td></td>
<td></td>
<td>+ WU₂: similar</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>WU₂; same as WU₁ + 15 x BhS</td>
<td>With WBV (30Hz)</td>
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<tr>
<td></td>
<td></td>
<td>WU₃; same as WU₁ + 15 x BhS</td>
<td>With WBV (50Hz)</td>
<td></td>
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<td></td>
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<tr>
<td>Rahimi 2007</td>
<td>12T (M)</td>
<td>WU₁: 0</td>
<td></td>
<td>NS</td>
<td>4</td>
<td>40 m</td>
<td>Overall time:</td>
<td>WU₂ (1.1%), WU₁</td>
<td>-</td>
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<tr>
<td></td>
<td></td>
<td>WU₂: 2 x 4 BS</td>
<td>60% 1RM</td>
<td></td>
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<td></td>
<td></td>
<td>(1.8%), WU₁⁺</td>
<td>-</td>
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<td></td>
<td></td>
<td>WU₃: 2 x 4 BS</td>
<td>70% 1RM</td>
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<td></td>
<td></td>
<td></td>
<td>(3%)&lt;WU₁⁺</td>
<td>-</td>
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<tr>
<td></td>
<td></td>
<td>WU₄: 2 x 4 BS</td>
<td>85% 1RM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>WU₃&lt;WU₂⁺</td>
<td>-</td>
</tr>
<tr>
<td>McBride et al. 2005</td>
<td>15T (M)</td>
<td>WU₁: 5 min cycle 70rpm</td>
<td></td>
<td>70rpm</td>
<td>4 (“slow” walk)</td>
<td>40 m</td>
<td>Overall time:</td>
<td>WU₃&lt;WU₁⁺; WU₂⁺ (0.9%)&lt;WU₁⁺; WU₂⁺ 0-10 m: WU₁⁺ 1.4%)&lt;WU₁</td>
<td>-</td>
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<tr>
<td></td>
<td></td>
<td>WU₂: 5 min cycle 4 min walk</td>
<td>“slow”</td>
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<tr>
<td></td>
<td></td>
<td>3 x BS</td>
<td>90% 1RM</td>
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<tr>
<td></td>
<td></td>
<td>WU₃: 5 min cycle 4 min walk</td>
<td>“slow”</td>
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<tr>
<td></td>
<td></td>
<td>3 x CMJ</td>
<td>30% 1RM (BS)</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Matthews et al. 2004</td>
<td>20T (M)</td>
<td>WU₁: 20 m</td>
<td>Max sprint</td>
<td>NS</td>
<td>10</td>
<td>20 m</td>
<td>Overall time:</td>
<td>WU₂⁺ (0.1 sec)&lt;WU₁⁺</td>
<td>-</td>
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<tr>
<td></td>
<td></td>
<td>WU₂: 20 m</td>
<td>Max sprint</td>
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<td></td>
<td></td>
<td>5 x BS</td>
<td>5RM</td>
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</tbody>
</table>

1RM 1 repetition maximum, BhS back half squat, BM body mass, BS back squat, BW body weight, CMJ counter-movement jump, F female, HR heart rate, HR_max maximal heart rate (bpm), IS isometric squat, IKE isometric knee extension, M male, m metres, max maximal, min minute, NS not stated, La’ blood lactate concentration (mmol/L), RP race pace, RPM revolutions per minute, T trained runners, WBV whole-body vibration, WU warm-up intervention, VO₂ oxygen uptake, VO₂max maximal oxygen uptake, *denotes p < 0.05.
which sprint performance should commence, with a transition phase of 15 min found to elicit the best performances. The remaining nine studies utilised transition durations of 1 min, and 10 min, with only one study extending the transition phase to 20 min. Given that the marshalling time in competitive running events, particularly track events, can last between 10 and 20 min, arguably a focus for future studies should be to employ more competition-realistic timelines.

In terms of recommendations, it appears that completion of at least one race-pace effort for middle-distance races and a set of at least five near-race-pace efforts for sprint races results in subsequent faster running performance. For sprint events, performing a set of heavy-resistance exercises, such as back squats, may also enhance performance, though the feasibility of completing such exercises in the competition environment is questionable. Finally, much of the existing research has been conducted in sprint performance, so less is known about optimal warm-up strategies for middle- and long-distance running events.

### 2.8.2 Cycling

Cyclists competing in events on the road and the track in both sprint and endurance-focused events typically complete a warm-up either on a portable ergometer or on the competition surface itself. Much of the research conducted into endurance cycling performance has utilised time to exhaustion testing as the criterion task, with participants required to ‘pace’ themselves according to their VO$_2$ or heart rate (HR). In this review, however, we chose to examine only studies in which the criterion task sought to simulate a competitive event with a clearly defined endpoint. In keeping with these criteria, a total of five studies were chosen for review (Table 2). Each of these studies investigated the influence of warm-up on sprint events lasting 6–60 s in duration. In terms of warm-up duration and intensity, reducing the duration and the intensity of the initial aerobic portion (from 20 to 15 min) and the number of activation sprints completed (1 vs 4) resulted in higher peak power outputs during a 30 s Wingate test. In this example, it appears that the change in warm-up structure likely reduced fatigue, providing a better balance between fatigue and performance potentiation.
<table>
<thead>
<tr>
<th>Reference</th>
<th>Participants</th>
<th>Warm-up Volume</th>
<th>Intensity</th>
<th>Post warm-up Changes</th>
<th>Transition (min)</th>
<th>Criterion test</th>
<th>Performance results</th>
<th>Physiological results</th>
<th>Biomechanical results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Munro 2013</td>
<td>6T: 4M, 2F</td>
<td>WU1: 5 min</td>
<td>60% HR&lt;sub&gt;max&lt;/sub&gt;</td>
<td>NS</td>
<td>T&lt;sub&gt;1&lt;/sub&gt;: 4</td>
<td>6 sec</td>
<td>Time required to reach max velocity: WU&lt;sub&gt;2&lt;/sub&gt; + T&lt;sub&gt;1&lt;/sub&gt;&lt;WU&lt;sub&gt;1&lt;/sub&gt; + WU&lt;sub&gt;1&lt;/sub&gt;*</td>
<td>-</td>
<td>Optimal cadence, Mean PO: WU&lt;sub&gt;1&lt;/sub&gt; + T&lt;sub&gt;2&lt;/sub&gt;&gt;WU&lt;sub&gt;2&lt;/sub&gt; + WU&lt;sub&gt;1&lt;/sub&gt;*</td>
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<tr>
<td></td>
<td></td>
<td>5 min</td>
<td>65% HR&lt;sub&gt;max&lt;/sub&gt;</td>
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<td>T&lt;sub&gt;2&lt;/sub&gt;: 8</td>
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<td></td>
<td>5 min</td>
<td>70% HR&lt;sub&gt;max&lt;/sub&gt;</td>
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<td>T&lt;sub&gt;2&lt;/sub&gt;: 16</td>
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<td>6 sec</td>
<td>Max sprint</td>
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<td>1.5 min</td>
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<td>WU2: same as WU&lt;sub&gt;1&lt;/sub&gt; + 4 x 4 pedal strokes</td>
<td>Max sprints, 2 min rest/sets</td>
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<tr>
<td></td>
<td></td>
<td>WU3: same as WU&lt;sub&gt;1&lt;/sub&gt; + 4 x 4 (5 sec IC)</td>
<td>2 min rest/sets</td>
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<tr>
<td>Thatcher et al. 2012</td>
<td>10T (M)</td>
<td>WU1: 0</td>
<td>La&lt;sup&gt;a&lt;/sup&gt;, VO&lt;sub&gt;2&lt;/sub&gt;:</td>
<td>T&lt;sub&gt;1&lt;/sub&gt;: 5</td>
<td>30 sec (5,</td>
<td>-</td>
<td></td>
<td>WU1*</td>
<td>PPO: WU1 + T&lt;sub&gt;2&lt;/sub&gt;&gt;WU2 + T&lt;sub&gt;2&lt;/sub&gt; for 5, 10 sec splits*</td>
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<tr>
<td></td>
<td></td>
<td>WU2: 5 min</td>
<td>60 W</td>
<td>WU2&gt;WU1*</td>
<td>10, 30</td>
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<td>1 x 5 DL</td>
<td>50% 1RM</td>
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<td></td>
<td>1 x 5 DL</td>
<td>85% 1RM</td>
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<td>Wittekind et al. 2012</td>
<td>8T (M)</td>
<td>WU1: 6 min</td>
<td>40% PaP</td>
<td>La&lt;sup&gt;a&lt;/sup&gt;: WU1</td>
<td>10</td>
<td>30 sec</td>
<td>-</td>
<td>HHb: similar</td>
<td>Mean PO: WU1&gt;WU2&gt;WU&lt;sub&gt;1&lt;/sub&gt;*</td>
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<td></td>
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<td>40% PaP</td>
<td>(~4)&gt;WU&lt;sub&gt;2&lt;/sub&gt;</td>
<td>T&lt;sub&gt;2&lt;/sub&gt;: 10</td>
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<tr>
<td></td>
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<td>1 min</td>
<td>80% PaP</td>
<td>(~2)&gt;WU&lt;sub&gt;1&lt;/sub&gt;</td>
<td>T&lt;sub&gt;2&lt;/sub&gt;: 20</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>WU1: 5 min</td>
<td>40% PaP</td>
<td>(1)*</td>
<td>T&lt;sub&gt;1&lt;/sub&gt;: 30</td>
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<td></td>
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<td>1 min</td>
<td>110% PaP</td>
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<tr>
<td>Wittekind &amp; Beneke 2011</td>
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<td>WU1: 6 min</td>
<td>40% PaP</td>
<td>La&lt;sup&gt;a&lt;/sup&gt;: WU1</td>
<td>10</td>
<td>1 min</td>
<td>-</td>
<td>La&lt;sup&gt;a&lt;/sup&gt;: WU&lt;sub&gt;1&lt;/sub&gt; + WU&lt;sub&gt;2&lt;/sub&gt;&gt;WU&lt;sub&gt;1&lt;/sub&gt;*;</td>
<td>Mean PO: similar</td>
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<tr>
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<td>WU2: 5 min</td>
<td>40% PaP</td>
<td>(~4)&gt;WU&lt;sub&gt;2&lt;/sub&gt;</td>
<td>T&lt;sub&gt;2&lt;/sub&gt;&gt;WU&lt;sub&gt;1&lt;/sub&gt;*;</td>
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<td>1 min</td>
<td>80% PaP</td>
<td>(~2)&gt;WU&lt;sub&gt;1&lt;/sub&gt;</td>
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<td></td>
<td></td>
<td>WU1: 5 min</td>
<td>40% PaP</td>
<td>(1)*</td>
<td>WU&lt;sub&gt;1&lt;/sub&gt;&gt;WU&lt;sub&gt;1&lt;/sub&gt;*;</td>
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<td>Tomaras &amp; MacIntosh 2011</td>
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<td>HR&lt;sub&gt;max&lt;/sub&gt;;</td>
<td>12.5</td>
<td>30 sec</td>
<td>-</td>
<td>T&lt;sub&gt;skin&lt;/sub&gt;: similar</td>
<td>PPO: WU2&gt;WU&lt;sub&gt;1&lt;/sub&gt;*;</td>
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<td>Max sprints, 8 min rest</td>
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<td>La&lt;sup&gt;a&lt;/sup&gt;:</td>
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<td>WU1&gt;WU&lt;sub&gt;2&lt;/sub&gt;*</td>
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**Table 2.** Performance, physiological and biomechanical changes following active warm-up in cycling.

**1RM** 1 repetition maximum, **F** female, **DL** Deadlift, **HHb** deoxyhaemoglobin, **HR** heart rate (bpm), **HR<sub>max</sub>** maximal heart rate, **IC** isometric contraction, **M** male, **m** metres, **max** maximal, **min** minute, **NS** not stated, **La** blood lactate concentration (mmol/L), **PaP** peak aerobic power, **PO** power output, **PPO** peak power output, **T** trained cyclists, **T<sub>skin</sub>** skin temperature, **VO<sub>2</sub>** oxygen uptake, **WU** warm-up intervention, **W** watts. *denotes *p* < 0.05.*
Two groups have examined the influence of PAP-inducing exercises on sprint cycling performance. The addition of 4 x 4 dynamic contractions (four pedal revolutions against heavy resistance) to an existing warm-up involving a 15 min aerobic effort [60–70 % of maximum heart rate (HR_{max})] and a single 6 s sprint resulted in a faster time to maximal velocity and higher peak power output during a subsequent 6 s sprint. Additionally, participants reached maximal velocity quickest after only a 4 min transition, whereas the highest mean power output was recorded after a 16 min transition phase. In support of these findings, the completion of 2 x 5 deadlifts enhanced peak power output within the first 5 and 10 s of a 30 s sprint bout following a 10 min transition phase. It appears that short-duration (5–10 s) sprint performance (peak power and mean power output) can be enhanced following completion of a minimum of two sets of 4–5 repetitions of a dynamic heavy-resistance exercise prior to a 10–16 min transition phase.

The composition of an active warm-up strategy also appears to depend on the duration of the criterion task. In two studies conducted by the same research group, the same three active warm-up strategies were examined. Each strategy involved participants completing a total of 5 min of cycling at 40% of their peak aerobic power, followed by 1 min at either 40, 80 or 110% of peak aerobic power, with a 10 min transition phase then being observed. Participants performed either a 60 s maximal sprint or a 30 s maximal sprint. In both studies, La⁻ was increased by the active warm-ups and remained elevated up until the time-trial start in the 110% condition (~4 mmol) versus the 80% (~2 mmol) and 40% (~1 mmol) conditions. While there was no difference in mean power output during the 60 s effort, mean power output during the 30 s sprint was highest following the 40% condition compared with the 80 and 110% conditions, suggesting that residual acidosis has a greater effect on performance in shorter (i.e. 30 s) rather than longer (i.e. 60 s) sprint events.

In summary, for cycling, it appears that longer, higher-intensity aerobic warm-up strategies do not translate into better sprint cycling performance in comparison with relatively shorter, lower-intensity aerobic efforts followed by a few activation sprint efforts. Addition of several sets of dynamic heavy-resistance exercises towards the end of an active warm-up should promote sprint cycling performance but might only be practical in a training session. The duration of the criterion task is also important to consider, as ‘pure’ (i.e. ≤ 30 s) sprint events might be more sensitive to fatigue induced by a prior active warm-up than longer events (i.e. 30–60 s). Finally, there is a lack of studies examining the influence of active warm-up on
simulated endurance competition events (e.g. a 4000 m individual pursuit). Future research should seek to rectify this issue.

2.8.3 Swimming

Pool-based warm-ups are the most commonly utilised type of active warm-up strategy for swimmers competing at all levels, with many coaches believing that these are superior to dry-land-based warm-ups as they assist swimmers in gaining a ‘feel for the water’. Of the nine studies in the review, four demonstrated improvements in performance following completion of an active pool or dry-land-based warm-up, while the remaining five studies reported no improvements in swimming performance following active warm-up completion (Table 3). Three studies directly compared the influence of a pool-based warm-up on sprint swimming performance, with varying results. Significantly faster (100 m freestyle) or similar (50 m freestyle) performances were recorded following a 1000 m pool-based warm-up compared with no warm-up. The improved performance occurred following completion of a set of short-duration (25 m) race-pace efforts within the 1000 m warm-up, while in the remaining two studies, swimmers were simply requested to complete 1000 m at a ‘freely’ chosen exercise intensity. In addition, swimmers who completed a set of race-pace efforts produced faster 50 m split times. Completion of at least one set of race-pace efforts during the pool warm-up appears necessary to sufficiently prime swimmers for an upcoming sprint swim event.

In terms of total pool warm-up volume, three studies specifically compared the influence of short (91.4 m) and long-duration (457.2–1200 m) pool warm-ups on subsequent sprint (45.7 m) swimming performance. Two of these studies reported that the total volume had no influence on subsequent performance, while the remaining study reported faster sprint swimming times following a pool warm-up of ~1200 m in volume in comparison with a 91.4 m warm-up or no warm-up. It appears that the significantly higher HR reported following the longer-duration warm-up may have positively influenced subsequent sprint performance by elevating cardiac output prior to the start and potentially speeding VO2 kinetics. It could also be speculated that the shorter warm-up and the no-warm-up conditions may not have altered T_muscle significantly from baseline. Individual differences were observed, however,
with 19% of participants swimming faster after a short-duration warm-up and 37% swimming faster after no warm-up at all. It seems that the total pool warm-up volume can influence subsequent performance; however, individual responses can vary substantially. In terms of dry-land-based warm-ups, three research groups reported that either upper body vibration, an exercise routine including skipping and vertical jumps or heavy-resistance exercises (87% 1RM back squats) yielded swimming performances similar to those produced following a pool-based warm-up. These findings indicate that for athletes unable to access a pool, variations of a dry-land-based warm-up may be a feasible alternative. It appears that the performance of these exercises induces a PAP response, which most likely underpins subsequent improvements in short-duration events, such as sprint swimming.

In swimming, the duration of the transition phase is of particular importance because competitive swimmers are routinely required to report to the marshalling area ~15–20 min prior to the start of their race, effectively preventing them from completing additional active warm-up activities during this time. Prior to this, swimmers must complete their pool warm-up, change into their race swimsuit and receive any final communications from their coach. Thus, transition phases of 30–45 min are not uncommon. Only limited research has been conducted to quantify the impact of the transition duration on subsequent swimming performance. Reducing the transition duration from 45 to 10 min was associated with improvements (~1.4%) in 200 m swimming performance, but this paradigm does not reflect the competition reality (a ~15–20 min marshalling period). Similarly, a transition phase of 20 min yielded performance superior (~1.5%) to that of a 45 min transition. The participants’ core remained elevated during the 20 min transition, suggesting that improved maintenance of core may enhance subsequent exercise performance. In future studies, researchers should ensure that the study format accounts for the lengthy transition phases experienced by competitive swimmers and should identify effective methods for improving core maintenance.

From the studies reviewed, several recommendations can be made. Swimmers should complete between ~500 and 1200 m and include at least one set of short-duration race-pace efforts towards the end of their pool warm-up. Swimmers could also incorporate dry-land activities or even passive heat maintenance devices, such as heated athletic garments (as have been trialled in cycling studies) to maintain an elevated body temperature during lengthy
### Table 3. Performance, physiological and biomechanical changes following active warm-up in swimming.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Participants</th>
<th>Warm-up</th>
<th>Intensity</th>
<th>Dryland</th>
<th>Changes</th>
<th>Transition (min)</th>
<th>Criterion test</th>
<th>Performance results</th>
<th>Physiological results</th>
<th>Biomechanical results</th>
</tr>
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<tbody>
<tr>
<td>Neiva et al. 2014</td>
<td>20T: 10M, 10F</td>
<td>WU1:0</td>
<td>Easy</td>
<td>-</td>
<td>NS</td>
<td>10</td>
<td>100 m Free</td>
<td>Overall, 50 m split time: WU2 &lt; WU1*</td>
<td>LA', RPE: similar</td>
<td>WU2 &gt; WU1*</td>
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<td></td>
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<td>Nawaiseh et al. 2013</td>
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<td>45.7 m Free</td>
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<td>4 x 45.7</td>
<td>Kick/swim 1 min</td>
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<td>LA', RPE: similar</td>
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<td></td>
<td>45.7</td>
<td>90% VO&lt;sub&gt;2&lt;/sub&gt;max</td>
</tr>
<tr>
<td>Zochowski et al. 2007</td>
<td>10T: 5M, 5F</td>
<td>WU&lt;sub&gt;1&lt;/sub&gt;:300</td>
<td>Easy</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6 x 100</td>
<td>Pull/kick</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10 x 50</td>
<td>RP</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100</td>
<td>Easy</td>
</tr>
</tbody>
</table>

1 repetition maximum, back backstroke, bpm beats per minute, breast breaststroke, BS back squat, F female, free freestyle HR heart rate, HR<sub>max</sub> maximal heart rate (bpm), Hz hertz, IM individual medley, M male, m metres, Mast masters swimmers, max maximal, min minute, NS not stated, La blood lactate concentration (mmol/L), PHF peak horizontal force, PVF peak vertical force, RP race pace, RPE rate of perceived exertion, SC stroke count, SI stroke index, SL stroke length, SR stroke rate, T trained swimmers, T<sub>1</sub> transition duration, T<sub>core</sub> core temperature, UBV upper body vibration, VJ vertical jump, VO<sub>2</sub> oxygen uptake, WU warm-up intervention, *denotes p < 0.05.
transition phases. Finally, much research has been conducted on the influence of warm-up on short-duration (50–100 m) freestyle swimming events, but evidence is lacking for events lasting 200 m or more in freestyle and in other strokes (e.g. breaststroke).

2.8.4 Football, Rugby and Repeat-Sprint Performance

Athletes competing in field-based team sports, such as football and rugby, typically complete an active warm-up compromising running and mobility exercises, as well as sport-specific drills with or without the ball prior to a competitive match.\textsuperscript{177} These pre-match warm-ups on average last ~30 min, with a ~12 min transition between the end of the warm-up and the start of the match.\textsuperscript{38,162} A 10–15 min break between the first and second halves is also common.\textsuperscript{38,162} Fourteen studies feature in the review, with nine examining the influence of different pre-match warm-up strategies on performance (Table 4), while the remaining five investigated the efficacy of various rewarm-up strategies completed during the half-time break (Table 5). Five studies demonstrated that a non-sport-specific pre-match warm-up consisting of heavy-resistance exercises, such as back squats,\textsuperscript{143,178} back half-squats,\textsuperscript{179} front squats\textsuperscript{178,180} and leg press exercises,\textsuperscript{177} enhanced subsequent CMJ, repeat-sprint and reactive agility performance. However, sport-specific warm-ups, including activities such as small-sided games (SSGs), provide additional ergogenic benefits over a generic conditioning warm-up strategy by priming neural pathways and increasing neuromuscular activation.\textsuperscript{181} SSGs are designed to simulate the skill and physical/physiological demands of a particular sport by incorporating activities and movement patterns specific to competitive team-sport tasks, such as passing, shooting and ball control activities.\textsuperscript{182} The current evidence surrounding SSGs is equivocal, however, with reports of both improvements in CMJ, repeat-sprint and reactive agility performance following 3 x 2 min (2 min rest between) SSGs compared with a standard team-sport active warm-up (mobility drills, sprints and ball drills),\textsuperscript{177} and no improvements in reactive agility, vertical jump or sprint performance.\textsuperscript{183} A limitation of the latter study,\textsuperscript{183} however, was that the prescribed warm-up strategy was 22 min in duration, longer than previous recommendations,\textsuperscript{12} and included static stretching, which is known to impair subsequent performance.\textsuperscript{184} An over-long warm-up may needlessly deplete energy stores and decrease heat storage capacity,\textsuperscript{185} resulting in impaired performance. This theory is supported by work demonstrating that shorter-duration (12/16 min) warm-ups\textsuperscript{177,186} including SSGs produce better performance than longer-duration (22/23 min) warm-ups involving SSGs.\textsuperscript{183}
<table>
<thead>
<tr>
<th>Reference</th>
<th>Participants</th>
<th>Warm-up</th>
<th>Post warm-up measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anderson et al.</td>
<td>11T (M)</td>
<td>WU₁: 0 10 min running</td>
<td>HR, La', RPE: WU₁ + WU₂⁺ WU₄ &gt; WU₁ + WU₂⁺; T&lt;sub&gt;cst&lt;/sub&gt;: WU₄ &gt; WU₁, WU₂, WU₃⁺</td>
</tr>
<tr>
<td>et al. 2014</td>
<td></td>
<td>WU₂: 10 min running</td>
<td>5 RST: 15 x 20 m Overall time: WU₁ &lt; WU₁ + WU₂ + WU₃⁺</td>
</tr>
<tr>
<td></td>
<td></td>
<td>WU₁: 10 min running</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>WU₄: 10 min running</td>
<td></td>
</tr>
<tr>
<td>Pringle et al.</td>
<td>28T (M)</td>
<td>WU₁: 22 min of static stretching, mobility drills, ball drills, SSGs</td>
<td>HR: WU₂ &gt; WU₁; RPE: similar</td>
</tr>
<tr>
<td>et al. 2013</td>
<td></td>
<td>WU₂: 16 min of mobility drills, ball drills, sprint drills, SSGs</td>
<td>5 40 m Sprint time: WU₁ &lt; WU₁⁺; 10, 20 m split time, VJ: similar</td>
</tr>
<tr>
<td></td>
<td></td>
<td>WU₃: 10 min running</td>
<td></td>
</tr>
<tr>
<td>Zois et al.</td>
<td>10T (M)</td>
<td>WU₁: 3 x 2 min SSGs</td>
<td>3 vs. 3 (2 min rest) 70-85% HR&lt;sub&gt;max&lt;/sub&gt; “Jog”</td>
</tr>
<tr>
<td>2011</td>
<td></td>
<td>WU₂: 5 min 5RM leg press</td>
<td>T&lt;sub&gt;cst&lt;/sub&gt;: WU₁ &gt; WU₂ &gt; WU₃; HR, La': WU₁ &gt; WU₂ &gt; WU₃; RA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>WU₃: 23 min of strides, mobility drills, ball drills and 40 m sprints</td>
<td>4 RST: 15 x 20 m Sprint time: WU₁ &gt; WU₂ &gt; WU₃⁺</td>
</tr>
<tr>
<td>Needham et al.</td>
<td>20T (M)</td>
<td>WU₁: “Jog”</td>
<td>CMJ: WU₁ &lt; WU₂ &lt; WU₃⁺; Sprint time: WU₁ &lt; WU₂ &lt; WU₃⁺</td>
</tr>
<tr>
<td>et al. 2009</td>
<td></td>
<td>10 min static stretching</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>WU₂: “Jog”</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>10 min dynamic stretching</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>WU₃: same as WU₂ + 8 x FS</td>
<td></td>
</tr>
<tr>
<td>Till &amp; Cooke</td>
<td>12T (M)</td>
<td>WU₁: “Jog”</td>
<td></td>
</tr>
<tr>
<td>2009</td>
<td></td>
<td>WU₂: “Jog”</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>5RM DL</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>WU₃: 5 min, 1 x 5 TJ</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>WU₄: 5 min, 3 x 3 sec IC KE</td>
<td></td>
</tr>
<tr>
<td>Reference</td>
<td>Participants</td>
<td>Warm-up</td>
<td>Post warm-up measures</td>
</tr>
<tr>
<td>----------------------------</td>
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<td>---------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Gabbit et al. 2008</td>
<td>14T; 6 M, 8 F</td>
<td>WU₁: 7 min mobility exercises, static stretching, 15 min ball drills and SSGs WU₂: same as WU₁ + 15 min skipping, acceleration runs, CoD running, 20 m sprints</td>
<td>NS 0 RA, 20 m sprint, CoD speed, VJ; similar</td>
</tr>
<tr>
<td>Kilduff et al. 2008</td>
<td>20T (M)</td>
<td>WU₁: 5 min rowing, mobility exercises 3 x 3 BS 87% 1RM</td>
<td>NS T₁: 0.25 T₂: 4 T₃: 8 T₄: 12 T₅: 16 T₆: 20 T₇: 24 CMJ Jump height: WU₁ + T₃<em>T₄-T₅</em></td>
</tr>
<tr>
<td>Yetter &amp; Moir 2008</td>
<td>10T (M)</td>
<td>WU₁: 5 min cycling WU₂: 5 min cycling 5, 4, 3 x BS WU₁: same as WU₂ except FS</td>
<td>NS 4 RST: 3 x 30 m (3 min rest) WU₁&lt;WU₂* 0-10 m time: WU₂&lt;WU₁* 30-40 m time: WU₁&lt;WU₂+ WU₂*</td>
</tr>
<tr>
<td>Chatzopoulos et al. 2007</td>
<td>15T (M)</td>
<td>WU₁: 3 x 30 m 10 x BhS 100% VO₂max 90% 1RM</td>
<td>NS T₁: 3 T₂: 5 RST: 3 x 30 m Overall time: T₁&lt;T₂ Initial 10 m time: T₁&lt;T₂*</td>
</tr>
</tbody>
</table>

1RM 1 repetition maximum, AT anaerobic threshold, BhS back half squat, BM body mass, BS back squat, CMJ counter-movement jump, CoD change of direction, DL deadlift, F female, FS front squat, HR heart rate, HRmax maximal heart rate (bpm), Hz hertz, IC isometric contraction, KE knee extension, kp kilo pound, La lactate concentration (mmol/L), LaT lactate threshold, M male, m metres, max maximal, min minute, NS not stated, PPO peak power output, RA repeat agility, RPE rate of perceived exertion, RST repeat-sprint test, SSGs small-side-games, T trained team sport athletes, Tcore core temperature, TJ tuck jump, VJ vertical jump, VO₂ oxygen uptake, WU warm-up intervention. *denotes p < 0.05.
<table>
<thead>
<tr>
<th>Reference</th>
<th>Participants</th>
<th>Warm-up</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Edholm et al. 2014</td>
<td>22T (M)</td>
<td>Re-WU1; 0</td>
<td>HR: Re-WU1; &gt; RPE: similar</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Re-WU2; 7 min</td>
<td>clock, “jogging” 70% HRmax + “light” calisthenics</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>15 (2 x 45 min simulated game play)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>RST: 2 x 10 m sprints; Sprint time: Re-WU1; &gt; Re-WU2; &gt; Re-WU1; &gt; Re-WU1</td>
</tr>
<tr>
<td>Lovell et al. 2013</td>
<td>10T (M)</td>
<td>Re-WU1; 0</td>
<td>T_muscle: Re-WU1; &gt; Re-WU2; &gt; Re-WU1; &gt; HR, VO2; &gt; Re-WU1; &gt; Re-WU1; &gt; Re-WU1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Re-WU2; 5 min</td>
<td>15 (2 x 45 min simulated game play)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>RST: 3 x 10 m sprints; Sprint time: Re-WU1; &gt; Re-WU2; &gt; Re-WU1; &gt; Re-WU1; &gt; Re-WU1; &gt; Re-WU1</td>
</tr>
<tr>
<td>Zois et al. 2013</td>
<td>8T (M)</td>
<td>Re-WU1; 0</td>
<td>RPE: similar</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Re-WU2; 3 min SSG</td>
<td>2 vs. 2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Re-WU3; 5RM leg press</td>
<td>RPE: similar</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>15 (2 x 26 min intermittent running)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>CMJ; RSA; Re-WU1; &gt; Re-WU2; &gt; Re-WU1; &gt; Re-WU1</td>
</tr>
<tr>
<td>Lovell et al. 2007</td>
<td>7T (M)</td>
<td>Re-WU1; 0</td>
<td>HR: Re-WU1; &gt; RPE: similar</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Re-WU2; 7 min cycle</td>
<td>70% HRmax; 70% HRmax</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>15 (2 x 16.5 min intermittent running)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>RST: 40 x 15 sec; Total distance covered in RST: Re-WU1; &gt; Re-WU1; &gt; Re-WU1; &gt; Re-WU1; &gt; Re-WU1</td>
</tr>
<tr>
<td>Mohr et al. 2004</td>
<td>25T (M)</td>
<td>Re-WU1; 0</td>
<td>HR: 70% HRmax ~135bpm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Re-WU2; 7 min running</td>
<td>15 (2 x 45 min game play)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>RST: 3 x 30 m (25 sec rest)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Sprint time: Re-WU1; &gt; Re-WU1; &gt; Re-WU1; &gt; Re-WU1; &gt; Re-WU1; &gt; Re-WU1</td>
</tr>
</tbody>
</table>

**Table 5.** Performance, physiological and biomechanical changes following active half-time re-warm-up in football, rugby and upon repeat-sprint performance.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Participants</th>
<th>Warm-up</th>
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<tbody>
<tr>
<td>Edholm et al. 2014</td>
<td>22T (M)</td>
<td>Re-WU1; 0</td>
<td>HR: Re-WU1; &gt; RPE: similar</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Re-WU2; 7 min</td>
<td>clock, “jogging” 70% HRmax + “light” calisthenics</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>15 (2 x 45 min simulated game play)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>RST: 2 x 10 m sprints; Sprint time: Re-WU1; &gt; Re-WU2; &gt; Re-WU1; &gt; Re-WU1</td>
</tr>
<tr>
<td>Lovell et al. 2013</td>
<td>10T (M)</td>
<td>Re-WU1; 0</td>
<td>T_muscle: Re-WU1; &gt; Re-WU2; &gt; Re-WU1; &gt; HR, VO2; &gt; Re-WU1; &gt; Re-WU1; &gt; Re-WU1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Re-WU2; 5 min</td>
<td>15 (2 x 45 min simulated game play)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>RST: 3 x 10 m sprints; Sprint time: Re-WU1; &gt; Re-WU2; &gt; Re-WU1; &gt; Re-WU1; &gt; Re-WU1; &gt; Re-WU1</td>
</tr>
<tr>
<td>Zois et al. 2013</td>
<td>8T (M)</td>
<td>Re-WU1; 0</td>
<td>RPE: similar</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Re-WU2; 3 min SSG</td>
<td>2 vs. 2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Re-WU3; 5RM leg press</td>
<td>RPE: similar</td>
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<tr>
<td></td>
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<td></td>
<td>15 (2 x 26 min intermittent running)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>CMJ; RSA; Re-WU1; &gt; Re-WU2; &gt; Re-WU1; &gt; Re-WU1</td>
</tr>
<tr>
<td>Lovell et al. 2007</td>
<td>7T (M)</td>
<td>Re-WU1; 0</td>
<td>HR: Re-WU1; &gt; RPE: similar</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Re-WU2; 7 min cycle</td>
<td>70% HRmax; 70% HRmax</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>15 (2 x 16.5 min intermittent running)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>RST: 40 x 15 sec; Total distance covered in RST: Re-WU1; &gt; Re-WU1; &gt; Re-WU1; &gt; Re-WU1; &gt; Re-WU1</td>
</tr>
<tr>
<td>Mohr et al. 2004</td>
<td>25T (M)</td>
<td>Re-WU1; 0</td>
<td>HR: 70% HRmax ~135bpm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Re-WU2; 7 min running</td>
<td>15 (2 x 45 min game play)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>RST: 3 x 30 m (25 sec rest)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Sprint time: Re-WU1; &gt; Re-WU1; &gt; Re-WU1; &gt; Re-WU1; &gt; Re-WU1; &gt; Re-WU1</td>
</tr>
</tbody>
</table>

**Table 5.** Performance, physiological and biomechanical changes following active half-time re-warm-up in football, rugby and upon repeat-sprint performance.

**Notes:** HRM 1 repetition maximum, bpm beats per minute, CMJ counter-movement jump, CoD change of direction, HR heart rate, HRmax maximal heart rate (bpm), Hz hertz. IAE intermittent agility exercises, LSPT Loughborough soccer passing test, M male, m metres, min minute. Re-WU re-warm-up intervention. RPE rate of perceived exertion, RSA repeat-sprint ability, RST repeat-sprint test, SSGs small-side-games, T trained team sport athletes, Tcore core temperature, T_muscle muscle temperature, velocitypeak peak velocity, WBV whole-body vibration, WU warm-up intervention. * denotes p < 0.05.
The intensity of the pre-match warm-up strategy is also important. An active warm-up completed at an intensity just above the anaerobic threshold was more effective than a warm-up performed below the anaerobic threshold.\textsuperscript{6} While transition phases of 3 min,\textsuperscript{179,180} 6 min\textsuperscript{180} and 8 min\textsuperscript{143} have resulted in improved subsequent CMJ and repeat-sprint performance, this finding is not consistent with similar improvements in 20 m sprint and vertical jump performance reported following transition phases ranging from 4 to 9 min in the same study.\textsuperscript{187} Although these results are informative, in the competition environment, transition phases of ~12 min in duration are the norm, with some sports stipulating that pre-match warm-ups must be concluded no later than 10 min prior to match start.\textsuperscript{192} Thus, use of other activities, including passive heat maintenance strategies, is of interest in future research.

A number of studies have identified a decline in player work rate\textsuperscript{193-195} within the initial phase of the second half in comparison with the corresponding phase in the first half. Several reasons for this have been postulated, but, of pertinence here, sub-optimal preparation as a consequence of no re-warm-up completion during the half-time break\textsuperscript{16,191,193} may be a contributing factor. Compounding this issue is the fact that at the elite level, in particular, there is limited time during the half-time break for rewarm-up activities to be undertaken with practitioners (e.g. sport scientists, coaches), suggesting that only a ~3 min window is available.\textsuperscript{162} In the only study that investigated a 3 min re-warm-up strategy, players were required to play a two versus two SSG or complete a 5RM leg press or no re-warm-up at all, with subsequent performance in a repeat sprint, CMJ and football-specific criterion task all shown to be superior following completion of either of the two re-warm-up strategies.\textsuperscript{190} Regarding longer re-warm-up strategies, completion of a 5 min repeat-sprint drill enhanced repeat-sprint and CMJ performance in comparison with no re-warm-up,\textsuperscript{189} while a 7 min repeat-sprint drill or cycle exercise prompted an increase in the distance covered within the second half.\textsuperscript{191} Improvement in second-half performance was also correlated with better $T_{\text{core}}$ maintenance resulting from completion of either of the two active re-warm-up strategies.\textsuperscript{191}

Finally, a 7 min half-time re-warm-up strategy involving continuous running at 70% HRmax improved\textsuperscript{196} and maintained repeat-sprint performance\textsuperscript{16} in comparison with no activity. Ball possession in the second half was also greater following a continuous sub-maximal re-warm-up,\textsuperscript{196} while the decline in $T_{\text{core}}$ and $T_{\text{muscle}}$ was attenuated during a 15 min half-time break (0.97 ± 0.1°C and 2.17 ± 0.1°C higher than control, respectively)\textsuperscript{16} with this re-warm-up strategy. It appears that completion of an active re-warm-up during the half-time break can
enhance subsequent performance, and although only a small timeframe has been identified (~3 min) for a re-warm-up to be completed, it is known that steady-state moderate-intensity exercise increases $T_{\text{muscle}}$ at a rate of 0.15–0.38°C per minute.\textsuperscript{97,197} Thus, players may still be able to partially offset the 1.5°C to 2.0°C reduction shown to occur in $T_{\text{muscle}}/T_{\text{core}}$ during a 15 min half-time break\textsuperscript{16} or substitution periods.

In summary, the inclusion of SSGs in a pre-match warm-up strategy for sports such as football and rugby may enhance subsequent performance but only if the duration of the warm-up strategy is $\leq$ 16 min. The pre-match warm-up should also be completed as close to match start as possible, with passive heat maintenance strategies considered if the transition duration exceeds 10 min. Completion of a 3–7 min half-time re-warm-up strategy involving activities such as SSG, repeat-sprint drills or continuous running can also enhance second-half and repeat-sprint performance by minimizing the decline in $T_{\text{core}}/T_{\text{muscle}}$ during the half-time break.

### 2.9 Future Directions

Although completion of a pre-event warm-up is common practice in sports, several questions remain unanswered. Much research has investigated the influence of warm-up completion on sprint and sustained high-intensity performance, with few studies on endurance performance. In addition, researchers should expand study designs beyond simply comparing one warm-up intervention strategy, either passive or active, with a control strategy in which no warm-up is performed, given that these days it is virtually standard for athletes to complete some form of pre-event warm-up. Studies in which multiple warm-up strategies are examined and then compared for their efficacy are needed to provide more meaningful information. Access to equipment and transition/marshalling period length have been overlooked, and future studies should replicate competition conditions as closely as possible for external validity. Finally, within cycling and rugby, passive heat maintenance strategies, such as heated athletic garments, have been shown to assist in maintaining some of the beneficial temperature effects induced by an active warm-up throughout lengthy transition phases. It would be pertinent to examine the influence of passive heat maintenance in sports such as athletics and swimming, where the transition phase also extends beyond ~10–15 min.
2.9.1 Conclusions

Despite a previous scarcity of well-controlled studies and minimal empirical evidence supporting coaches’ and athletes’ belief that a pre-event warm-up is essential for optimal performance, extensive research over the past decade has provided substantial support for pre-competition warm-up completion. Passively or actively elevating $T_{\text{muscle}}$ can markedly influence subsequent exercise performance via mechanisms such as increases in ATP turnover and muscle cross-bridge cycling rate, as well as improvements in muscle fibre functionality and conduction velocity. Athletes competing in sprint and sustained high-intensity events seem the most likely beneficiaries of elevations in body temperature due to increases in muscle glycogen availability and the rate of force development. A speeding of VO$_2$ kinetics following completion of a priming exercise bout may also enhance subsequent endurance performance, possibly via sparing of finite anaerobic stores and/or prompting an increase in motor unit recruitment, such that the ‘strain’ placed on each individual muscle fibre is reduced. The short-term contractile history of skeletal muscle has also been shown to have a significant effect upon a muscle’s ability to generate force. Athletes seeking to harness the benefits of PAP should complete several sets of ballistic exercises, such as drop jumps or CMJs, while wearing a weighted vest, and should experiment with different transition durations to determine the optimal length. The majority of the recent research supports the notion that a well-structured active warm-up elicits improvements in performance across a wide range of sports, while passive heat maintenance devices, such as heated athletic garments and blizzard survival jackets, can preserve the beneficial temperature effects induced via an active warm-up during lengthy transition phases. The initial aerobic portion of an active warm-up should be shortened to < 15 min, and a few (e.g. 1–5) activation sprints/race-pace efforts or dynamic PAP-inducing exercises should be completed to elicit improvements in subsequent sprint and sustained high-intensity events. Finally, for team sports, such as football or rugby, the addition of SSGs to the pre-match warm-up, as well as completion of a brief, sub-maximal active re-warm-up involving activities such as repeat-sprint drills or continuous running during the half-time break, elicits improvements in repeat-sprint and second-half performance.
CHAPTER 3: Literature Review Update

The articles contained in the preceding literature review were published prior to the 1st of May 2014. Since this time, several new research papers have been published which pertain to the three main themes investigated in this thesis: 1) swimming-specific warm-up strategies; 2) passive heat maintenance strategies; 3) ballistic-style PAP-inducing exercises. The information below provides a summary of the most recent research conducted in these three areas (up until 1st December 2015). In addition, a review of studies investigating same-day priming exercise is provided. Compiling this literature review update involved the identification of articles via systematic searches of the EBSCO, Medline and SPORTDiscus databases and examination of the reference lists of the selected articles.

3.1 Swimming-Specific Warm-Up Strategies

Five recent papers have investigated the influence of active warm-up completion on subsequent sprint swimming performance (Table 6). A pool warm-up volume of 1200 m was demonstrated to produce superior 100 m freestyle performance to that of a 600 or 1800 m warm-up, with the longer warm-up producing the slowest times. Greater stroke length and higher stroke efficiency index in the second 50 m were identified as major contributing factors. These findings are in line with previous research demonstrating that improvements in stroke length are associated with faster swimming performance.

Another group investigated the influence of adding 4 x 10 m ‘resisted’ sprint swims (via an in-water power-rack) to a 900 m pool warm-up. Swimming performance was faster when these ‘resisted’ swims were completed, possibly due to an up-regulation of the participants’ glycolytic energy system as evidenced by the higher post time-trial La− concentrations recorded. A PAP stimulus consisting of lunges and YoYo squats, also resulted in similar performances to that of a pool-based warm-up. While these results are important, the feasibility of completing ‘resisted swims’ or heavy resistance exercises as part of a warm-up within a competitive setting is questionable. More practical, ballistic-style exercises may be required. However in a recent investigation, completion of ballistic-style exercises such as
Table 6. Summary of research focusing on swimming warm-up, passive heat maintenance strategies and ballistic priming exercises published between May 2014 to December 2015.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Participants</th>
<th>Warm-Up In Pool Volume (m)</th>
<th>Intensity</th>
<th>Passive</th>
<th>Dryland</th>
<th>Changes Transition (min)</th>
<th>Criterion Test</th>
<th>Performance Results</th>
<th>Physiological Results</th>
<th>Biomechanical Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neiva et al. 2015 198</td>
<td>11T (M)</td>
<td>WU1:150</td>
<td>Breathe 5th Stroke 25 m kick/high SL 50 m drill/50 Build to RP, 25m</td>
<td>-</td>
<td>-</td>
<td>HR, RPE: similar; La: WU1, WU3; TC: WU2, WU3</td>
<td>10</td>
<td>100 m Free</td>
<td>Overall time: WU3 &lt; WU1 &lt; WU1*</td>
<td>La, TC: WU2 &lt; WU3</td>
</tr>
<tr>
<td>Hancock et al. 2015 200</td>
<td>30T:15M, 15F</td>
<td>WU1:900</td>
<td>“Resisted”</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>6</td>
<td>100 m Free</td>
<td>Overall time: WU2 &lt; WU1*</td>
<td>La: WU2 &gt; WU1</td>
</tr>
<tr>
<td>Sarramian et al. 2015 30</td>
<td>18T:10M, 8F</td>
<td>WU1:30 min</td>
<td>Swim, kick, “short sprints”</td>
<td>WU2:PU 3RM WU1:5 x CMJ 10% BM (WV) WU4: WU2 + WU3</td>
<td>-</td>
<td>WU1:15 WU3,4:4, 8 or 12</td>
<td>50 m Free</td>
<td>Overall time: WU1 &lt; WU2*</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Table 6. continued

<table>
<thead>
<tr>
<th>Reference</th>
<th>Participants</th>
<th>Warm-Up In-Pool Volume (m)</th>
<th>Intensity</th>
<th>Passive</th>
<th>Dryland</th>
<th>Changes Transition (min)</th>
<th>Criterion Test</th>
<th>Performance Results</th>
<th>Physiological Results</th>
<th>Biomechanical Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cuenca-Fernandez et al. 2015</td>
<td>14T:10M, 4F</td>
<td>WU₁,₂,₃:200 50</td>
<td>Easy</td>
<td>-</td>
<td>WU₁,₂,₃: Dynamic stretching</td>
<td>8</td>
<td>Free</td>
<td>Overall time: WU₁&lt; WU₃*; 5 min time: WU₁&lt; WU₃&lt; WU₁; Dive distance: WU₁&gt; WU₂&gt; WU₁*</td>
<td>Flight time, MHHV: WU₁&lt; WU₂&lt; WU₁*</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>WU₂:3 x lunge 85% 1RM</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>WU₃: x max YoYo Squat</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adams et al. 2014</td>
<td>8T (M)</td>
<td>WU₁:20 min WU₂:10 min</td>
<td>-</td>
<td>WU₂: 20 min sauna 80°C</td>
<td>HR,RPE: WU₁&gt; WU₂&gt; WU₁</td>
<td>20</td>
<td>Overall time: similar</td>
<td>HR,RPE: WU₁&lt; WU₂&lt; WU₁*</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>WU₂: 10 min sauna 80°C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>West et al. 2015</td>
<td>16T (M)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>WU₃: Tcore, PPO: similar</td>
<td>20</td>
<td>CMJ, RSTmean: WU₃ &lt; WU₃</td>
<td>WU₁ + WU₂* WU₁ &gt; WU₂ &gt; WU₂*</td>
<td>LB PO: WU₁ &gt; WU₃* WU₂ &gt; WU₁*</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>WU₁: jogging, skipping, dynamic stretching, sprints</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>WU₃: WU₁ + 3 x 5 CMJ + 20% BM (WV) WU₂: WU₁ + WU₂ + WU₃</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Passive Heat Maintenance Strategies**

- CMJ: Countermovement Jump
- RST: Run-Sprint-Throw
- Tcore: Core Temperature
- LB PO: Lower Body Power Output
<table>
<thead>
<tr>
<th>Reference</th>
<th>Participants</th>
<th>Warm-Up</th>
<th>Post Warm-Up Measures</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>In-Pool Volume (m)</td>
<td>Intensity</td>
</tr>
<tr>
<td>Russell et al. 2015</td>
<td>18T (M)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Andrade et al. 2015</td>
<td>10 (M)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Margaritopoulos et al. 2015</td>
<td>10T:5M,5F</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Buttifant &amp; Hrysomallis 2015</td>
<td>12T (M)</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

**Ballistic-Style PAP-inducing Exercises**
Table 6. continued

<table>
<thead>
<tr>
<th>Reference</th>
<th>Participants</th>
<th>Warm-Up</th>
<th>Post Warm-Up Measures</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>In-Pool Volume</td>
<td>Intensity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(m)</td>
<td></td>
</tr>
<tr>
<td>Turner et al. 2015</td>
<td>23T (M)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Enyia &amp; Olson 2014</td>
<td>6T:3M,3F</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

pull-ups (3 repetition maximum; RM) and countermovement jumps (CMJ; 5 x wearing weight vest of 10% of the participant’s bodyweight) resulted in slower swimming performances in comparison to those reported following a pool-based warm-up.\(^\text{30}\) One explanation for this outcome is that the intensity used to complete the ballistic-style exercises was not sufficient to induce a PAP response strong enough to be carried through to the criterion task. It may be possible to increase the intensity of ballistic-style exercises by increasing the load to be moved (e.g. CMJs with 15% bodyweight weight vest) or by increasing the number of repetitions (e.g. 2 x 3RM pull-ups) completed.

In the final study reviewed, passive warming in an 80°C sauna elicited similar performance times to that of an active pool warm-up or a combination warm-up consisting of passive (sauna) and active (pool exercise) components.\(^\text{201}\) Although changes in body temperature were not monitored within this investigation, it is plausible that the different warm-up conditions resulted in a similar increase in body temperature, which may explain the comparable subsequent performance time results.

In summarising these recent findings, it appears that pool warm-up volume can have a significant effect upon subsequent sprint freestyle performance, with greater swimming volumes shown to elicit a negative response. The inclusion of a set of ‘resisted’ sprints to a pool warm-up can add to the performance benefits elicited from pool warm-up completion. Undertaking a PAP stimulus of weighted lunges and YoYo squats can also produce similar subsequent swimming performances to that of a pool warm-up. However the feasibility of completing “resisted swims” and heavy resistance exercises within the competition environment is questionable. Future research should determine whether a greater PAP and performance response can be induced, by increasing the intensity with which ballistic-style exercises are completed within a warm-up. Critically only two studies\(^\text{30,201}\) utilised transition phases which accounted for the typical length of swimming competition marshalling periods of 15-20 min.\(^\text{15,34}\) The remaining three studies\(^\text{44,198,200}\) used transition phases of 4-10 min. However, no study utilised a transition phase of adequate duration to account for the combined time required following a pool warm-up to don a race swimsuit, have a final discussion with the coach as well as the length of the marshalling period (~30-40 min).
3.2 Passive Heat Maintenance Strategies

Only two studies have recently examined the influence of passive heat maintenance strategies on subsequent athletic performance with both studies completed by the same research group (Table 6). The aim of the first study was to determine if blizzard survival jackets could ameliorate the decline in $T_{core}$ during a simulated half-time break (15 min) in rugby and subsequently enhance lower-body power output and repeat-sprint performance. The second study utilised a similar design to ascertain temperature and performance changes following a 20 min transition phase.

As part of the two studies, three additional warm-up strategies were undertaken within the transition phase: passive heat maintenance via blizzard survival jackets, and/or a supplementary dryland-based warm-up consisting of $3 \times 5$ CMJ (with a 20% body mass load). The blizzard survival jackets (Blizzard Survival Jacket, Blizzard Protection Systems Ltd, UK) were tailor-made with long sleeves and fell to below knee length. The jackets were also tight fitting so as to trap warm air, reduce convection and improve insulation, with a reflective surface to limit radiative heat loss. Of the $T_{core}$ gained through the warm-up procedure, ~85-88% was lost when the blizzard jackets were not worn. Conversely, an improvement in $T_{core}$ maintenance was seen in the blizzard jacket alone, and combination blizzard jacket and jumps condition, with only a ~29-30% loss in $T_{core}$ during the transition phase. The combination blizzard jacket and jumps condition was shown to be superior to that of the no jacket and blizzard jacket alone conditions, resulting in significant improvements in mean repeat-sprint performance (~0.06 sec and ~0.02 sec, respectively, $p < 0.05$). A similar $T_{core}$ response was seen in the blizzard jacket alone condition following a simulated half-time break, with significant increases in lower-body peak power output (~3.2%) and mean total repeat-sprint performance (~1.4%).

Although additional passive heat was not applied to the entire lower-body, with the blizzard survival jackets only falling to just below the knee, lower-body peak power output was still improved when these jackets were worn. This outcome is likely due to the enhancement in $T_{core}$ maintenance observed when the blizzard survival jackets were worn. Conversely, when the blizzard survival jackets were not worn, a greater decline in $T_{core}$ occurred during the transition phase and this was associated ($r = 0.63$) with reduced lower-body peak power.
output.\textsuperscript{40} These studies affirm the importance of utilising strategies to maintain elevated body temperature, particularly $T_{\text{core}}$, during lengthy transition phases in order to enhance subsequent exercise task performance. Utilising blizzard survival jackets during the transition phase appears as a practical and effective passive heat maintenance strategy for enhancing subsequent short-duration exercise performance, at least in the context of rugby-related performance.

### 3.3 Ballistic-Style PAP-inducing Exercises

Ballistic-style exercises such as weighted/un-weighted drop jumps and plyometric exercises may provide practical alternatives for swimmers to utilise on pool deck in comparison to traditional, heavy-resistance exercises (e.g. back squats with Olympic barbells).\textsuperscript{29} Only studies which utilised jumping, short-duration (< 1 min) or sprint tasks as their criterion performance measurement were reviewed, given that the enhancement of sprint swimming performance was a key focus of this thesis.

Five studies were chosen for review (Table 6). Two groups examined the influence of drop jumps on subsequent performance,\textsuperscript{202,206} with the remaining three studies investigating tuck jumps,\textsuperscript{203} resistance band squats\textsuperscript{204} or weighted/un-weighted plyometric bounds.\textsuperscript{205} A set of 3 x 8 drop jumps combined with 3 x 8 CMJ improved subsequent squat jump performance,\textsuperscript{202} though a set of 3 x 5 drop jumps added to a dynamic active warm-up did not enhance ground reaction force during an athletics block start.\textsuperscript{206} Drop jumps in both studies were completed from a height of ~60 cm for males, so the PAP load was similar between conditions. Completion of a different jump stimulus, tuck jumps (3 x 5), also only elicited a marginal (~2.5 cm), though significant ($p < 0.01$) improvement in CMJ performance.\textsuperscript{203} It is possible that the transition phase (5 min)\textsuperscript{203,206} may not have been sufficient to elicit an improvement in subsequent exercise performance, given that PCr resynthesis typically occurs ~4-8 min following a preloading stimulus.\textsuperscript{48}

In another study, researchers investigated if ballistic exercises could produce a similar performance response to that of heavy resistance exercises.\textsuperscript{204} Semi-professional Australian rules football players completed either 3 x 3 barbell squats equating to their 3RM or 3 x 3
back squats with resistance bands (load equivalent to ~101kg) looped over their shoulders. Compared to a static stretching warm-up, lower-body power output was greater in both squat conditions, with no difference in power output recorded between squat protocols. In considering these findings, squats with resistance bands appear to be an effective method for enhancing lower-body power output and a practical alternative to heavy resistance squats, at least in the context of Australian Rules football.

Finally, 23 plyometric-trained males completed a warm-up consisting of jogging, dynamic stretching and short sprints alone or combined with 3 x 10 plyometric bounds (body mass only) or 3 x 10 plyometric bounds (body mass plus 10%, via a weight vest). Following transitions of 15 sec, 2, 4, 8, 12 or 16 min, participants completed a 20 m sprint. Sprinting velocity over the initial 10 m was higher in both plyometric bounds conditions following the 4 and 8 min transitions. Overall (20 m) sprinting velocity was greater in the plyometric bounds plus 10% body weight condition after the 4 and 8 min transitions were observed. In addition, total sprint time was significantly faster in both plyometric bounds conditions after the 4 min transition phase compared to the standard warm-up, with the bounds plus 10% body weight condition also producing the fastest times after the 8 min transition. These results are in line with previous research demonstrating that 8 min is the optimum transition phase duration following a PAP stimulus. The enhancement in sprint performance was greater in the faster participants than the slower participants. This outcome demonstrates that more experienced athletes, with whom training adaptation may protect against muscle damage, are more likely to respond optimally to pre-loading activities.

It appears that drop or tuck jumps completed alone or in addition to an active warm-up, have the potential to enhance subsequent short-duration performance if a sufficient (8 min) transition phase is observed. Squats completed with resistance bands or weighted/unweighted plyometric bounds can also enhance subsequent lower-body power output and sprint performance. The addition of several sets of plyometric bounds with and without extra resistance (10% body mass via a weight vest) to an active warm-up can enhance performance in a 20 m sprint task, with the additional load condition shown to produce superior performances. The ballistic exercises investigated in the above discussed studies are feasible and practical alternatives to traditional heavy resistance PAP-inducing exercises (e.g. power cleans) and are capable of inducing a comparable PAP response. From an applied swimming perspective, each of these exercises could viably be completed on pool deck as part of
swimmers’ dryland-based warm-up, given they require minimal equipment, space and time to complete.

### 3.4 Same-Day Priming Exercise Bouts

Only studies pertaining to the acute assessment of physical, physiological or biomechanical performance following completion of a priming exercise bout several hours prior (at least 4 hr) to a criterion task were included in this literature review. Information gathered from studies utilising this particular design could be useful for athletes who complete two training sessions per day (morning and afternoon) in which benchmark sessions are completed in the second session or those athletes who compete in morning heats and afternoon/evening finals sessions. Studies investigating diurnal changes in performance, in which participants completed an exercise task in either the morning or afternoon, were not included as these studies do not determine whether completion of a prior exercise bout influences performance in a subsequent exercise bout. Studies that did not include a control condition (e.g. non-completion of a morning exercise bout) were also excluded as an adequate reference point could not be determined.

All six studies chosen for review investigated the influence of a morning resistance exercise bout on subsequent afternoon exercise performance, with two studies also examining the influence of prior morning sprint exercise (Table 7). Completion of back squat and power clean exercises performed to fatigue 4-6 hr prior to an explosive power test (backward overhead squat throw with weight) enhanced shot-put throwing performance by 40 cm compared to when no exercise was completed. A 4-6 hr break between sessions was chosen as a typical gap between a resistance exercise session and an initial competition throw on competition day. Although the reported performance improvement may not appear large, in competitive throws events at the elite level final placing’s are typically separated by only a few centimetres.

Completion of 3 x 5 clean and snatch pulls at 85% 1RM can also enhance subsequent clean and jerk and snatch lift performance, as well as vertical jump height following a 5.5 hr break. However, this group also recorded participant’s anxiety profiles and determined that
Table 7. Summary of studies investigating the influence of same-day priming bout completion on subsequent later day exercise performance across all sports.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Participants</th>
<th>Morning Exercise</th>
<th>Afternoon Exercise</th>
<th>Volume</th>
<th>Intensity</th>
<th>Changes</th>
<th>Break (hours)</th>
<th>Baseline Measurements</th>
<th>Criterion Task</th>
<th>Performance Results</th>
<th>Physiological Results</th>
<th>Biomechanical results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Russell et al. 2015</td>
<td>15T (M)</td>
<td>ME₁:0</td>
<td>ME₂;5 x 10 BP</td>
<td>75%</td>
<td>1RM</td>
<td>Test: ME₁* &gt; ME₂*</td>
<td>5</td>
<td>Test: ME₁* &gt; ME₂*</td>
<td>CMJ height, RSP</td>
<td>ME₁ &gt; ME₂</td>
<td>-</td>
<td>Reaction time: similar</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ME₂;6 x 6s cycling</td>
<td>ME₃;6 x 40 m sprints</td>
<td>7.5%</td>
<td>BM</td>
<td>ME₂ &gt; ME₃</td>
<td></td>
<td>Cort: similar</td>
<td>CMJ height:</td>
<td>ME₁, ME₂ &gt; ME₃</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>RSP</td>
<td>ME₁ &gt; ME₂</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Cook et al. 2013</td>
<td>18T (M)</td>
<td>ME₁:0</td>
<td>ME₂; 5 x 40 m sprints</td>
<td>1 min</td>
<td>rest</td>
<td>Test, Cort: ME₂ &gt; ME₁</td>
<td>6</td>
<td>Test: ME₁* &gt; ME₂*</td>
<td>3RM BS + BP, CMJ PO</td>
<td>ME₁ &gt; ME₂ + ME₃, ME₂ &gt; ME₃, ME₁ &gt; ME₃</td>
<td>-</td>
<td>ME₁ &gt; ME₂ + ME₃</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+ ME₁* &gt; ME₂* &gt; ME₃*</td>
<td></td>
<td>Cort: ME₂ &gt; ME₃</td>
<td>3 x 40 m sprint:</td>
<td>ME₁ &lt; ME₂ + ME₃* &gt; ME₃ &gt; ME₁</td>
<td>-</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>similar &gt; ME₃ *</td>
<td></td>
<td></td>
<td>CMJ PO</td>
<td>similar</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Ekstrand et al. 2013</td>
<td>14T: 7M, 7F</td>
<td>ME₁:0</td>
<td>ME₂; PC 4 x 6</td>
<td>35%</td>
<td>1RM</td>
<td>-</td>
<td>4-6</td>
<td>-</td>
<td>BOST, VJ PO</td>
<td>ME₁ &gt; ME₂</td>
<td>-</td>
<td>VJ PO: similar</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>BS 1 x 6</td>
<td>50%</td>
<td>1RM</td>
<td></td>
<td></td>
<td></td>
<td>BOST;</td>
<td>ME₁ &gt; ME₂</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1 x 6</td>
<td>85%</td>
<td>1RM</td>
<td></td>
<td></td>
<td></td>
<td>ME₁ &gt; ME₂</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>BS + PC “to fatigue”</td>
<td>100%</td>
<td>3RM</td>
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<td>5 min stretching</td>
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<td>ME₂,4,6 &gt; ME₄*</td>
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<th>Reference</th>
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<tr>
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<td>Volume</td>
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1RM 1 repetition maximum, AT anaerobic threshold, B break duration, BM body mass, BOST backwards overhead squat throw, BP bench press, BS back squat, CMJ countermovement jump, Cort cortisol, CP clean pull, DIP dumbbell incline press, DJ drop jump, F female, HC hang clean, HS half squat, hr hour, km kilometre, M male, m metres, ME morning exercise intervention, min minute, OP overhead press, PJ push jerk, PLC prone leg curl, PO power output, rpm revolutions per minute, RSP repeat-sprint ability, s seconds, SP snatch pull, T trained athletes, Test testosterone, VJ vertical jump. *denotes $p < 0.05$.  

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only participants with high anxiety levels responded positively to completion of a morning resistance exercise bout.\textsuperscript{55} Optimal lifting performance is in part dependent upon arousal levels\textsuperscript{209} and excessive anxiety can impair performance.\textsuperscript{210} Gross motor tasks including many heavy weight lifting movements, can benefit from high arousal levels.\textsuperscript{211} A high level of precision also is required to execute Olympic lifts (which were the criterion task in this study) and thus, regulation of arousal and anxiety levels is paramount for eliciting optimal weight lifting performance. Elevated anxiety can manifest somatically, though completion of physical activity has been demonstrated to ameliorate this particular form of anxiety.\textsuperscript{212} This is important as elevated anxiety levels can be accompanied by increased electromyographic (EMG) activity, resulting in increased fatigue.\textsuperscript{213} It is plausible that completion of the morning resistance exercise bout may have alleviated a proportion of the participants (the responders only) feelings of anxiety. This may have subsequently resulted in a non-increase in EMG activity and contributed to the reported improvement in afternoon Olympic lifting and jumping performance.

Athletes typically complete two training sessions per day and competitions often commence in the afternoon/evening. Therefore, information about the time-course of the acute response following a prior resistance exercise bout is useful to both coaches and sport scientists. A recent study examined a morning session consisting of heavy resistance exercises completed together or separately to loaded/un-loaded CMJs, or a volleyball-specific warm-up, followed by either a 5 min or 6 hr break.\textsuperscript{136} Drop jump height was higher following the 5 min break and remained elevated following the 6 hr break in the loaded CMJ only, resistance exercise only and volleyball-specific exercise conditions.\textsuperscript{136} However, jump squat power output was only maintained following the 6 hr break in the loaded CMJ only condition.\textsuperscript{136} It would be pertinent in future investigations to examine further how this time-course response changes depending upon different break durations between sessions (e.g. 1, 2, 4 hr post exercise session).

Anaerobic performance can be influenced by the time of day a task is completed. Physiological markers, including heart rate\textsuperscript{60} and $T_{\text{core}}$\textsuperscript{59,60} exhibit circadian rhythmicity with an early morning nadir and a subsequent peak in the afternoon with the reverse reported for cortisol\textsuperscript{214-216} and testosterone.\textsuperscript{215,216} A resistance-based exercise bout (bench press and back squats) completed 6 hr prior to an afternoon testing session elicited improvements in 3RM bench press (by 2-6 kg), 3RM back squat (by 4-8 kg), CMJ peak power output (by 110-182
watts) and 40 m sprint time (by 0.02-0.08 sec) performance. The circadian decline in testosterone was substantially less following the morning resistance and sprint sessions with pre afternoon session testosterone concentrations also higher in comparison to when no morning exercise was undertaken. Prior to the afternoon session, cortisol concentrations were also substantially higher in the resistance and sprint exercise conditions in comparison to the no exercise condition. A movement-specific priming effect was postulated, given that completion of the morning sprint session substantially enhanced afternoon sprint but not strength performance.

In a follow-up study conducted by the same group, a morning exercise bout consisting of resistance exercise (bench press) and running (repeat sprints with one 180° change of direction included) was reported to enhance initial sprint performance in an afternoon repeat running sprint task, with the morning running session eliciting the superior performance (resistance exercise: 0.15-0.16 sec; running: 0.15-0.17 sec). Interestingly, morning cycle exercise (repeat sprints on an ergometer) did not enhance afternoon repeat running sprint performance though CMJ height was greater in the afternoon following a morning cycling (by 0.01 m) exercise bout. In contrast with their previous work, morning running exercise was also shown to enhance (by 0.02 m) afternoon CMJ performance. This finding suggests the specificity of the morning exercise task relative to the criterion afternoon task may not be as crucial as was initially thought, though the authors did acknowledge that this was a preliminary investigation. The decline in testosterone concentration between the morning and afternoon session was attenuated in all three conditions (cycling, resistance, running), with completion of the morning running exercise bout permitting players to enter the afternoon session with the highest testosterone concentrations. This finding is in line with previous work demonstrating that acute free testosterone levels appear predictive of ensuing physical performance.

Only one study reported no improvement following completion of a morning resistance exercise bout, with afternoon basketball-specific shooting, vertical jump and Wingate test performance similar to a no exercise control following a 6 hr break. This was the only study to examine sport-specific technical skill performance following same day priming bout completion, with the other four studies reviewed utilising criterion tasks which assessed anaerobic and strength performance. While afternoon basketball technical and physical performance is not adversely affected by a morning resistance exercise bout, the findings of
this study do contrast the existing body of evidence. One possible explanation for the lack of improvement reported in vertical jump and Wingate test performance is that the intensity (60-70% 1RM) with which the morning resistance exercise session was completed may not have been high enough. In each of the four studies reporting improvements in afternoon performance, at least one set of a particular resistance exercise was performed at the intensity of 85% 1RM or above. Therefore, the intensity of the morning exercise bout should be taken into consideration in future investigations.

In summary it appears that completion of a morning resistance-based or sprint-based exercise bout can enhance athletic performance completed 4-6 hr later. Inclusion of at least one set of a heavy-intensity (at least 85% 1RM) resistance exercise may be required to ensure the transfer of beneficial effects of a morning bout through to an afternoon criterion task. A movement-specific priming effect was also demonstrated with completion of a morning sprint session enhancing afternoon sprint but not strength performance. Finally, it is important to monitor athlete’s anxiety levels as athletes exhibiting high anxiety profiles may be more likely to respond positively several hours later following a bout of resistance exercise.

Future research should seek to further elucidate the physical and physiological mechanisms responsible for the reported performance improvements. It would also be pertinent to examine in more detail how the acute time-course response changes depending upon the duration of the break between sessions (e.g. 1, 2, 4 or 6 hr post exercise session). Information gathered from such investigations could be useful to athletes competing away from home. For example, if a similar positive performance response is demonstrated following a 2 or 4 hr break, athletes can work with their coach and team managers to plan their competition day preparation strategies around facility access and venue travel to optimise their response to a same-day priming exercise bout.

In terms of swimming, it is typical for swimmers to compete in morning heats and then semi-finals in the afternoon/evening of the same day. Swimmers qualifying for finals in the 50, 100 and 200 m events are faced with the question of whether to complete a morning exercise bout prior to racing later that day or to simply rest. Completion of two training sessions, one in the early morning (e.g. 6:00-8:00) and one in the afternoon (16:00-18:00) is also common for most swimmers, with benchmark test sets typically completed in the afternoon session. These
are two possible scenarios in which data collected regarding completion of same-day priming bouts may be applied in swimming.

3.5 Summary and comparative analysis of dryland-based sports and swimming

Performance in sport-specific tasks is improved following the completion of active warm-ups consisting of sport-specific tasks or generic conditioning/non-sport-specific tasks. However, it has been speculated that active warm-ups consisting of sport-specific tasks provide additional ergogenic benefits over generic conditioning warm-ups by priming neural pathways and increasing neuromuscular activation. For instance in football, small-sided games are utilised as sport-specific active warm-up tasks as they are designed to simulate the skill and physical/physiological demands of a football game, incorporating activities and movement patterns specific to football such as passing, shooting and ball control activities. Thus, for optimal criterion task performance to be attained, it appears imperative to ensure activities performed within an active warm-up closely replicate the movement patterns to be executed in a subsequent criterion task. As outlined previously, swimming coaches typically prescribe an active pool-based warm-up be completed prior to a competitive race. It has been suggested that these pool-based warm-ups are superior to dryland-based warm-ups as they provide swimmers with an opportunity to gain a “feel” for the water. Therefore in swimming, the sport-specificity component of the active warm-up appears satisfied.

The duration of the transition phase following an active warm-up is important to consider when determining the effectiveness of the pre-competition warm-up. While potentiation of muscle twitch is greatest immediately following a PAP stimulus, PCr resynthesis requires ~4-8 min following completion of a preloading activity. For land-based athletes preparing to compete in short-duration and/or power-focused criterion tasks, a transition duration of 7–10 min is deemed optimal for eliciting peak power outputs in experienced individuals. Furthermore, T_muscle and T_core begin to decline immediately following exercise cessation, with a significant reduction occurring ~15–20 min after exercise termination. Considering this, it appears that the optimal transition phase duration following an active warm-up is > 4 min but < 15 min.
In swimming, competitive swimmers are routinely required to report to the marshalling area ~15–20 min prior to the start of their race, preventing them from completing additional swimming-specific active warm-up activities during this time. Prior to this, swimmers complete their pool warm-up, change into their race swimsuit (~10-15 min) and receive any final communications from their coach (~5-10 min). Thus, transition phases of 30–45 min are not uncommon. While in land-based sports such as track sprint running (e.g. 100 m, 200 m), transition phases of > 20 min have also been reported, again due to lengthy marshalling periods, at major competitions such as the World Championships and the Olympic Games, these athletes are given an additional opportunity to complete a final pre-event warm-up on the track surface itself within ~5 min of starting their event, which falls within the optimal transition phase duration period. Competitive swimmers are not afforded the same opportunity for logistical reasons. Thus, sport scientists and coaches must seek to develop new active warm-up strategies for maintaining elevated body temperature and muscle activation throughout lengthy transition phases for competitive swimmers. A plausible alternative may be the completion of dryland-based exercises, within 4-15 min of a race, which seeks to closely replicate common swimming movements.

With regards to the intra-day priming effect, where morning exercise bouts have been demonstrated to positively influence afternoon exercise performance, as with active warm-up, optimal afternoon performance appears linked to the sport-specificity or movement-specificity of the exercise tasks completed in the morning exercise bout. Indeed, completion of a morning sprint session was reported to enhance afternoon sprint but not strength performance in rugby players. It is plausible then that completion of a morning exercise bout consisting of swimming-specific, pool-based movements may positively influence afternoon swimming performance. However at major events such as the Olympic Games, athletes are typically based in the village quite a distance (up to an hour), from the competition or training venues. Unlike rugby players who could feasibly access a stretch of ground to complete a morning sprint session, for swimmers to complete a morning exercise bout consisting of sport-specific pool-based activities they would need to travel up to an hour each way to reach the swimming training venue. Therefore, although completing a swimming-specific morning exercise session may elicit positive performance benefits to races competed in later that same day, coaches may choose not to complete such as session due to concerns about the impact the additional travel may have upon their athletes afternoon performance.
performance. In this instance, a non-sport-specific morning exercise bout, such as a series of ballistic-resistance exercises, may serve as a possible alternative. Recent evidence has demonstrated that both sport-specific and non-sport-specific activities performed in a morning session can elicit significant enhancements to afternoon exercise performance in sports such as rugby, athletics throws and weightlifting. Sport scientists should determine if a similar effect can be elicited in competitive swimmers.
DECLARATION OF CO-AUTHORED PUBLICATION

CHAPTER 4

Declaration by candidate

In the case of Chapter 4, the nature and extent of my contribution to the work was the following:

<table>
<thead>
<tr>
<th>Nature of contribution</th>
<th>Extent of contribution (%)</th>
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</thead>
<tbody>
<tr>
<td>Developing the research question and research design, data collection and analysis, write-up and editing the manuscript</td>
<td>80%</td>
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The following co-authors contributed to the work.

<table>
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<th>Name</th>
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<tr>
<td>Dr Ben Rattray</td>
<td>Research design, editing the manuscript</td>
<td>6%</td>
<td>N</td>
</tr>
<tr>
<td>Prof David Pyne</td>
<td>Research design, editing the manuscript</td>
<td>6%</td>
<td>N</td>
</tr>
<tr>
<td>Prof Kevin Thompson</td>
<td>Research design, editing the manuscript</td>
<td>4%</td>
<td>N</td>
</tr>
<tr>
<td>Prof John Raglin</td>
<td>Research design, editing the manuscript</td>
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Candidate’s Signature 27/03/2016

Declaration by co-authors

The undersigned hereby certify that:

(7) the above declaration correctly reflects the nature and extent of the candidate’s contribution to this work, and the nature of the contribution of each of the co-authors.
(8) they meet the criteria for authorship in that they have participated in the conception, execution, or interpretation, of at least that part of the publication in their field of expertise;
(9) they take public responsibility for their part of the publication, except for the responsible author who accepts overall responsibility for the publication;
(10) there are no other authors of the publication according to these criteria;
(11) potential conflicts of interest have been disclosed to (a) granting bodies, (b) the editor or publisher of journals or other publications, and (c) the head of the responsible academic unit; and
(12) the original data are stored at the following location(s) and will be held for at least five years from the date indicated below:

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[Please note that the location(s) must be institutional in nature, and should be indicated here as a department, centre or institute, with specific campus identification where relevant.]

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CHAPTER 4: Current warm-up practices and contemporary issues faced by elite swimming coaches

The manuscript contained within this chapter has been accepted for publication and has been formatted to comply with the publishing journal’s guidelines: McGowan CJ, Pyne DB, Raglin JS, Thompson KG & Rattray B. Current warm-up practices and contemporary issues faced by elite swimming coaches. The Journal of Strength and Conditioning Research. March 26th 2016. [Epub ahead of print]

4.1 Manuscript Information

In order to improve the effectiveness of a warm-up strategy it is important to have an understanding of the current status quo. In this initial study, a survey of a large cohort of elite swimming coaches was conducted to gather data about their current pre-competition warm-up practices. Coaches provided information pertaining to the pool warm-ups they currently prescribed in terms swimming volume, the intensity prescribed for the various stages of the pool warm-up and the length of the recovery intervals observed between various warm-up efforts. Information regarding dryland-based warm-up structure, including the type and volume of the exercises prescribed and the intensity (and subsequent recovery intervals set) at which these exercises were completed, was also collected. The elite swimming coaches were also requested to provide information regarding any issues faced while trying to complete the final stage of their athletes’ competition preparation.

4.1.1 Research Objectives

1. Determine the structure (i.e. intensity, duration, recovery) of the pool and dryland-based warm-up strategies currently prescribed by elite swimming coaches within the competition environment.
2. Ascertain the issues and challenges faced by athletes and coaches during the final stages of event preparation.
4.2 Accepted Manuscript

4.2.1 ABSTRACT

A better understanding of current swimming warm-up strategies is needed to improve their effectiveness. Objectives: The purpose of this study was to describe current pre-competition warm-up practices and identify contemporary issues faced by elite swimming coaches during competition. Methods: Forty-six state-international level swimming coaches provided information via a questionnaire on their prescription of volume, intensity and recovery within their pool and dryland-based competition warm-ups, and challenges faced during the final stages of event preparation. Results: Coaches identified four key objectives of the pre-competition warm-up: physiological (elevate body temperature and increase muscle activation), kinaesthetic (tactile preparation, increase “feel” of the water), tactical (race-pace rehearsal) and mental (improve focus, reduce anxiety). Pool warm-up volume ranged from ~1300-2100 m, beginning with 400-1000 m of continuous, low-intensity (~50-70% of perceived maximal exertion) swimming, followed by 200-600 m of stroke drills and 1-2 sets (100-400 m in length) of increasing intensity (~60-90%) swimming, concluding with 3-4 race or near race-pace efforts (25-100 m; ~90-100%) and 100-400 m easy swimming. Dryland-based warm-up exercises, involving stretch cords and skipping, were also commonly prescribed. Coaches preferred swimmers complete their warm-up 20-30 min prior to race start. Lengthy marshalling periods (15-20+ min) and the time required to don racing suits (> 10 min) were identified as complicating issues. Conclusions: Coaches believed the pool warm-up affords athletes the opportunity to gain a tactile “feel” for the water and surrounding pool environment. The combination of dryland-based activation exercises followed by pool-based warm-up routines appears to be the preferred approach taken by elite swimming coaches preparing their athletes for competition.

4.2.2 INTRODUCTION

In preparation for competitive events, it is well recognised that swimming coaches prescribe a pre-competition warm-up, typically an active, pool-based warm-up. While evidence exists
regarding the design of optimal training programs for swimmers to be “race ready”, less is known about the actual pre-competition warm-up.

In swimming, the effectiveness of a warm-up strategy is determined by the intensity and duration of the swimming and dryland elements, as well as the time between warm-up end and the onset of the race, here termed the transition phase. Completion of active or passive warm-up strategies can enhance subsequent exercise performance. These in enhancements in performance are in part, attributed to elevations in muscle temperature, which facilitates improvements in muscle fiber conduction velocity, muscle metabolism and adenosine triphosphate (ATP) utilization. Elevations in muscle temperature can also positively alter the force–velocity relationship and concomitantly the power–velocity relationship, leading to higher power outputs in exercise tasks, with a ~3ºC augmentation in muscle temperature eliciting a measurable increase in both muscle fiber conduction velocity and power output.

An active warm-up, can also prompt a ‘speeding’ of oxygen uptake (VO2) kinetics and induce a postactivation-potentiation (PAP) response. In addition, the warm-up period is recognised as an opportunity for athletes to mentally prepare for an up-coming event by providing time to concentrate on the task ahead. Typical mental preparation strategies include visualization, saying of cue words, attentional focus and preparatory anxiety elevation or relaxation in order for athletes to achieve their optimal level of pre-competition anxiety and physiological activation.

A number of experimental studies have examined the influence of various warm-up strategies on swimming performance, but it appears that no observational or self-report information exists pertaining to the actual pre-competition warm-ups used in elite swimming. Knowledge about trends in pool and dryland-based pre-competition warm-up prescription could provide a needed reference for swimming coaches, strength and conditioning coaches, and sports scientists alike when designing pre-competition warm-ups and intervention studies. In addition, it is important for conditioning coaches and sport scientists to understand the situational factors coaches and swimmers face within the competition environment. Therefore, the aim of this study was to describe the current pre-competition warm-up practices in swimming and identify contemporary issues faced by elite swimming coaches and their athletes within the competition environment.
4.2.3 METHODS

Experimental Approach to the Problem

This exploratory, descriptive study was designed to provide comprehensive descriptive information regarding the current competition warm-up practices of elite swimming coaches. An observational study design was utilised with data collected via a self-administered questionnaire (see page 153-155 in the appendices) consisting of eighteen questions including nine multiple choice and nine open-ended questions.

Subjects

Forty-six (n=43 male, 43 ± 13 y; n=3 female, 36 ± 9 y) currently practicing swimming coaches based in Australia (n = 43), Britain (n = 2) and Canada (n = 1) were informed of the benefits and risks of the investigation and provided their written informed consent to participate in the study. All recruited coaches were required to hold a minimum of a State-level coaching license to participate in the investigation. This study was approved by the Human Research Ethics Committee at the University of Canberra.

Research Instrument

The questionnaire (see appendix, page 165-167), developed by the research team in consultation with three expert (holding National Open level coaching license) coaches, was designed to ascertain the current warm-up practices and identify contemporary issues faced by elite swimming coaches and their athletes during competitions. The theoretical framework for questionnaire design as outlined by Patton,\textsuperscript{225} was used to inform questionnaire design within the present study. In addition, a number of the items in the questionnaire were modelled after items used by investigators in previously published studies in which questionnaires were used to gather information about elite coaching practices.\textsuperscript{226-228} Pilot testing of the questionnaire was completed with five swimming coaches (State-National level) prior to the commencement of the study at local swimming meets to provide face validity and ensure its appropriateness for use within this population, in accordance with previously described methods.\textsuperscript{162,226,229} The feedback gathered from this pilot testing was
used to refine the questions and wording to better reflect current swimming coaching terminology (no pilot study data was utilised as part of the present investigation).

The initial section of the questionnaire involved items inquiring about coaches’ previous swimming competitive history, how long they had been coaching, formal swimming coaching qualifications currently held, and the typical competitive level of the swimmers they coached on a weekly basis. In the next section, coaches were asked to provide specific information about the pool warm-ups they prescribed for the 100, 200 and 400 m freestyle events in terms of the volume, intensity and recovery for each particular stage of the pool warm-up. We chose to focus the questionnaire around these particular events as six (including freestyle and medley relays) of the sixteen Olympic pool-based swimming events require an individual to complete either a 100, 200 or 400 m freestyle effort. In the final section, the swimming coaches were asked to describe any dryland-based warm-ups they employ and any external factors they felt could alter the potential benefits of a precompetition warm-up. While it is well documented that the warm-up period is a time for physical as well as mental preparation for an upcoming event, our focus here is an in-depth understanding of the actual physical preparation undertaken by elite swimmers immediately prior to competing.

**Procedures**

Initially, coaches were contacted through an introductory letter describing the study and provided with a consent form as well as a copy of the swimming warm-up questionnaire. A reminder email was sent out one month after initial contact was made. The second point of recruitment was face-to-face contact. The majority (n = 31) of respondents were approached in person at several national-level swimming competitions conducted within Australia. These coaches were provided with a verbal and written description of the study at the beginning of the swimming competition. Coaches were then given a hardcopy version of the consent form and the questionnaire to complete individually at their leisure during the competition. Coaches completed the questionnaire alone with no members of the research team present. The questionnaires were then placed in a sealed envelope and collected individually from each participating coach after the meet. These efforts to standardise contact procedures were undertaken in an attempt to minimise extraneous factors which might influence swimming
coach responses. Of the 58 coaches approached, 80% of coaches responded and completed the questionnaire.

Statistical Analysis

We employed a cross-sectional descriptive survey of swimming competition warm-ups. All fixed response and closed-question data was analysed using frequencies to determine the percentage response from the cohort of coaches. A student’s t-test was used to compare differences in total pool warm-up volume between the 100, 200 and 400 m events as well as the volumes of the various stages of the pool warm-up. Significance was set at $p < 0.05$. Effect size (ES) was calculated using Cohen’s d and evaluated as trivial (0–0.19), small (0.20–0.49), medium (0.50–0.79) and large (0.80 and greater). Precision of estimation was indicated with 95% confidence intervals. Answers to open-ended questions (for example, “What do you believe are the primary benefits of the warm-up?”) were content analysed according to standardised protocols.\textsuperscript{225} Initially, the lead researcher generated raw data and higher-order themes using inductive content analysis. These themes were later independently validated by the remaining co-authors using deductive analysis to ensure all raw data themes were represented.

4.2.4 RESULTS

Descriptive characteristics of the surveyed coaches are provided in Table 8. The mean coaching experience (how long they had been coaching competitive swimmers) of the respondents was $18 \pm 11$ y (mean ± standard deviation). The typical age of the swimmers (coached on a weekly basis) was 15–21 y. All surveyed coaches reported they were presently instructing swimmers competing at both age-group and open competitive levels.

The coaches were asked what they believed were the primary benefits associated with precompetition warm-up completion, and their responses were content analysed. This resulted in the creation of four higher-order themes, including, (a) mental, (b) kinaesthetic/tactile, (c) physiological, and (d) tactical. Table 9 lists these higher-order themes
and the total number of coaches whose responses made up each theme as well as representative raw data associated with each higher-order theme.

Table 8. Descriptive characteristics of the surveyed swimming coaches.

<table>
<thead>
<tr>
<th>Previous competitive experience as a swimmer</th>
<th>Formal Coaching Qualifications Held</th>
<th>Type of swimmers coached</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td>State Level</td>
<td>6 (Age), 2 (Open)</td>
<td>7</td>
</tr>
<tr>
<td>National Level</td>
<td>7 (Age), 15 (Open)</td>
<td>32</td>
</tr>
<tr>
<td>International Level</td>
<td>2 (Age), 11 (Open)</td>
<td>7</td>
</tr>
</tbody>
</table>

An overview of the pool warm-ups prescribed for the 100, 200 and 400 m distances is presented in Table 10. The typical volume of the pre-competition pool-based warm-up for the 100 m race distance was 1440 ± 660 m (mean ± standard deviation) which was less than that of the 200 m and 400 m race distances (1650 ± 670 m, \( p = 0.02 \), standardised difference (ES) -0.34; 1870 ± 830 m, \( p < 0.01 \), ES -0.65, respectively). The total pool warm-up prescribed for the 200 m race distance was also less than that of the 400 m (\( p < 0.01 \); ES -0.30).

Table 9. Main objectives of the warm-up identified by the swimming coaches.

<table>
<thead>
<tr>
<th>Higher order themes</th>
<th>Number of responses</th>
<th>Select raw data representing responses to the question</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mental preparation</td>
<td>18</td>
<td>Need to be mentally alert but composed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Must be relaxed and focused on race plan</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Get into the zone and focus on the task at hand while</td>
</tr>
<tr>
<td></td>
<td></td>
<td>staying relaxed especially if there are delays in the</td>
</tr>
<tr>
<td></td>
<td></td>
<td>schedule</td>
</tr>
<tr>
<td>Kinaesthetic/Tactile preparation</td>
<td>32</td>
<td>Proprioceptively get a feel for the water</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Skill reminders for stroke technique, starts and turns</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Get comfortable in the pool environment including</td>
</tr>
<tr>
<td></td>
<td></td>
<td>start blocks and walls</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Technical skill refinement and get a feel for the</td>
</tr>
<tr>
<td></td>
<td></td>
<td>water</td>
</tr>
<tr>
<td>Physiological preparation</td>
<td>34</td>
<td>Warming-up and loosening muscles</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Elevate heart rate and get muscles ready to race</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stimulate the relevant energy systems</td>
</tr>
<tr>
<td>Tactical preparation</td>
<td>32</td>
<td>Get a sense for race-pace, speed and technique</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Race-pace rehearsal</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pacing practice</td>
</tr>
</tbody>
</table>
Table 10. Overview of the typical pool warm-ups prescribed by coaches for the 100, 200, and 400 m distances in terms of total distance (m), examples of specific efforts completed (including use of additional devices), type of effort (continuous: nonstop swimming for ≥50 m; build: efforts completed with the intensity increasing; and sprint: efforts completed at >90% PME).

<table>
<thead>
<tr>
<th>Race Distance</th>
<th>Warm-Up Stage</th>
<th>Mean ± SD (CI) Total Distance</th>
<th>Example of Specific Efforts Completed</th>
<th>Additional Devices Utilised</th>
<th>Type of Effort</th>
<th>Intensity (% PME)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 m</td>
<td>1</td>
<td>567 ± 172</td>
<td>400-600 m swim or 5 x 100 m swim</td>
<td>-</td>
<td>Continuous</td>
<td>50-70%</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>339 ± 150</td>
<td>8 x 50 m swim or 3 x 100 m</td>
<td>KB, PB, HP</td>
<td>Continuous/Build</td>
<td>60-90%</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>205 ± 122</td>
<td>4 x 25 m swim or 3 x 50 m swim</td>
<td>-</td>
<td>Sprint/Continuous</td>
<td>80-100/50%</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>159 ± 87</td>
<td>3 x 25 m dive or start/turn practice</td>
<td>-</td>
<td>Sprint/Continuous</td>
<td>100/50%</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>173 ± 121</td>
<td>100-300 m swim</td>
<td>-</td>
<td>Continuous</td>
<td>40-60%</td>
</tr>
<tr>
<td>200 m</td>
<td>1</td>
<td>639 ± 220*</td>
<td>400-800 m swim or 3 x 200 m swim</td>
<td>-</td>
<td>Continuous</td>
<td>50-70%</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>399 ± 158*</td>
<td>4 x 100 m swim or 3 x 200 m swim</td>
<td>KB, PB, HP</td>
<td>Build</td>
<td>60-90%</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>221 ± 118</td>
<td>3 x 50 m swim or 6 x 50 swim descending to race pace</td>
<td>-</td>
<td>Sprint/Continuous</td>
<td>80-100/50%</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>196 ± 91*</td>
<td>4 x 50 m dive or 3 x 50 m</td>
<td>-</td>
<td>Sprint/Continuous</td>
<td>80-100/50%</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>203 ± 69</td>
<td>100-300 m swim</td>
<td>-</td>
<td>Continuous</td>
<td>40-50%</td>
</tr>
<tr>
<td>400 m</td>
<td>1</td>
<td>690 ± 282*</td>
<td>3 x 400 m swim or 600 m swim</td>
<td>-</td>
<td>Continuous</td>
<td>50-70%</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>441 ± 183*</td>
<td>6 x 100 m swim or 300 pull/kick</td>
<td>KB, PB, HP</td>
<td>Build</td>
<td>70-90%</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>245 ± 114</td>
<td>6 x 50 m swim or 3 x 100 m swim</td>
<td>-</td>
<td>Sprint/Build</td>
<td>80-100%</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>213 ± 120*</td>
<td>4 x 50 m dive or 3 x 100 m swim at</td>
<td>-</td>
<td>Sprint/Continuous</td>
<td>80-100/50%</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>263 ± 106*</td>
<td>200-400 m swim</td>
<td>-</td>
<td>Continuous</td>
<td>40-50%</td>
</tr>
</tbody>
</table>

CI 95% confidence intervals, HP hand paddles, KB kickboard, PB pull buoy, PME perceived maximal exertion, SD standard deviation. *Significantly greater than 100 m for that particular stage distance (p < 0.05).

During the pool warm-up, coaches requested their swimmers utilise additional devices such as kickboards (14%), pull buoys (11%), hand paddles (14%), fins (8%), snorkels (8%) or a combination of these devices (46%). In between swimming efforts, various rest intervals were prescribed, with the majority of coaches prescribing 30-60 sec (40%) or 1-2 min (46%) rest periods. To monitor warm-up intensity, the coaches reported using split times (13%),
heart rate (9%), stroke rate (13%), stroke count (9%), as well as swimmer’s own perceived maximal exertion (9%), or a combination of these measures (48%).

The majority (78%) of coaches prescribed a dryland-based warm-up lasting ~15-20 min on the pool deck in addition to the pool-based warm-up. Regarding the exercises prescribed, responses were content analysed, which resulted in the creation of nine higher-order themes. Table 11 lists these higher-order themes, the total number of coach responses to each theme and select representative raw data within each higher-order theme. The coaches requested that this dryland-based warm-up be completed either prior to the pool warm-up (86%) or during the transition phase (14%). These dryland warm-ups were reported to be completed in a small space, typically on pool deck.

**Table 11.** Dryland-based warm-up exercises prescribed by the swimming coaches.

<table>
<thead>
<tr>
<th>Higher order themes</th>
<th>Number of responses</th>
<th>Select raw data representing responses to the question</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arm/leg swings</td>
<td>34</td>
<td>3 sets of 3 reps arm/legs per limb</td>
</tr>
<tr>
<td>Core activation exercises</td>
<td>12</td>
<td>2 sets of 8-10 reps with 30 sec rest between sets of sit-ups followed by 2 x 1 min prone holds</td>
</tr>
<tr>
<td>Foam roller exercises</td>
<td>7</td>
<td>5-10 min focusing on shoulders and lower-back</td>
</tr>
<tr>
<td>Jumps</td>
<td>17</td>
<td>1 set of 12-15 reps with 10 sec rest between reps, trying to jump as high as possible</td>
</tr>
<tr>
<td>Lunges</td>
<td>3</td>
<td>1-2 sets of 4-6 reps on both sides with 45 sec between sets, making sure back knee gets low to the ground</td>
</tr>
<tr>
<td>Push-ups</td>
<td>3</td>
<td>4 sets of 10 reps, stretching shoulders out between sets</td>
</tr>
<tr>
<td>Static stretching</td>
<td>16</td>
<td>Stretching out muscles in the upper and lower body, focusing on shoulders in particular for backstroke, butterfly and freestyle and legs for breaststroke swimmers</td>
</tr>
<tr>
<td>Skipping</td>
<td>8</td>
<td>4 sets of 45 sec or 5 min continuous, focusing on fast feet off the ground</td>
</tr>
<tr>
<td>Stretch cord exercises</td>
<td>18</td>
<td>2 sets of 12 reps of multi-directional shoulder rotations, single-arm rows</td>
</tr>
</tbody>
</table>

During the transition phase, coaches reported that their swimmers typically changed into their race swimsuit and a tracksuit and relaxed while sitting down and listening to music. Swimmers spend 18 ± 8 min undertaking these activities and following this, the coaches
reported that swimmers enter a marshalling period which lasts ~15-20 min. The majority of coaches believe the optimal transition duration is $\geq 30$ min (46%), with others stating that 20 min (13%) or 25 min (11%) was optimal.

Several issues which limited the effectiveness of the pre-competition warm-up were identified by the coaches. Responses were content analysed which resulted in the creation of four higher-order themes, including (a) delayed event schedules due to technical or equipment issues, overly long marshalling periods ($> 15$ min), the lengthy time required for their swimmers to don race swimsuits ($> 10$ min), and lack of lane space to effectively complete the pool warm-up. Table 12 lists these higher-order themes, the total number of coach responses to each theme and select representative raw data described within each higher-order theme.

**Table 12.** Issues faced by the coaches during the final competition preparation phase.

<table>
<thead>
<tr>
<th>Higher order themes</th>
<th>Number of responses</th>
<th>Select raw data representing responses to the question</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delays in the competition schedule</td>
<td>21</td>
<td>Program runs behind schedule</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Program timeline changes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Timing system fails, so schedule is delayed</td>
</tr>
<tr>
<td>Lack of pool lane space</td>
<td>5</td>
<td>Crowded warm-up pool</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Poor pool warm-up facility access</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Too many other swimmers in the warm-up pool</td>
</tr>
<tr>
<td>Lengthy time required to don a race swimsuit</td>
<td>20</td>
<td>Swimsuit malfunctions</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Race swimsuit takes too long to put on and swimmer gets stressed, particularly girls</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Swimsuit rips and have to find a replacement</td>
</tr>
<tr>
<td>Overly long marshalling periods</td>
<td>18</td>
<td>Marshalling period is too long</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Swimmers spend too much time in marshalling, 15 min plus, and they start to get cold</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Marshalling takes longer than 20 min</td>
</tr>
</tbody>
</table>

Finally, the coaches were asked if they requested their swimmers to practice their competition warm-ups in general training sessions. Responses were content analysed, which resulted in the creation of four higher-order themes. The majority of coaches reported that their swimmers utilise their pre-competition warm-up prior to specific race-distance time-trials conducted within training (54%), prior to benchmark or test sets (20%) or just in general training sessions prior to the main set (13%). Some coaches (13%) also reported that their swimmers practice using their race warm-up in each training session in the three weeks prior
to competition, during the taper phase for example. The Table 13 lists these higher-order themes, the total number of coach responses to each theme and select representative raw data described within each higher-order theme.

<table>
<thead>
<tr>
<th>Higher order themes</th>
<th>Number of responses</th>
<th>Select raw data representing responses to the question</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prior to race-distance time-trials in training</td>
<td>36</td>
<td>We always do a race warm-up before time-trials</td>
</tr>
<tr>
<td></td>
<td></td>
<td>We get swimmers to do a full race warm-up and suit up before time-trials</td>
</tr>
<tr>
<td>Prior to benchmark or test sets</td>
<td>16</td>
<td>I like swimmers to use their race warm-up before test sets</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Swimmers use their race warm-up before quality test sets</td>
</tr>
<tr>
<td>Prior to the main set in daily training sessions</td>
<td>11</td>
<td>I get swimmers to practice their race warm-up throughout the season</td>
</tr>
<tr>
<td></td>
<td></td>
<td>I get swimmers to practice their race warm-up regularly so we can tweak it if necessary</td>
</tr>
<tr>
<td>In each training session within 1-3 weeks before</td>
<td>8</td>
<td>Swimmers use their race warm-up in the last 3 weeks prior to racing (taper)</td>
</tr>
<tr>
<td>competition (taper phase)</td>
<td></td>
<td>Swimmers practice their race warm-up during taper to simulate competition conditions</td>
</tr>
</tbody>
</table>

4.2.5 DISCUSSION

To our knowledge this is the first comprehensive survey of pre-competition warm-up practices in swimming. The information presented here provides useful insights into the contemporary practices and opinions of high-level swimming coaches. Swimming coaches can utilise these insights to review their personal warm-up practices and as a possible source for new components and designs.

In terms of warm-up design, initially coaches prescribed a dryland-based warm-up consisting of exercises involving stretch cords, skipping and jumps to be completed on pool deck. Following this swimmers complete a pool-based warm-up totaling ~1400 m (100 m), ~1650
m (200 m) and ~1870 m (400 m), which follows a similar structure, regardless of the race distance to be swum. Swimmers begin the pool warm-up with ~400 m (up to 1000 m for the 200 and 400 m events) of continuous, low-intensity (~50-70% of perceived maximal exertion) swimming. Following this a set (200-600 m) of specific stroke drills is completed including kick and pull drills. The intensity of the efforts then increases (~60-90%) with 1-2 sets of 100-400 m in distance completed, involving efforts of 25-100 m in length including dive start or turn drills. Towards the end of the pool warm-up, coaches prescribe 3-4 race or near-race pace (~90-100%) efforts of 25-100 m in length, with the warm-up typically concluding with a 100-400 m of continuous, low-intensity (~40-60%) swimming.

In order to increase the effectiveness of a warm-up, coaches must first have a clear idea of what they want their swimmers to gain from completing a warm-up. Elite swimming coaches identified four key objectives of the pre-competition warm-up: (a) To increase body temperature and muscle activation (physiological preparation); (b) To increase swimmers “feel’ of the water, familiarization with start blocks and walls (kinesthetic/tactile preparation); (c) To practice race-pace (tactical preparation); (d) To improve focus and reduce excessive anxiety (mental preparation), with the first two deemed the most important. Elevating body temperature by either passively or actively warming-up elicits improvements in subsequent exercise performance,\(^3\)\(^3\)\(^3\)\(^2\)\(^2\)\(^3\) with sprint and short (< 2 min) sustained high-intensity events shown to be the greatest beneficiaries from elevated body temperature pre-event.\(^3\)\(^2\)\(^2\) Thus, swimmers competing in the 50, 100 and 200 m events in swimming are most likely to obtain an advantage from completing a warm-up which increases body temperature.

The tactile preparation afforded to swimmers completing a pool-based warm-up is likely useful for swimmers competing over all distances. This is probably why the surveyed swimming coaches stated they preferred to prescribe pool-based warm-ups over dryland exercises to provide swimmers with an opportunity to gain a “feel” for the water and to familiarise themselves with the start blocks and walls. The coaches also identified that the pool warm-up permitted swimmers to get a feel for the pacing used in the subsequent race, hence the inclusion of a set of race or near race-pace efforts towards the end of the pool warm-up. At least one set of race-pace efforts can enhance subsequent exercise performance more so than when such efforts are not completed.\(^5\)\(^1\)\(^6\)
The total pool warm-up volume prescribed by the coaches was ~1400 m (100 m events), ~1650 m (200 m events) and ~1900 m (400 m events). These distances are substantially greater than previous recommendations ~1000-1500 m. Sprint performance (for example the 100 m freestyle) in particular, can be adversely affected by large volumes of exercise completed in a warm-up. However, in the present study, coaches prescribed significantly less total swimming volume prior to competition in shorter (100 and 200 m) than longer events (400 m). In addition, for the sprint race distance (100 m) coaches requested the set of race or near race pace efforts completed towards the end of the pool warm-up be shorter in length (25-50 m efforts) than those completed prior to the longer (200-400 m) race distances (50-100 m efforts).

One explanation for the large variation in the distances prescribed for each stage of the pool warm-up is a possible carry-over from coach’s general training prescription practices. For example it is conceivable that coaches who typically prescribe high swimming volumes in their daily training do the same in the competition warm-up, possibly with the belief that their swimmers are "more conditioned" to high volumes and perform better following a longer pool warm-up. Studies are equivocal regarding the influence of pool warm-up volume on subsequent performance, with low volume (91.4 m or ~450 m) or high volume (1000 – 1200 m) pool warm-ups resulting in similar or faster (short volume) sprint (45.7 m) performance. Further investigation is required across a wider range of competition distances and strokes to fully ascertain the influence of pool warm-up volume on subsequent swimming performance.

The coaches used split times, heart rate, stroke rate and stroke count alone, or in combination, to monitor swimmer’s intensity throughout the pool warm-up. These are simple and practical methods for monitoring swimmers intensity within the pool environment and provide valid and meaningful information. However, it remains difficult for coaches to obtain real-time swimming (via telemetry for example) heart rate data from their swimmers. Although this is perhaps more of an issue within the training environment, information of this type could be valuable to coaches immediately before competition for controlling warm-up intensity and monitoring fatigue.

To complement rather than replace the pool warm-up, an additional dryland-based warm-up was prescribed by the majority of coaches. Commonly prescribed exercises included leg and arm swings, single-arm rows using stretch cords, skipping, core activation exercises and
jumps. As these dryland warm-ups were reported to typically be completed on pool deck, swimming coaches require the design of exercises that satisfy the aims of the pre-competition warm-up, require minimal equipment, and can easily be completed within a small area. These situational factors are important considerations for strength and conditioning coaches consulting with high-level swimming squads to take into account. Interestingly, the majority of coaches requested the dryland-based warm-up be completed prior to the pool warm-up, though several coaches opted for the dryland warm-up to be completed during the transition phase. One possible reason to explain the popularity of the first approach is that coaches may be using the dryland warm-up to evaluate if a swimmer has any physical or mobility issues that may require last minute attention.

Although both dryland and pool-based warm-ups were thoroughly prescribed and warm-up intensity constantly monitored via heart rate, stroke rate and split time feedback, several external factors were identified by the coaches that could potentially mitigate the benefits of these warm-ups. The first of these was the lengthy time required to don a race swimsuit (> 10 min). Loose fitting swimsuits can increase drag in comparison to tight fitting suits and racing swimsuits have become increasingly form fitting. As a result, these suits are difficult to put on. However, given the different swimsuits worn by male (shorts only) and female (combination of traditional swimsuit design and shorts) swimmers, males may spend less time than females putting their race swimsuits on. The second issue identified by the elite coaches was delays in the competition schedule. Though frustrating, it is difficult to predict when these delays will occur and how long they will last, thus coaches must rely on their previous experience in an attempt to work around these delays.

The final issue identified was the duration of the marshalling period. The length of the marshalling period in national and international swimming competitions has previously been reported to last 20 min, which is similar to the time-frame indicated by the surveyed coaches (~15-20 min). This “recovery” period is substantially longer than what is needed to produce optimal 200 m freestyle performance (10 or 20 min). In addition, the swimming coaches indicated that the optimal transition phase duration was ~30 min. However, the time to don a race swimsuit (> 10 min), delays in the competition schedule, and the length of the marshalling period (~15–20 min) contribute to the extension of the transition phase beyond 10-20 min.
The length of the transition phase was a source of much concern for the coaches, with many expressing the belief of a negative impact on swimming performance with swimmers “cooling” down or beginning to feel “flat, or both, during this period. Indeed muscle temperature begins to decline immediately following the cessation of exercise, with a significant reduction occurring ~15-20 min after exercise termination. While reducing the duration of the transition phase can enhance swimming performance, this option is likely not feasible within swimming competitions. Subsequently, strength and conditioning coaches and sport scientists are seeking to develop new methods for maintaining elevated body temperature and muscle activation throughout lengthy transition phases. The combination of an active warm-up (through a cycle ergometer) and passive heating (through heated tracksuit pants), during transition improved muscle temperature maintenance and power output within a subsequent sprint cycling task. A similar effect was also recently demonstrated in swimming, with a brief (5 min) dryland-based exercise circuit completed alone, or in combination with heated tracksuit jackets during the transition phase, shown to enhance sprint swimming performance. Attenuation in the decline of core temperature and a reduction in start time appeared as likely mechanisms.

A limitation of this study was that the majority of surveyed coaches were Australian-based with only a small number of respondents from Great Britain and Canada. It is possible that the practices of the Australian coaches might differ to those of their international counterparts, so replication of a similar study may be warranted to encapsulate different countries practices. However, the present findings regarding the situational factors and challenges faced by elite coaches and athletes during the final preparation phase should be useful for all practicing swimming coaches, sport scientists, and strength and conditioning coaches.

A second limitation was that the swimming coaches were not requested to provide separate information or comments on how they prepare their age-group or open level swimmers. As it is possible that there indeed could be a difference in the preparation strategies of these two competitive groups’ future studies should take this into account. Finally, although the coaches were requested to provide answers which directly pertained to their current pre-competition warm-up practices, it is possible that their responses may differ somewhat from actual their coaching practices.
4.2.6 CONCLUSIONS

According to our knowledge, this is the first study of its kind to be completed with elite swimming coaches. One of the primary outcomes of this study is that swimming coaches now have a source of collective ideas with which they can compare with and potentially incorporate into their own pre-competition warm-up practices. The combination of dryland-based activation exercises followed by pool-based warm-up routines appears to be the preferred approach taken by elite swimming coaches preparing their athletes for competition.

4.2.7 PRACTICAL APPLICATIONS

A dryland-based warm-up consisting of exercises involving stretch cords, skipping, core activation and jumps is commonly prescribed. Given these dryland warm-ups are typically completed on pool deck, strength and conditioning coaches should prescribe specific exercises which satisfy the aims of the pre-competition warm-up, require minimal equipment, and can easily be completed within a confined area during competitions. Furthermore, as swimmers are currently completing pool warm-ups prior to time-trials and/or benchmark sets within training sessions throughout the season (as reported by the surveyed coaches), a similar set of dryland-based exercises could also be employed on a routine basis. Using a dryland warm-up in training and time trials should promote faster swimming performance in those activities, permit rehearsal of these strategies prior to minor and major competitions, and further refine protocols prior to competitive races.

In comparison with middle-distance swimmers (200–400 m), sprinters (100 m) complete less swimming volume (~1400 vs. 1650–1900 m) in the pool warm-up and undertake fewer (3–4 efforts vs. 3–8 efforts) and shorter (25–50 vs. 50–100 m) efforts towards the end of the warm-up. Regardless of competition race distance, coaches prescribe 3–4 race or near race pace (~90–100% of perceived maximal exertion) efforts to be completed towards the end of the pool warm-up to assist swimmers in gaining a feel for the pace required in their upcoming race. Several factors such as the lengthy time required to don a race swimsuit, delays in the competition schedule and lengthy marshalling periods cause delays in the transition from warm-up to racing which may mitigate the benefits of the dryland and pool warm-ups. The
information provided in this study is useful for coach education purposes by informing trainee swimming coaches about the practices of their elite counterparts and strength and conditioning coaches and sport scientists about the situational factors coaches and swimmers face within the competition environment.
DECLARATION OF CO-AUTHORED PUBLICATION

CHAPTER 5

Declaration by candidate

In the case of Chapter 5, the nature and extent of my contribution to the work was the following:

<table>
<thead>
<tr>
<th>Nature of contribution</th>
<th>Extent of contribution (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Developing the research question and research design, data collection and analysis, write-up and editing the manuscript</td>
<td>75%</td>
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The following co-authors contributed to the work.

<table>
<thead>
<tr>
<th>Name</th>
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<th>Contributor is also a student at UC Y/N</th>
</tr>
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<tbody>
<tr>
<td>Dr Ben Rattray</td>
<td>Research design, analysis, editing the manuscript</td>
<td>9%</td>
<td>N</td>
</tr>
<tr>
<td>Prof David Pyne</td>
<td>Research design, analysis, editing the manuscript</td>
<td>8%</td>
<td>N</td>
</tr>
<tr>
<td>Prof Kevin Thompson</td>
<td>Research design, editing the manuscript</td>
<td>5%</td>
<td>N</td>
</tr>
<tr>
<td>Prof John Raglin</td>
<td>Research design, editing the manuscript</td>
<td>3%</td>
<td>N</td>
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</tbody>
</table>

Candidate’s Signature: [Signature]

11/02/2016

Declaration by co-authors

The undersigned hereby certify that:

(13) the above declaration correctly reflects the nature and extent of the candidate’s contribution to this work, and the nature of the contribution of each of the co-authors.
(14) they meet the criteria for authorship in that they have participated in the conception, execution, or interpretation, of at least that part of the publication in their field of expertise;
(15) they take public responsibility for their part of the publication, except for the 
responsible author who accepts overall responsibility for the publication;
(16) there are no other authors of the publication according to these criteria;
(17) potential conflicts of interest have been disclosed to (a) granting bodies, (b) the editor 
or publisher of journals or other publications, and (c) the head of the responsible 
academic unit; and 
(18) the original data are stored at the following location(s) and will be held for at least 
five years from the date indicated below:

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<th>Location(s)</th>
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[Please note that the location(s) must be institutional in nature, and should be indicated here 
as a department, centre or institute, with specific campus identification where relevant.]

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CHAPTER 5: Heated jackets and dryland-based activation exercises used as additional warm-ups during transition enhance sprint swimming performance

The manuscript contained within this chapter has been accepted for publication and has been formatted to comply with the publishing journal’s guidelines: McGowan CJ, Thompson KG, Pyne DB, Raglin JS & Rattray B. Heated jackets and dryland-based activation exercises used as additional warm-ups during transition enhance sprint swimming performance. Journal of Science and Medicine in Sport, April 30th 2015. [Epub ahead of print]

5.1 Manuscript Information

Information presented in the previous chapter revealed that during the final preparation phase, elite swimming coaches face a number of challenges which may negatively influence their swimmers race preparation, with the duration of the transition phase highlighted as a major issue. Transition durations of 20-40 min were regarded as typical, with the time to don a race swimsuit (> 10 min), delays in the competition schedule, and the length of the marshalling period (> 15 min) all identified as factors contributing to the extension of the transition phase. Coaches are concerned that their swimmer’s subsequent race performance may be negatively impacted, with suggestions that swimmers may “cool” down and/or begin to feel “flat”, as a result of these lengthy transition phases. Indeed previous evidence has demonstrated that following the cessation of exercise, $T_{\text{muscle}}$ begins to decline, with appreciable reductions evident after ~15-20 min.$^{16}$

Reducing the duration transition phase can produce faster subsequent swimming performances,$^{15,34}$ though the feasibility of altering swimming competition schedules is debatable. Therefore, new methods require development to assist swimmers in maintaining elevated body temperature and muscle activation throughout lengthy transition phases. Heated athletic garments$^{35,36}$ and blizzard survival jackets$^{37-39}$ worn during lengthy transitions have previously been demonstrated to limit the decline in $T_{\text{muscle}}$$^{34,35}$ and $T_{\text{core}}$$^{37,38}$ during transition and subsequently improve cycling,$^{34,35}$ and repeat-sprint performance in rugby players.$^{37-39}$ In addition, dryland-based exercise routines consisting of ballistic exercises such
as jumps can also improve performance in short-duration tasks.\textsuperscript{142} As yet, neither of these methods has been explored in swimming. Therefore, the aim of the study discussed in the following chapter was to determine whether combining swimmers’ active pool warm-up with the application of additional passive heat (via heated tracksuit jackets) alone or together with the completion of dryland-based activation exercises during the transition phase would elicit improvements in subsequent sprint freestyle performance in junior swimmers.

5.1.1 Research Objectives

1. Determine whether the application of additional passive heat and/or the completion of dryland-based activation exercises within the transition phase can enhance sprint freestyle swimming performance in junior athletes.

2. Examine if any observed differences in the maintenance of $T_{\text{core}}$ during the transition phase are associated with improvements in overall swimming time-trial performance.
5.2 Accepted Manuscript

5.2.1 ABSTRACT

Objectives: The lengthy competition transition phases commonly experienced by competitive swimmers may mitigate the benefits of the pool warm-up. To combat this, we examined the impact of additional passive and active warm-up strategies on sprint swimming performance. Design: Counterbalanced, repeated-measures cross-over study. Methods: Sixteen junior competitive swimmers completed a standardised pool warm-up followed by a 30 min transition and 100 m freestyle time-trial. Swimmers completed four different warm-up strategies during transition: remained seated wearing a conventional tracksuit top and pants (Control), wore an insulated top with integrated heating elements (Passive), performed a 5 min dryland-based exercise circuit (Dryland), or a combination of Passive and Dryland (Combo). Swimming time-trial performance, core and skin temperature and perceptual variables were monitored. Time variables were normalised relative to Control. Results: Both Combo (-1.05 ± 0.26%; mean ± 90% confidence limits, \( p < 0.01 \)) and Dryland (-0.68 ± 0.34%; \( p = 0.02 \)) yielded faster overall time-trial performances, with start times also faster for Combo (-0.37 ± 0.07%; \( p < 0.01 \)) compared to Control. Core temperature declined less during transition with Combo (-0.13 ± 0.25°C; \( p = 0.01 \)) and possibly with Dryland (-0.24 ± 0.13°C; \( p = 0.09 \)) compared to Control (-0.64 ± 0.16°C), with a smaller reduction in core temperature related to better time-trial performance (\( R^2 = 0.91; p = 0.04 \)). Conclusions: Dryland-based exercise circuits completed alone and in combination with the application of heated tracksuit jackets during transition can significantly improve sprint swimming performance. Attenuation in the decline of core temperature and a reduction in start time appear as likely mechanisms.

5.2.2 INTRODUCTION

In swimming, the effectiveness of a warm-up strategy is determined by the intensity and duration of the swimming and dryland elements, and the time between warm-up end and competitive event start, here termed the transition phase.\(^{12,13,34}\) After the pool warm-up,
swimmers must change into their racing swimsuit, confer with their coach and report to marshalling ~15-20 min prior to race start,\textsuperscript{34} thus transition phases of 30-45 min are not uncommon.\textsuperscript{34}

Several studies have demonstrated that reducing the transition from 45 to 20 min,\textsuperscript{34} or to 10 min,\textsuperscript{15} yields faster 200 m swimming performance (~1.5\% and ~1.4\%, respectively). Importantly, core temperature ($T_{\text{core}}$) remained elevated during the shorter transition.\textsuperscript{34} It seems there is a greater risk of a significant decline in $T_{\text{core}}$ with longer transitions. Indeed muscle temperature ($T_{\text{muscle}}$) declines immediately following exercise, with a significant reduction evident after ~15-20 min of recovery.\textsuperscript{16}

However, it is difficult to alter swimming competition schedules by such large (> 25 min) margins. New methods need developing to assist swimmers in maintaining elevated body temperature and muscle activation throughout lengthy transition phases. We postulate that the decline in body temperature, in particular $T_{\text{core}}$, during transition could be offset by combining a sport-specific active warm-up (i.e. pool warm-up) with passive heating and/or additional active warm-up strategies. Recently the combination of active warm-up and passive heating (via heated tracksuit pants), during transition improved $T_{\text{muscle}}$ maintenance and power output during a sprint cycling task.\textsuperscript{35,36} There appears to be a sound basis for additional passive heating to enhance body temperature maintenance during lengthy transitions in competitive swimming. The combination of passive heating and activities such as box jumps, known to induce postactivation-potentiation (PAP) related changes,\textsuperscript{142} during transition may yield additional performance benefits.

The objective of this study was to determine whether the application of additional passive heat and/or the completion of dryland-based activation exercises within the transition phase could improve sprint swimming performance. Specifically, we investigated if any observed differences in the maintenance of $T_{\text{core}}$ during transition were related to overall swimming time-trial performance.
5.2.3 METHODS

Sixteen national junior swimmers (age 16 ± 1 yr; n=11 males, stature 1.79 ± 0.08 m, 72.2 ± 9.8 kg; n=5 females, 1.67 ± 0.06 m, 61.6 ± 1.5 kg; mean ± standard deviation) provided written informed consent to participate in the study. The swimmers had a personal best 100 m freestyle time of 59.41 ± 3.48 s; 548.60 ± 30.10 Fédération internationale de natation, FINA2013 scoring points (mean ± 90% confidence limits). This study was approved by the University of Canberra’s Human Research Ethics Committee.

Using a randomised cross-over design, each swimmer completed four testing sessions within a fortnight (two sessions per week) during an aerobic training phase, separated by 48 h. Swimmers completed all testing in either a morning (06:00-08:00 am) or afternoon (17:00-19:00 pm) timeslot as per their normal training routine, with each swimmer acting as their own control and tested within the same time slot for all their sessions. Familiarisation with the experimental protocols and equipment was completed a week prior to testing commencement.

In each session, swimmers completed a 25 min standardised pool warm-up followed by a 30 min transition phase and 100 m freestyle time-trial. The standardised pool warm-up entailed: 400 m freestyle (easy pace); 3 x 100 m individual medley (100 m: kick, drill, swim); 3 x 100 m freestyle (80, 90, 95% race pace); 4 x 50 m (15 m race pace, 35 m easy); 4 x 25 m freestyle (dive start, race pace). The 30 min transition consisted of three segments: 1) post-pool warm-up (30-21 min pre-time-trial) swimmers changed into their race swimsuit and tracksuit; 2) swimmers remained seated (21-16 min pre-time-trial) with minimal activity unless required to perform the dryland-based exercise circuit; 3) swimmers entered a simulated marshalling area for the final 15 min prior to the time-trial.

In all conditions, swimmers wore a t-shirt and tracksuit (top and pants) and remained seated throughout the transition phase (Control condition) unless otherwise stated. The Control condition was designed to mimic the contemporary race preparations undertaken by competitive swimmers. During transition, three additional warm-up strategies were investigated: Passive, swimmers wore a tracksuit jacket with additional heating elements sewn into the garment over the chest (pectoralis major) and lower back (latissimus dorsi
and quadratus lumborum) regions (City heated jacket, Venture Heated Clothing, Melbourne, Australia), along with a t-shirt and standard tracksuit pants. The heating elements were powered by a 7.4 V lithium ion battery and set to 51°C. The swimmers wore the heated jacket throughout transition until immediately prior to the time-trial. In Dryland, swimmers wore the same apparel as during Control and completed a 5 min dryland-based exercise circuit between 21-16 min prior to time-trial start. The circuit was designed to simulate common swimming movements in a sequence replicating the kinetic chain of a swim start: 3 x medicine ball (2 kg) throw downs (underwater arm pull through), 3 x 10 s simulated underwater butterfly kick whilst in a streamline position holding a BodyBlade® (Mad Dogg Athletics Inc., California, USA) oscillation device above the head, and 3 x 0.4 m box jumps (jumping off the start blocks). All exercises were completed at maximum effort, with the circuit completed twice and 10 s rest taken between each exercise. The Combo strategy involved a combination of the Passive and Dryland warm-up strategies. Swimmers wore a heated jacket throughout transition, including during the dryland circuit, and until immediately prior to time-trial start.

Swimmers were requested to maintain the same nutrition (no caffeine in the 12 h prior) and sleep routine prior to each testing session and refrain from completing heavy exercise (in the pool or gym) within two days prior and on the day of testing. With the cooperation of the coaches, training volume and intensity were also kept consistent (on a weekly basis) throughout the study duration. Quantitative feedback on swimming performance (e.g. times and stroke characteristics) was delayed until study completion.

Pool warm-ups and time-trial swims were performed in a 50 m indoor pool (pool temperature 27.2 ± 0.4°C, air temperature 25.8 ± 0.4°C, relative humidity 52.4 ± 1.3%). Swimmers began the time-trials from a dive start, utilising starting blocks. Overall and 25 m split-times were recorded by an elite coach (holding an Australian State-National level licence) using a manual stopwatch (SVAS003 Seiko, Tokyo, Japan). Footage from digital video cameras (Canon Legria FS21, Tokyo, Japan) positioned at the 5, 15, 25 and 45 m marks was used to determine start and turn times as well as mid-pool velocity (m.s⁻¹), stroke rate (Hz), stroke length (m) and stroke efficiency index (m².stroke⁻¹.s⁻¹) for both time-trial laps through established methods.233-235
Ingestion of a temperature sensor (CorTemp™ Ingestible Core Body Temperature Sensor, HQ Inc., Palmetto, USA) 6 h prior to each testing session permitted measurement of \( T_{core} \). The CorTemp pills were administered and calibrated in accordance with the manufacturer’s instructions. This ingestible \( T_{core} \) device has previously been shown to be a reliable and valid method for monitoring \( T_{core} \).\(^{236}\) Skin temperature (\( T_{skin} \)) sensors (DS1922L Thermochron iButton®, Maxim Integrated Products, Inc., Sunnyvale, USA) were fitted to swimmers at four sites: chest, forearm, mid-thigh, and mid-calf to estimate mean \( T_{skin} \).\(^{237}\) Capillary blood lactate concentration (La\(^{-} \); Lactate Pro, Arkray, Shiga, Japan) and heart rate (Polar RS400, Polar Electro Oy Kempele, Finland) were monitored using previously described methods.\(^{238,239}\) Sample points for \( T_{core} \), \( T_{skin} \) and HR were: pre-pool warm-up, immediately post pool warm up, pre- dryland circuit, post-dryland circuit, pre-time-trial, one and four min post-time-trial. La\(^{-} \) was sampled post-pool warm up, pre-time-trial, one and four min post-time-trial with peak post-time-trial La\(^{-} \) concentration determined from the higher of the post-time-trial sample points. Ratings of perceived exertion (RPE) were determined using the 10-point Borg scale\(^{240}\) following the pool warm-up, dryland circuit and time-trial. Swimmers views regarding competition warm-up strategies, and their opinions relating to the additional warm-up strategies were assessed via questionnaires (multiple choice and Likert format) created for this study. The questionnaires were completed 1) prior to study commencement; 2) prior to each testing session; 3) after each testing session, and 4) at study conclusion.

Statistical analysis was performed using SPSS software (version 21; SPSS Inc., Chicago, USA) with significance set at \( p \leq 0.05 \) and \( p \geq 0.05 – p \leq 0.10 \) determined as possibly different.\(^{241}\) Effect size (ES) was calculated using Cohen’s \( d \) with the ranges of 0.2-0.6, 0.61-1.19 and \( > 1.20 \) considered small, medium and large effects respectively.\(^{242}\) Precision of estimation was indicated with 90% confidence limits. All raw time-based data was analysed using a one-way within-participant analysis of variance (ANOVA) comparing all conditions. To estimate differences in performance time, all raw time-based data was normalised against Control and analysed using a one-way within-participant ANOVA comparing the three intervention conditions (Passive, Dryland, Combo) relative to Control. Relationships between 100 m time-trial performance and change in \( T_{core} \) during transition (calculated from group mean \( T_{core} \) values recorded at 1) post-pool warm-up and 2) pre-time-trial) for each warm-up condition were evaluated with a Pearson’s product-moment correlation (GraphPad Software Inc., V6, La Jolla, USA). Mean stroke characteristics were analysed using a one-way within-participant ANOVA.
Change scores were calculated for $T_{core}$, $T_{skin}$ and HR between the time points of 1) post-pool warm-up and pre-time-trial, and 2) pre-dryland and post-dryland exercise circuit (when performed). Where appropriate, differences in change score data were analysed using a two-way repeated-measures ANOVA accounting for timing and condition. $T_{core}$, $T_{skin}$ and HR values recorded at the individual sample points were also analysed using a two-way repeated-measures ANOVA. Analysis of La$^-$ data was completed in a similar fashion. Bonferroni adjustment was conducted where relevant on ANOVA results. RPE data was analysed using the Wilcoxon signed rank test. All questionnaire data was analysed using frequencies to determine the percentage response swimmers provided for the various questions.

5.2.4 RESULTS

Compared to Control (60.70 ± 3.36 s; mean ± 90% confidence limits) 100-m swim time-trials were significantly faster for Combo (59.90 ± 3.70 s; −1.05 ± 0.26%; $p < 0.01$; ES, 0.27) and Dryland (60.26 ± 3.50 s; −0.68 ± 0.34%; $p = 0.02$; ES, 0.18), and marginally faster for Passive (60.37 ± 3.15; −0.43 ± 0.36%; $p = 0.49$; ES, 0.12), (Fig. 1A). Start times were faster in Combo (6.86 ± 0.19 s; −0.37 ± 0.08%; $p < 0.01$; ES, 0.92) and possibly faster in Passive (7.03 ± 0.24 s; −0.20 ± 0.11%; $p = 0.08$; ES, 0.45) compared to Control (7.23 ± 0.17 s), (Fig. 1B).

![Fig. 1 One hundred meter freestyle time-trial times for the three additional warm-up intervention conditions (Passive, Dryland, Combo). Times were normalised against the Control condition (no additional warm-up). A) Overall 100 m freestyle time-trial times. B) Time to 15 m (start time). Data are presented as mean ± 90% confidence limits. Significantly different to Control * $p < 0.01$, # $p < 0.05$.](image-url)
Turn times were possibly faster for Passive (9.14 ± 0.43 s; −1.23 ± 0.65%; \(p = 0.05\); ES, 0.89) and Dryland (9.12 ± 0.52 s; −1.25 ± 0.70%; \(p = 0.09\); ES, 0.86) compared to Control (10.37 ± 0.82 s). Split times for the 25–50 m section were faster for Passive (16.04 ± 0.32 s; −0.50 ± 0.18%; \(p < 0.01\); ES, 0.73) and possibly faster for Combo (16.12 ± 0.30 s; −0.42 ± 0.24%; \(p = 0.08\); ES, 0.64) compared to Control (16.54 ± 0.30 s). Mean stroke efficiency index was higher (3.5 ± 0.3 m².stroke⁻¹.s⁻¹; \(p = 0.03\); ES, -0.35) in Passive compared to Control (3.3 ± 0.2 m².stroke⁻¹.s⁻¹), with no other significant differences in stroke characteristics recorded.

\(T_{core}\), \(T_{skin}\), HR and \(Lactate^-\) readings were not significantly different between conditions at baseline or following pool warm-up. \(T_{core}\) increased by ∼0.7 ± 0.1°C during pool warm-up in all conditions. During transition, \(T_{core}\) decreased under all conditions, though the decline was less in Combo (−0.13 ± 0.25°C; \(p = 0.01\); ES, −1.18; from 37.86 ± 0.33°C to 37.73 ± 0.29°C) and possibly less in Dryland (−0.24 ± 0.13°C; \(p = 0.09\); ES, −1.36; from 37.76 ± 0.44°C to 37.53 ± 0.48°C) compared with Control (−0.64 ± 0.16°C; from 37.88 ± 0.37°C to 37.25 ± 0.36°C), (Fig. 2). A smaller reduction in \(T_{core}\) during transition was also highly correlated with faster over-all time-trial performance (\(R^2 = 0.91\); \(p = 0.04\)). \(T_{skin}\) was higher immediately pre-time-trial in Passive (0.87°C; \(p = 0.04\); ES, −1.35) and Combo (1.18°C; \(p = 0.03\); ES, −2.35) compared with Control (Table 14). \(Lactate^-\) concentrations only differed once between conditions with peak post-time-trial \(Lactate^-\) higher in Passive (\(p = 0.03\); ES, −0.60) versus Control (Table 14). Completion of the dryland circuit (Dryland and Combo) elicited a ∼22–29 beats per min rise in HR (\(p < 0.01\); ES, −2.48) compared to when the circuit was not completed. HR was not different between conditions immediately pre-time-trial (Table 14).

RPE was not different between conditions following the pool warm-up or post-time-trial. Completion of the dryland circuit yielded a median 1.5 point rise in Dryland (\(p = 0.03\)) and a 2 point rise in Combo (\(p = 0.02\)) with a 3.3 point (range 0-4 points) rise in the interquartile range reported for both conditions. There were no differences between conditions regarding pre-time-trial motivation levels with all swimmers confirming they employed similar intensities of effort across all conditions for the time-trials. Prior to study commencement, swimmers ranked the four conditions in order of preference for competition use: Combo (69%), Control (25%), Passive (6%) and Dryland (0%). Following study completion, swimmers re-ranked the conditions: Combo (50%), Dryland (38%),
Passive (12%) and Control (0%). All swimmers stated they would choose to utilise the heated jackets and dryland-based exercise circuits in competition if possible.

![Graph showing change in core temperature (°C) for different warm-up interventions.]

**Fig. 2** Change in core temperature ($T_{\text{core}}$) during the 30 min transition phase, from post-pool warm-up to pre 100 m freestyle time-trial, for each additional warm-up intervention (Passive, Dryland, Combo) and for Control (no additional warm-up). Data are presented as mean ± 90% confidence limits. Significantly different to Control $^# p \leq 0.05$.

**Table 14.** Lactate ($La^-$), heart rate (HR) and skin temperature ($T_{\text{skin}}$) values recorded immediately post pool warm-up and pre time-trial with calculated values sampled at 1 and 4 minutes post time-trial (peak post time-trial) presented.

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<td>Warm-Up</td>
<td>$La^-$ (mmol/L)</td>
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<td>$HR$ (bpm)</td>
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<td>$T_{\text{skin}}$ (°C)</td>
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<td>28.9 ± 0.4</td>
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</tr>
<tr>
<td>$La^-$ (mmol/L)</td>
<td>1.1 ± 0.1</td>
<td>1.0 ± 0.1</td>
<td>0.9 ± 0.1</td>
<td>1.0 ± 0.1</td>
</tr>
<tr>
<td>$HR$ (bpm)</td>
<td>95 ± 8</td>
<td>94 ± 6</td>
<td>98 ± 6</td>
<td>99 ± 6</td>
</tr>
<tr>
<td>$T_{\text{skin}}$ (°C)</td>
<td>33.1 ± 0.3</td>
<td>33.9 ± 0.3$^#$</td>
<td>33.3 ± 0.3</td>
<td>34.3 ± 0.1$^#$</td>
</tr>
<tr>
<td>Peak Post</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time-Trial</td>
<td>$La^-$ (mmol/L)</td>
<td>8.6 ± 1.1</td>
<td>10.2 ± 1.2$^#$</td>
<td>9.4 ± 0.8</td>
</tr>
<tr>
<td>$HR$ (bpm)</td>
<td>156 ± 8</td>
<td>152 ± 6</td>
<td>154 ± 4</td>
<td>160 ± 5</td>
</tr>
<tr>
<td>$T_{\text{skin}}$ (°C)</td>
<td>33.1 ± 0.5</td>
<td>33.7 ± 0.4</td>
<td>32.8 ± 0.4</td>
<td>34.1 ± 0.7</td>
</tr>
</tbody>
</table>

All data are mean ± 90% confidence limits. $^#$ Significantly different to control $p < 0.05$. 

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5.2.5 DISCUSSION

An improvement in 100 m freestyle time-trial performance was demonstrated when dryland-based activation exercises were completed alone (~0.7%), and in combination with the wearing of a heated tracksuit jacket (~1.1%), during a 30 min transition phase which followed a contemporary swimming warm-up, compared to when no intervention was utilised during transition. Because enhancements in performance of as little as ~0.4% in swimming can increase the chances of earning a medal at the elite level, these observed improvements are likely to be practically significant. Furthermore, we demonstrated that a smaller decline in $T_{core}$ during transition was strongly associated with faster time-trial performance. Overall, the Combo strategy was considered to be the most effective intervention for eliciting faster time-trial performance.

Elevated $T_{core}$ and/or $T_{muscle}$ prior to competition are recognised as key determinants for sprint- and power-based events by facilitating increases in muscle fibre conduction velocity, muscle metabolism and ATP utilisation rate. In the present study, $T_{core}$ increased during the pool warm-up by a similar magnitude (~0.7 ± 0.1°C) to previous reports. However during transition, $T_{core}$ declined within all conditions, with a significant ~0.6°C reduction recorded under the Control condition. This magnitude of reduction in $T_{core}$ is greater than previously reported, though a longer transition phase (more common in swimming competitions) was investigated in this study (30 versus 10-20 min). Under the three intervention conditions however, the mean decline in $T_{core}$ during transition was reduced, with the Combo and Dryland interventions in particular eliciting substantially smaller reductions in $T_{core}$. In addition, we demonstrated that these smaller reductions in $T_{core}$ during transition, i.e. improved $T_{core}$ maintenance, were strongly associated with enhanced subsequent time-trial performance. These findings are in accordance with previous results demonstrating that better $T_{core}/T_{muscle}$ maintenance within the transition phase is the likely mechanism responsible for improved lower leg power production and power production in sprint cycling.

The application of passive heating alone was not as effective at limiting $T_{core}$ decline during transition as the combination of passive heating and activation exercises. Previous work however has demonstrated that heated tracksuit pants alone were sufficient in maintaining
T\textsubscript{muscle} during a 30 min transition.\textsuperscript{35,36} In the present study T\textsubscript{skin} values immediately pre-time-trial were higher in the two conditions in which the heated jackets were worn. T\textsubscript{skin} is correlated with changes in T\textsubscript{muscle},\textsuperscript{8} suggesting that although passive heating alone did not maintain T\textsubscript{core}, T\textsubscript{muscle} may have been maintained in these conditions. In turn, these greater T\textsubscript{skin} readings coincided with improved start times, with the fastest start times recorded in the Passive and Combo conditions. These outcomes are practically significant as the swim start at the international competitive level contributes up to 30\% of total race performance.\textsuperscript{244} High velocity movements (e.g. the swim start) are also more temperature-dependent\textsuperscript{32} than low velocity movements with the rate of deterioration in muscle performance strongly associated with reductions in T\textsubscript{muscle}.\textsuperscript{33} It is likely that the heated jackets contributed to improved start times through elevated T\textsubscript{muscle} immediately prior to the time-trial.

The dryland-based exercise circuit completed alone, or in combination with the application of passive heat, resulted in a smaller decline in T\textsubscript{core} compared to Control. This observation is consistent with data indicating that dryland-based exercise attenuates the decline in T\textsubscript{core}\textsuperscript{16,191} as well as T\textsubscript{muscle}.\textsuperscript{16} The dryland circuit may also have played a “priming” or “re-activation” role. Although the 15 min marshalling period might have diminished any PAP effect, improvements in power production can occur up to 18.5 min following a PAP stimulus.\textsuperscript{152}

Swimmers were unable to be completely blinded to the interventions so our observations may have been influenced in part by a placebo effect. However swimmers reported being equally motivated, and applied similar levels of effort across the time-trials. We therefore consider it unlikely that an additional benefit was yielded by an improved perception of “readiness”. Our findings are also in line with earlier reports indicating that both passive heat maintenance\textsuperscript{35,36,38} and dryland-based exercise\textsuperscript{29} are effective methods for improving subsequent swimming performance. Finally, due to unavoidable logistical constraints, swimmers were tested in morning and afternoon sessions. To limit the direct influence of diurnal variation on performance and T\textsubscript{core} we ensured each individual swimmer acted their own control, and was tested within the same time slot, for all their testing sessions.
5.2.6 CONCLUSIONS

Time-trial performance (100 m freestyle) was faster when dryland-based activation exercises completed alone, and in combination with the wearing of heated tracksuit jackets, during a 30 min transition phase which followed a contemporary swimming warm-up, compared with a traditional swimming-only warm-up. Although $T_{\text{core}}$ declined during the 30 min transition, completion of dryland-based activation exercises separately, and in combination with the application of passive heating during transition, attenuated the reduction. More effective preservation of $T_{\text{core}}$ and $T_{\text{skin}}$ was deemed the likely primary mechanism for the enhancement of both initial start and overall sprint swimming performance.

5.2.7 PRACTICAL APPLICATIONS

Heated tracksuit jackets and dryland-based exercises are simple interventions that can be implemented in real-world competition settings. The combination of heated tracksuit jackets and dryland-based exercises provided the optimal strategy for maintaining $T_{\text{core}}$ during lengthy transitions. Completion of dryland-based exercises both separately and in combination with the wearing of heated tracksuit jackets are worthwhile strategies for enhancing sprint swimming performance.
CHAPTER 6: Elite competitor sprint swimming performance is enhanced by completion of additional warm-up activities

6.1 Manuscript Information

In the previous chapter, combining an active pool warm-up with the completion of dryland-based exercises both separately and in combination with the wearing of heated tracksuit jackets during a 30 min transition phase was shown to enhance subsequent sprint freestyle performance in junior swimmers. The combination strategy of heated tracksuit jackets and dryland-based exercises was deemed the optimal strategy of those examined for maintaining $T_{core}$ during lengthy transitions and subsequently resulted in the fastest 100 m freestyle time-trial performances. The study discussed in the next chapter seeks to follow up from the previous chapter, investigating if the combination warm-up strategy can enhance sprint freestyle performance, this time in elite swimmers.

Although a particular intervention may elicit performance improvements in junior swimmers, the magnitude of improvement might not be as large in elite swimmers. This is in part due to the performance consistency between competitions being better amongst elite swimmers (~0.8% typical variation)\textsuperscript{243} than their less experienced, junior counterparts (~1.1%).\textsuperscript{245} Other factors such as physical\textsuperscript{246} or physiological\textsuperscript{247} characteristics and/or training age\textsuperscript{152} may also be responsible for differences in the response to certain training and racing interventions. Thus, it is pertinent to determine if a particular intervention can yield performance benefits to both junior and elite performers.

Acutely enhancing lower-body power output can elicit improvements in swim start performance.\textsuperscript{248} Consequently, the dryland-based routine was evaluated to determine if its completion positively altered swimmers’ lower-body power-output. Elevation of body temperature can also increase blood flow to skeletal muscles\textsuperscript{196,249} and shift the oxyhaemoglobin ($O_2$Hb) curve to the right,\textsuperscript{250} resulting in a potential increase in oxygen ($O_2$) availability to working muscles. As such, quantification of local tissue oxygenation was also undertaken using near-infra-red (NIRS) technology.
6.1.1 Research Objectives

1. Determine whether the application of additional passive heat, and completion of dryland-based activation exercises within the transition phase, can enhance sprint freestyle swimming performance in elite senior athletes.

2. Determine if this particular additional warm-up strategy enhances $T_{core}$ maintenance during the transition phase in elite senior athletes.

3. Investigate if this additional warm-up strategy can improve lower-body power output and subsequently elite senior freestyle start time (to 15 m) performance.

4. Quantify measures of near-infra-red-related (NIRS) local tissue oxygenation during completion of this additional warm-up strategy.
6.2 Submitted Manuscript

6.2.1 ABSTRACT

Objectives: This study investigated the impact of utilising additional warm-up strategies within the transition phase (interval between pool warm up and start of the race) on elite sprint swimming performance. Methods: Twenty-five elite swimmers; 12 male, 20±3 yr; 13 female, 20±2 yr, performance standard ~807 FINA2014 points) completed a standardised pool warm-up followed by a 30 min transition and a 100 m freestyle time-trial. During the transition phase, swimmers wore a tracksuit jacket with integrated heating elements and performed a dryland-based exercise routine (Combo), or a conventional tracksuit and remained seated (Control). Results: Combo yielded faster start (1.5% ± 1.0%, p = 0.02; mean ± 90% confidence limits) and 100 m time-trial (0.8% ± 0.4%, p < 0.01) performances than Control. Core temperature declined less (-0.2°C ± 0.1°C versus -0.5°C ± 0.1°C, p = 0.02) during the transition phase and total (local) haemoglobin concentration was greater immediately prior to the time-trial within Combo (81µM ± 25µM versus 30µM ± 18µM, p < 0.01; mean ± standard deviation) compared to Control. Conclusions: Passive heating and dryland-based activation exercises utilised within the transition phase can improve elite sprint swimming performance by ~0.8%.

6.2.2 INTRODUCTION

Warming-up prior to a competitive event is a widely accepted practice in modern sport, with athletes and coaches considering it an essential element for optimal performance. Both passive and active warm-up strategies can elicit improvements in exercise performance through increased muscle metabolism (as a result of increased body temperature), elevated oxygen uptake kinetics and post-activation potentiation (PAP). In competitive swimming, the time between cessation of the pool warm-up and start of the race, the so-called transition phase, is typically 30-45 min. Unfortunately muscle temperature (T_muscle) begins to decline immediately following exercise with a marked reduction after 15-20 min. Thus any potential benefits of the pool warm-up may be reduced.
Combining a sport-specific warm-up with passive heating via heated tracksuit pants\textsuperscript{35} or a blizzard survival jacket\textsuperscript{38} can improve body temperature maintenance (T\textsubscript{muscle}, core temperature, T\textsubscript{core}) within the transition phase and enhance peak power output\textsuperscript{35} and repeat-sprint performance.\textsuperscript{38} We have reported a \textasciitilde{}0.4\% improvement in sprint freestyle performance when junior swimmers wore heated tracksuit jackets within the transition phase.\textsuperscript{232} However, application of passive heat alone was not entirely effective for maintaining T\textsubscript{core}. Combining the wearing of heated tracksuit jackets with the completion of dryland-based exercises further enhanced T\textsubscript{core} maintenance during the transition phase and improved sprint swimming performance by \textasciitilde{}1.1\%.\textsuperscript{232}

Although a particular intervention may elicit performance improvements in junior swimmers, the magnitude of improvement might not be as large in elite swimmers. Factors such as performance variability\textsuperscript{243,245} and differences in physical\textsuperscript{246} or physiological\textsuperscript{247} characteristics and/or training age,\textsuperscript{152} could also influence responses to training and racing interventions. The primary aim of this study was to determine whether utilising a combination of passive heat and dryland-based activation exercises within the transition phase enhances sprint swimming performance in elite (senior) swimmers. Elevating body temperature can increase blood flow to working muscles\textsuperscript{196,249} and shift the oxyhaemoglobin (O\textsubscript{2}Hb) curve to the right,\textsuperscript{250} potentially enhancing oxygen (O\textsubscript{2}) availability to skeletal muscles. Improvements in lower-body power output are also associated with enhanced swim start (time to 15 m) performance.\textsuperscript{248} Therefore, we also investigated whether the transition phase warm-up interventions impacted upon swim start performance and local tissue oxygenation.

6.2.3 METHODS

Participants

Twenty-five national and internationally competitive swimmers (n=12 males: 20 ± 3 yr; stature 1.86 ± 0.03 m, 80.1 ± 6.7 kg; n=13 females: 20 ± 2 yr; 1.77 ± 0.05 m, 67.2 ± 5.8 kg; mean ± standard deviation) provided written informed consent to participate in the study. The participants were freestyle specialists, with eleven swimmers current members of the Australian senior team and two former senior team members (within the last yr), with the
remaining twelve swimmers currently competing at National-level within Australia (personal best time males, $50.8 \pm 1.8$ s; $791 \pm 76$ Fédération internationale de natation, FINA2014 scoring points; females, $55.6 \pm 1.2$ s; $824 \pm 56$ FINA2014 scoring points). This study was approved by the University of Canberra’s Human Research Ethics Committee (approval number 14-180).

**Experimental Design**

Using a randomised cross-over and counterbalanced design, swimmers completed two testing sessions (Control and Combo), separated by a minimum of 48 h, within a morning (05:30-09:30) timeslot. To ensure order effects were minimised, six male swimmers completed the Control condition first while the remaining six participated in the Combo condition. Given the additional one female participant ($n = 13$), it was decided that seven female swimmers would complete the Control condition first, while the other six swimmers completed the Combo condition. Familiarisation with the experimental protocols was completed one week prior to testing.

**Experimental Protocol**

Each session began with swimmers completing a standardised pool warm-up (Table 15) followed by a 30 min transition phase and a 100 m freestyle time-trial in a 50 m pool. The 30 min transition phase consisted of three segments: i) 30-21 min prior to the time-trial swimmers changed into their race swimsuit and tracksuit; ii) 21-16 min prior to the time-trial, swimmers remained seated with minimal activity unless required to perform the dryland-based exercise routine (see explanation below); and iii) in the final 15 min prior to the time-trial, swimmers entered a simulated marshalling area where they remained seated with minimal activity.

During the transition phase two different warm-up strategies were utilised. In the Control condition, swimmers wore a standard t-shirt and tracksuit (top and pants) and remained seated with minimal activity throughout the transition phase. The Control condition was designed to replicate the standard race preparation undertaken by most competitive swimmers. Within the experimental condition (Combo), swimmers wore an insulated heated jacket (City heated jacket, Venture heated clothing, Melbourne, Australia), similar in style to
a standard tracksuit jacket, but with additional heating elements integrated into the garment over the chest (pectoralis major) and lower back (latissimus dorsi and quadratus lumborum) regions, along with a t-shirt and standard tracksuit pants. The heating elements were set to 51°C and the jacket was worn throughout the transition phase. In addition, in Combo, swimmers completed a 5 min dryland-based exercise routine, as described previously between 21-16 min prior to the time-trial (bodyweight tuck rather than box jumps were completed).

Swimmers were requested to maintain the same nutrition and sleep routines, abstain from caffeine in the 12 h prior, and refrain from completing heavy exercise (in the pool or gym) within two days of and on the day of testing. With the cooperation of the coaches involved in the study, training volume and intensity were also kept consistent throughout the study. Quantitative feedback on swimming performance (e.g. times and stroke characteristics) during the time trials was deferred until completion of the study.

| Table 15. Standardised pool warm-up completed prior to 100 m freestyle time trial. |
|---|---|---|---|
| Distance | Stroke Type | Intensity | Rest |
| 400 m | FR | < 50% HRmax | NA |
| 4 x 100 m | FR | 60% HRmax | 1.20 min (cycle) |
| 4 x 50 m (drill; 25 m high SR, 25 m easy) | FR | 60% HRmax | 15 sec |
| 100 m | FR | 50% HRmax | NA |
| 2 x 50 m (with hand paddles) | FR | PB + 3 sec | 1 min (cycle) |
| 2 x 25 m dive | FR | 95% HRmax | 1 min (cycle) |
| 100 m | FR | 50% HRmax | NA |

FR freestyle, HRmax Heart rate max, PB personal best time, SR stroke rate

**Measurements**

Pool warm-ups and time-trial swims were performed in a 50 m outdoor pool (pool temperature 27.2 ± 0.4°C, air temperature 22.8 ± 3.8°C, relative humidity 62% ± 8%, wind speed 0.8 ± 0.3 m/s; mean ± standard deviation; Kestrel 4500 Pocket Weather Tracker, Nielsen-Kellerman Co., USA) with swimmers beginning the time-trials from a dive start, utilising starting blocks. Overall and 25 m split-times were recorded manually (SVAS003 Seiko, Tokyo, Japan) by an elite coach (holding an Australian State-National level licence). Footage from digital video cameras (Canon Legria FS21, Tokyo, Japan) positioned at the 5, 15, 25 and 45 m marks was used to calculate start and turn times. Lower-body impulse
was monitored via a portable force measurement system (Swift SpeedMat, Swift performance equipment, Carole Park, Australia). Swimmers were requested to perform three maximal vertical jumps prior to the warm-up, ten min before and four min after the 100 m time-trial. The peak and mean impulse calculated from these three jumps was recorded.

Ingestion of a temperature sensor (CorTemp™ Ingestible Core Body Temperature Sensor, HQ Inc., Palmetto, USA) 6 h prior to each testing session permitted measurement of $T_{\text{core}}$. Skin temperature ($T_{\text{skin}}$), $T_{\text{core}}$, capillary blood lactate concentration ($\bar{\text{La}}$) and heart rate (HR) were monitored according to previously established methods. To assess changes in a swimmer’s surface heat patterns, a 50 mm by 50 mm square reference point was marked on the right trapezius muscle and right rectus femoris muscle and images taken using a thermal camera (SC660, FLIR Systems, Inc., Oregon, USA). Sample points for $T_{\text{core}}$, $T_{\text{skin}}$, HR and thermal imaging were: before and after the pool warm-up, dryland routine and time-trial (one and four min post time-trial). $\bar{\text{La}}$ was sampled after the pool warm up, prior to the time-trial as well as one and four min post time-trial with peak post time-trial $\bar{\text{La}}$ concentration determined from the higher of the latter two values.

A portable near-infra-red spectrometer (NIRs) (Portamon, Artinis, Medical System, Zetten, The Netherlands) was used to monitor changes in a swimmer’s local tissue oxygenation during transition. The NIRs comprised a two-wavelength, continuous-wave system, which simultaneously used the modified Beer-Lambert and spatially resolved spectroscopy methods. While it would have been preferable to measure blood flow changes in the upper- and lower-body, this was not possible as only one unit was available. As the freestyle stroke requires a major contribution from muscles in the upper body, we chose to position the NIRs unit over a section of the right trapezius muscle (10 cm from the shoulder joint, along the vertical axis of the spine). The unit and the skin were covered with a black cloth to prevent contamination from ambient light and the unit affixed to the site with black strapping tape. Four different wavelength laser diodes (761, 762, 849 and 846 nm) provided the light source to detect changes in transmission of radiation as a function of time, distance, and wavelength. A differential path length factor was not determined; however a value of 3.83 was used to compare with previous studies. Values (in micromolar units, µM) for local tissue total haemoglobin concentration ($t\text{Hb}$) and haemoglobin difference ($Hb_{\text{diff}}$), (where $Hb_{\text{diff}} = O_{2}\text{Hb concentration} - \text{deoxyhaemoglobin concentration}$) were calculated from average data recorded over a 5 sec period prior to and post dryland routine (and at the
corresponding time point in Control) as well as pre and post 100 m time-trial. Baseline values were determined by averaging the recorded values from 30 s prior to participants putting on the heated tracksuit jacket within the transition phase.

The Borg 6–20 scale was used to determine swimmers’ subjective rating of perceived exertion (RPE) following completion of the pool warm-up, dryland routine and time-trial. Swimmers views regarding competition warm-up strategies as a whole, and their opinions relating to the additional warm-up strategies were assessed via questionnaires created for this study using multiple choice and Likert-format questions. The questionnaires were completed i) prior to study commencement; ii) before each testing session; iii) after each testing session, and iv) at the conclusion of the study. Swimmers thermal comfort was measured on a 6-point scale (+2 very comfortable, -2 very uncomfortable) while thermal sensation was reported on the ASHRAE 7-point scale (+3 hot, -3 cold) at the same time points used to collect $T_{core}$, $T_{skin}$, HR and thermal imaging data.

Statistics Analysis

A sample size of 22 participants was deemed adequate for a post-only cross-over design assuming a smallest worthwhile change in time-trial performance of 0.30% for elite swimmers, a typical error of hand-timing of 0.36% and values of 5% and 75% for type I and II errors respectively. Recruitment of elite swimmers for intervention studies is often difficult, primarily because the number of swimmers classed as “elite” is so small. Access to these athletes is further hampered as a consequence of their busy training and competitive schedules. Thus, while separate analyses of the male and female results would have been preferable, the limited number of swimmers available did not permit this.

Statistical analysis was performed using SPSS software (version 21; SPSS Inc., Chicago, USA) with significance set at $p \leq 0.05$. Effect size (ES) was calculated using Cohen’s $d$ with the ranges of 0.2–0.6, 0.61–1.19 and > 1.20 considered small, medium and large effects respectively. Precision of estimation was indicated with 90% confidence limits. All data was analysed using paired samples t-tests comparing the two conditions (Control and Combo). To estimate differences in performance time, all raw time-based data was normalised against Control and analysed using a paired samples t-test. Change scores were calculated for $T_{core}$, $T_{skin}$, HR and thermal imaging between the time points of i) post pool
warm-up and prior to the time-trial, and ii) prior to dryland and post the dryland routine (when performed). Where appropriate, differences in change score data were analysed using a paired samples t-test. All questionnaire data was analysed using frequencies to determine the percentage response of swimmers to the various questions.

6.2.4 RESULTS

Performance times and lower-body impulse

Across all swimmers, 100 m time-trials were 0.8% ± 0.4% (mean ± 90%, confidence limits) faster ($p < 0.01$) in Combo, with males improving from 53.7 ± 2.0 secs to 53.2 ± 1.5 secs (mean ± standard deviation) and females from 58.9 ± 2.2 secs to 58.4 ± 2.0 secs. Similarly Combo also yielded 1.5% ± 1.0% faster start times ($p = 0.02$) than Control for all swimmers (Fig 3) with males improving from 6.2 ± 0.3 secs to 6.1 ± 0.3 secs and females from 7.1 ± 0.4 secs to 6.9 ± 0.4 secs. Turn times were not different between conditions ($p = 0.83$). Lower-body peak impulse was similar between conditions at all sample points ($p$ value range = 0.36 - 0.85, ES range = -0.09-0.10).

Fig. 3 100 m time-trial performance times for the Control and Combo conditions. A) Overall 100 m time-trial times. B) Time to 15 m (start time). Data are presented as mean ± standard deviation. Significantly different to Control * $p \leq 0.05$. 

Warm-up intervention
Temperature and Blood Lactate

$T_{\text{core}}$, $T_{\text{skin}}$ and $\text{La}^-$ readings were similar between conditions at baseline and following the pool warm-up. $T_{\text{core}}$ increased by $\sim$0.7°C during pool warm-up and then declined during the transition phase under both conditions (Combo: from 37.8 ± 0.3°C to 37.6 ± 0.5°C; Control: from 37.8 ± 1.2°C to 37.3 ± 0.4°C; mean ± standard deviation). However, the decrease in $T_{\text{core}}$ during transition was substantially less (-0.2 ± 0.1°C; mean ± 90% confidence limits; $p = 0.03$, ES, 0.78) within Combo than Control (-0.5 ± 0.1°C) (Fig 4). Following completion of the pool warm-up, $T_{\text{skin}}$ increased moderately within the transition phase in both conditions, with $T_{\text{skin}}$ rising substantially higher 2.2 ± 0.3°C; $p = 0.03$, ES, 0.62) in Combo compared with Control (1.3 ± 0.6°C) (Fig 4). Better maintenance of $T_{\text{core}}$ within transition in Combo resulted in moderately higher $T_{\text{core}}$ readings (37.6 ± 0.5°C; mean ± standard deviation) immediately prior to the time-trial in Combo ($p = 0.09$, ES, 0.45) compared to Control (37.3 ± 0.4°C). In addition, the greater rise in $T_{\text{skin}}$ during transition in Combo elicited substantially higher prior to time-trial $T_{\text{skin}}$ readings (30.6 ± 1.0°C) in Combo ($p < 0.01$, ES, 1.10) in comparison with Control (29.1 ± 1.2°C). $\text{La}^-$ concentration one min post-time-trial was substantially higher (7.0 ± 2.7 mmol) in Control ($p = 0.03$, ES, -1.29) versus Combo (5.2 ± 4.2 mmol). Peak $\text{La}^-$ values are presented in Table 16.

![Graph showing change in core temperature ($T_{\text{core}}$) and skin temperature ($T_{\text{skin}}$) during the 30 min transition phase, from post-pool warm-up to pre 100 m time-trial, for the Control and Combo conditions. Data are presented as mean ± 90% confidence limits. Significantly different to Control * $p \leq 0.05$.](image)

*Fig. 4* Change in core temperature ($T_{\text{core}}$) and skin temperature ($T_{\text{skin}}$) during the 30 min transition phase, from post-pool warm-up to pre 100 m time-trial, for the Control and Combo conditions. Data are presented as mean ± 90% confidence limits. Significantly different to Control * $p \leq 0.05$. 

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Heart rate and NIRs

Completion of the dryland routine elicited a large ~30 bpm rise in HR ($p < 0.01$, ES, 2.15). Throughout the transition phase, local (trapezius) tHb values tended to increase in Combo such that, immediately prior to the 100-m time-trial, local tHb values were substantially greater in Combo ($81 \pm 25 \mu M$; $p < 0.01$, ES, 1.45) compared to Control ($30 \pm 18 \mu M$). Values for local Hb\textsubscript{diff} at the trapezius were also moderately higher prior to the time-trial in Combo ($2.4 \pm 5.2 \mu M$; $p = 0.07$, ES, 0.61) compared to Control ($1.1 \pm 3.9 \mu M$).

Table 16. Heart rate (HR), lactate (La\textsuperscript{−}) and upper and lower body surface temperature (as determined using a thermal imaging camera) values recorded immediately post pool warm-up and pre time-trial with calculated values sampled at one and four min post time-trial (peak post time-trial) presented.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Control</th>
<th>Combo</th>
<th>$p$ value</th>
<th>Effect size</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Post Pool Warm-Up</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HR (bpm)</td>
<td>116 ± 32*</td>
<td>102 ± 20</td>
<td>0.04</td>
<td>-0.36</td>
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<tr>
<td>La\textsuperscript{−} (mmol/L)</td>
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<td>Upper-body (°C)</td>
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<td>-1.08</td>
</tr>
<tr>
<td>Lower-body (°C)</td>
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<td>-0.26</td>
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<td><strong>Pre Time-Trial</strong></td>
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<tr>
<td>HR (bpm)</td>
<td>82 ± 14</td>
<td>83 ± 15</td>
<td>0.53</td>
<td>0.10</td>
</tr>
<tr>
<td>La\textsuperscript{−} (mmol/L)</td>
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<td>-0.07</td>
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<tr>
<td>Upper-body (°C)</td>
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<td>0.95</td>
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<tr>
<td>Lower-body (°C)</td>
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<td>29.4 ± 1.8</td>
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<td>0.05</td>
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<td><strong>Peak Post Time-Trial</strong></td>
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</tr>
<tr>
<td>HR (bpm)</td>
<td>172 ± 26</td>
<td>172 ± 23</td>
<td>0.97</td>
<td>0.02</td>
</tr>
<tr>
<td>La\textsuperscript{−} (mmol/L)</td>
<td>8.8 ± 2.0</td>
<td>8.7 ± 3.0</td>
<td>0.96</td>
<td>-0.30</td>
</tr>
<tr>
<td>Upper-body (°C)</td>
<td>29.7 ± 2.3</td>
<td>29.7 ± 2.8</td>
<td>0.71</td>
<td>-0.13</td>
</tr>
<tr>
<td>Lower-body (°C)</td>
<td>29.0 ± 2.4</td>
<td>28.0 ± 1.6</td>
<td>0.18</td>
<td>-0.44</td>
</tr>
</tbody>
</table>

All data are mean ± standard deviation. * Significantly different between conditions $p \leq 0.05$.

RPE, thermal comfort and thermal sensation

RPE was similar between conditions following the pool warm-up and time-trial. Completion of the dryland routine yielded a large 6 ± 4 point rise in the RPE ($p < 0.01$, ES, 0.77). Thermal comfort did not differ between conditions at any time point prior to or post time-
trial. Upper-body as well as whole-body thermal sensation increased towards feeling “warm” ("+2") in Combo throughout the transition phase and remain elevated until after the time-trial. Higher upper-body and whole-body thermal sensation values were recorded throughout the transition phase in Combo compared to Control ($p$ value range = 0.0-0.4, ES range = 0.61-1.18). Marginally higher lower-body sensation values were also recorded prior to the time-trial ($p = 0.02$, ES, 0.13). All swimmers stated they would use the heated jackets in competition if available, with the majority reporting they would incorporate the dryland activation exercises into their competition warm-up where possible.

6.2.5 DISCUSSION

Elite competitor 100 m freestyle performance was enhanced by ~0.8% when a traditional pool-based warm-up was combined with passive heating and dryland-based activation exercises during the transition phase. Enhanced $T_{\text{core}}/T_{\text{skin}}$ maintenance during transition was associated with faster start and overall time-trial performance. Greater local tHb and $Hb_{\text{diff}}$ values during the transition phase in Combo are plausible mechanistic explanations contributing to the improvement in swimming performance. These outcomes provide support for inclusion of these practical strategies to enhance competition performance in elite swimmers.

To remain in contention for a medal, Olympic swimmers need to improve their performance by ~1% within the year prior to competition.$^{243}$ Although various training interventions can elicit at least a ~1% improvement in performance$^{221}$, an additional ~0.3-0.4% improvement is needed to substantially increase a swimmer’s chances of winning a medal at the elite level.$^{243,257}$ Thus, the magnitude of the performance improvement reported in the present study (~0.8%) should be worthwhile in elite-level swimming competitions.

In competitive sprint swimming the swim start contributes up to 30% of total race performance$^{244}$ with improvements in lower-body power-output associated with faster start performance.$^{248}$ Although the dryland routine within the present study included exercises that could produce an increase in lower-body impulse (e.g. bodyweight tuck jumps), we did not observe any such increase, possibly because a PAP response strong enough to be carried
through to the start of the time-trial was not induced. Improvements in impulse have been observed as long as 18.5 min following a PAP stimuli, but this may require that exercises be executed with additional load. The addition of a weighted vest to the tuck jump exercise could be a practical alternative to improve lower-body impulse and subsequently start time performance.

Despite the lack of a measureable improvement in lower-body impulse, start time performance was still substantially faster following completion of the Combo strategy compared to Control. Upper-body exercises included within the dryland routine may have contributed to this improvement given the substantial role these muscles play in the propulsion phase within the freestyle stroke, but future research will need to clarify this effect. $T_{\text{core}}$ and $T_{\text{skin}}$ readings were also greater immediately prior to the time-trial in Combo compared to Control which likely contributed to the faster start times recorded in Combo. Elevation of body temperature prior to competition is beneficial to athletes competing in sprint and sustained high-intensity events by facilitating improvements in muscle fibre conduction velocity and cross-bridge cycling rate.

We have previously observed an association between improvements in sprint swimming performance and $T_{\text{core}}$ maintenance in junior swimmers, with a smaller decline in $T_{\text{core}}$ within transition correlating highly ($R^2 = 0.91$) with faster 100 m freestyle time-trial performance. Within the transition phase in the present study, $T_{\text{core}}$ declined under both conditions, but substantially less so within Combo than Control. However the magnitude of the decline in $T_{\text{core}}$ was greater than previously reported, possibly because trials in the present study were conducted in an outdoor pool.

Higher local tHb concentration and $Hb_{\text{diff}}$ values were observed throughout the transition phase in the Combo trial, and prior to the time-trial compared to Control. These findings coincided with improvements in $T_{\text{core}}$ maintenance and rise in $T_{\text{skin}}$ within the transition phase in the Combo condition. At higher body temperatures, blood flow to skeletal muscles has been reported to improve. Using the NIRs measurement we were not able to distinguish between skin and muscle blood flow. However it is plausible that greater local tHb and $Hb_{\text{diff}}$ values prior to the time-trial in Combo may have positively influenced performance by ensuring a better $O_2$ supply to skeletal muscles within the swimming time-trial, given that
changes in tHb concentration are a gross representation of alterations in blood flow, and likely to positively affect local tissue metabolism.

6.2.6 CONCLUSIONS

At the elite level, differences in performance between swimmers are often minimal, and so interventions that consistently provide small improvements should be considered by the coach and athlete. Swimming coaches can be advised that for elite freestyle swimmers, a combination of heated jackets and dryland-based activation exercises during the transition phase can yield up to a 0.8% improvement over 100 m. Improved maintenance of $T_{\text{core}}$ and $T_{\text{skin}}$ within transition as well as augmented local upper-body total haemoglobin concentration appear as key mechanisms contributing to faster overall sprint freestyle performance.

6.2.7 PRACTICAL APPLICATIONS

Given that the lengthy transition phases experienced by competitive swimmers are unavoidable, practical strategies that maintain elevated body temperature during these periods are paramount. Most swimmers wear a standard tracksuit jacket while waiting to race and thus substituting this with a heated jacket should not present any logistical challenges. The dryland routine outlined within this investigation consisted of exercises which could be completed on pool deck with minimal equipment and space. However the addition of load to the tuck jump exercise via a weight vest to determine if a greater PAP response can be elicited requires further attention. These strategies could also be applied to other situations in which it is difficult to maintain $T_{\text{core}}$ and/or $T_{\text{skin}}$ via metabolic heat production alone, such as between repeated exercise bouts (e.g. multiple races within a competition) or in training sessions.
DECLARATION OF CO-AUTHORED PUBLICATION
CHAPTER 7

Declaration by candidate

In the case of Chapter 7, the nature and extent of my contribution to the work was the following:

<table>
<thead>
<tr>
<th>Nature of contribution</th>
<th>Extent of contribution (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Developing the research question and research design, data collection and analysis, write-up and editing the manuscript</td>
<td>75%</td>
</tr>
</tbody>
</table>

The following co-authors contributed to the work.

<table>
<thead>
<tr>
<th>Name</th>
<th>Nature of contribution</th>
<th>Extent of contribution (%)</th>
<th>Contributor is also a student at UC Y/N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dr Ben Rattray</td>
<td>Research design, analysis, editing the manuscript</td>
<td>9%</td>
<td>N</td>
</tr>
<tr>
<td>Prof David Pyne</td>
<td>Research design, analysis, editing the manuscript</td>
<td>9%</td>
<td>N</td>
</tr>
<tr>
<td>Prof Kevin Thompson</td>
<td>Research design, editing the manuscript</td>
<td>7%</td>
<td>N</td>
</tr>
</tbody>
</table>

Candidate's Signature 11/02/2016

Declaration by co-authors

The undersigned hereby certify that:
(19) the above declaration correctly reflects the nature and extent of the candidate’s contribution to this work, and the nature of the contribution of each of the co-authors.
(20) they meet the criteria for authorship in that they have participated in the conception, execution, or interpretation, of at least that part of the publication in their field of expertise;
(21) they take public responsibility for their part of the publication, except for the responsible author who accepts overall responsibility for the publication;
(22) there are no other authors of the publication according to these criteria;
(23) Potential conflicts of interest have been disclosed to (a) granting bodies, (b) the editor or publisher of journals or other publications, and (c) the head of the responsible academic unit; and

(24) The original data are stored at the following location(s) and will be held for at least five years from the date indicated below:

<table>
<thead>
<tr>
<th>Location(s)</th>
<th>University of Canberra, Research Institute for Sport and Exercise</th>
</tr>
</thead>
</table>

[Please note that the location(s) must be institutional in nature, and should be indicated here as a department, centre or institute, with specific campus identification where relevant.]

<table>
<thead>
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<td>Signature 2</td>
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<tr>
<td>Signature 3</td>
<td>13/02/2016</td>
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</tbody>
</table>
CHAPTER 7: Additional warm-up strategies do not enhance elite sprint breaststroke performance

The manuscript contained within this chapter has been accepted for publication and has been formatted to comply with the publishing journal’s guidelines: McGowan CJ, Pyne DB, Thompson KG & Rattray B. Additional warm-up strategies do not enhance elite sprint breaststroke performance. International Journal of Sports Physiology and Performance, January 10th 2016. [Epub ahead of print]

7.1 Manuscript Information

In the previous two chapters, combining a swimmer’s active pool warm-up with the completion of a dryland based exercise routine and the wearing of heated tracksuit jackets during a 30 min transition phase was shown to enhance both senior (0.8%) and junior (1.1%) 100 m freestyle performance. The study discussed in the following chapter builds on the work of these two previous studies, examining if the combination warm-up strategy can also yield performance benefits to breaststroke specialists.

The relative muscle contribution to propulsion differs between the four swimming strokes.\textsuperscript{17} For example, unlike freestyle swimmers who derive propulsion primarily from their arms,\textsuperscript{260} breaststroke swimmers rely equally upon their arms and legs for propulsion through the water.\textsuperscript{261} It is therefore important to investigate how a particular warm-up intervention strategy influences performance across the four swimming strokes. Previous research in cycling has revealed that combining an active cycle ergometer warm-up with the application of passive heat (via heated tracksuit pants), during a 30 min transition can improve $T_{\text{muscle}}$ maintenance and power output during a subsequent sprint cycling task.\textsuperscript{35,36} Therefore, in the following chapter, a combination additional warm-up strategy completed during a 30 min transition phase consisting of lower-body passive heating (via heated tracksuit pants) and dryland-based exercises was evaluated to ascertain if $T_{\text{core}}$ maintenance, lower-body power output and sprint breaststroke performance was positively influenced.
7.1.1 Research Objectives

1. Determine whether the application of additional passive heat, and completion of dryland-based activation exercises within the transition phase, can enhance sprint breaststroke swimming performance in elite senior athletes.

2. Determine if this particular additional warm-up strategy enhances $T_{\text{core}}$ maintenance during the transition phase in elite senior athletes.

3. Investigate if this combination additional warm-up strategy can improve lower-body power output and subsequently elite senior breaststroke start time (to 15 m) performance.
7.2.1 ABSTRACT

Purpose: Targeted passive heating and completion of dryland-based activation exercises within the warm-up can enhance sprint freestyle performance. We investigated if these interventions would also elicit improvements in sprint breaststroke swimming performance.

Methods: Ten national and internationally competitive swimmers (~805 FINA2014 scoring points; 6 male, 20 ± 1 yr; 4 female, 21 ± 3 yr) completed a standardised pool warm-up (1550 m) followed by a 30 min transition and a 100 m breaststroke time-trial. Within transition, swimmers wore a conventional tracksuit and remained seated (Control) or wore tracksuit pants with integrated heating elements and performed a 5 min dryland-based exercise routine (Combo) in a cross-over design.

Results: 100 m time-trial performance (Control: 68.6 ± 4.0 s; mean ± SD; Combo: 68.4 ± 3.9 s; \( p = 0.55 \)) and start times to 15 m (Control: 7.3 ± 0.6 s; Combo: 7.3 ± 0.6 s; \( p = 0.81 \)) were not different between conditions. It was unclear (\( p = 0.36 \)) whether Combo (-0.12 ± 0.19°C; mean ± 90% confidence limits) elicited an improvement in core temperature maintenance within transition compared to Control (-0.31 ± 0.19°C). Skin temperature immediately prior to time-trial commencement was higher (by ~1°C, \( p = 0.01 \)) within Combo (30.13 ± 0.88 °C; mean ± SD) compared to Control (29.11 ± 1.20 °C). Lower-body power output was not different between conditions pre time-trial.

Conclusions: Targeted passive heating and completion of dryland-based activation exercises within transition does not enhance sprint breaststroke performance despite eliciting elevated skin temperature immediately prior to time-trial commencement.

7.2.2 INTRODUCTION

At the elite level, a transition phase of 30-45 min from the end of the pool warm-up to the start of the race start is not uncommon and can impair swimming performance. Muscle temperature (\( T_{\text{muscle}} \)) declines following exercise, with a substantial reduction evident after ~15–20 min of recovery. Passive heating via heated tracksuit pants, jacket or blizzard survival jacket, within transition can ameliorate declines in body temperature (\( T_{\text{muscle}} \) or
core, $T_{\text{core}}$) and enhance peak-power output$^{35,38}$ by $\sim$3-11%, single-sprint performance$^{232}$ by $\sim$0.4% and repeat-sprint performance. Additional enhancements of $\sim$0.7% in sprint freestyle performance were observed when passive heating was combined with dryland-based activation exercises within transition.$^{232}$ Dryland-based exercises can enhance lower-body power output and freestyle swim start time to 15 m.$^{29}$ Unlike, freestyle swimmers who derive propulsion primarily from their arms,$^{260}$ breaststroke swimmers rely equally upon their arms and legs for propulsion through the water.$^{261}$ Therefore, we investigated whether combining lower-body passive heating and the completion of dryland-based activation exercises during transition enhances $T_{\text{core}}$ maintenance and sprint breaststroke performance.

7.2.3 METHODS

Subjects

Following ethical approval, six male (20 ± 1 yr; stature 1.85 ± 0.06 m, 78.8 ± 6.8 kg; personal best time: 63.1 ± 2.3 s; 800 ± 86, FINA2014 scoring points; mean ± standard deviation) and four female (21 ± 3 yr; 1.68 ± 0.09 m, 61.3 ± 5.9 kg; personal best time: 69.2 ± 3.9 s, 813 ± 126 FINA2014 scoring points) breaststroke specialist swimmers were recruited. Four swimmers were current Australian senior team members, three former members (within the last yr) and three swimmers currently competed at Australian National-level.

Design

Using a randomised cross-over design, swimmers completed two testing sessions (Control and Combo), separated by 48 h, within a morning (06:30-09:30) timeslot. Each individual acted as their own control and familiarisation with experimental protocols was completed one week prior to testing.

Methodology

Initially, swimmers completed a standardised pool warm-up (Table 17; developed in consultation with the four elite swimming coaches involved in the study and utilizing
information from a recent review, followed by a 30 min transition phase and a 100 m breaststroke time-trial. The transition phase was divided as follows: 1) post-pool warm-up (30-21 min pre-time-trial) swimmers changed into their racing swimsuit and tracksuit; 2) remained seated (21-16 min pre-time-trial) with minimal activity unless required to perform the dryland-based exercise routine (see explanation below); 3) entered a simulated marshalling area for the final 15 min prior to time-trial commencement.

Within transition, swimmers wore a standard t-shirt and tracksuit and remained seated with minimal activity (Control), or wore heated tracksuit pants (Tri-Zone Heated Base Layer Bottoms, Venture heated clothing, Melbourne, Australia), with integrated heating elements over the backside (gluteus maximus) and knee (lower-section of rectus femoris and vastus medialis and upper-section of tibialis anterior) and completed a 5 min dryland-based exercise routine, as described previously (tuck rather than box jumps were completed) between 21-16 min prior to time-trial start (Combo). The heating elements were powered by a 7.4 V lithium ion battery set to 51°C and the total surface area covered equated to 0.01m$^2$ over the backside and 0.08m$^2$ over each knee region. Throughout the transition phase, swimmers were situated in an undercover area to minimise the influence of radiant heat from the sun.

<table>
<thead>
<tr>
<th>Distance</th>
<th>Stroke Type</th>
<th>Intensity</th>
<th>Rest</th>
</tr>
</thead>
<tbody>
<tr>
<td>400 m</td>
<td>FR</td>
<td>&lt; 50% HR$_{\text{max}}$</td>
<td>NA</td>
</tr>
<tr>
<td>4 x 100 m</td>
<td>FR</td>
<td>60% HR$_{\text{max}}$</td>
<td>1.20 min (cycle)</td>
</tr>
<tr>
<td>4 x 50 m (drill; 25 m high SR, 25 m easy)</td>
<td>BR</td>
<td>60% HR$_{\text{max}}$</td>
<td>15 sec</td>
</tr>
<tr>
<td>100 m</td>
<td>FR</td>
<td>50% HR$_{\text{max}}$</td>
<td>NA</td>
</tr>
<tr>
<td>2 x 50 m (with hand paddles)</td>
<td>FR</td>
<td>PB + 3 sec</td>
<td>1 min (cycle)</td>
</tr>
<tr>
<td>2 x 25 m dive</td>
<td>BR</td>
<td>95% HR$_{\text{max}}$</td>
<td>1 min (cycle)</td>
</tr>
<tr>
<td>100 m</td>
<td>FR</td>
<td>50% HR$_{\text{max}}$</td>
<td>NA</td>
</tr>
</tbody>
</table>

BR breaststroke, FR freestyle, HR$_{\text{max}}$ Heart rate max, PB personal best time, SR stroke rate

Pool warm-ups and time-trial swims were completed in a 50 m outdoor pool (pool temperature 27.2 ± 0.4°C, air temperature 22.8 ± 3.8°C, relative humidity 62 ± 8%; wind speed 0.7 ± 0.2 m/s; mean ± standard deviation; Kestrel 4500 Pocket Weather Tracker, Nielsen-Kellerman Co., USA). Split (25 m) and overall times were manually recorded by a national coach. Digital video cameras (Canon Legria FS21, Tokyo, Japan) positioned at the 5, 15, 25 and 45 m marks were used to determine start and turn times. Lower-body peak-power output was assessed using a portable force measurement system (Swift SpeedMat,
Swift performance equipment, Carole Park, Australia). Swimmers performed three maximal vertical jumps at: pre-pool warm-up, 8 min pre-time-trial and 4 min post-time-trial.

Ingestion of a temperature sensor (CorTemp™, HQ Inc., Palmetto, USA) permitted measurement of Tcore. Skin temperature (Tskin), Tcore, blood lactate concentration (La¯) and heart rate (HR) were monitored according to established methods. Changes in surface heat patterns were assessed via images taken of each swimmer’s right trapezius muscle and right rectus femoris muscle (marked by a 50 mm by 50 mm square reference point) using a thermal imaging camera (SC660, FLIR Systems, Inc., Oregon, USA). Subjective ratings of perceived exertion (RPE, Borg 6–20 scale) followed the pool warm-up, dryland routine and time-trial.

Statistical Analysis

Data were analysed using a paired sample t-test comparing the Control and Combo conditions. Significance was set at p ≤ 0.05 and effect size (ES) calculated using Cohen’s d (value ranges of 0.2–0.6, 0.61–1.19 and > 1.20 considered small, medium and large effects, respectively). Precision of estimation was indicated with 90% confidence limits.

7.2.4 RESULTS

100 m time-trial performance was not substantially different (p = 0.55; ES, -0.05) between conditions (Control: 68.6 ± 4.0 s; mean ± standard deviation; Combo: 68.4 ± 3.9 s), with start (Control: 7.3 ± 0.6 s; Combo: 7.3 ± 0.6 s; p = 0.81; ES, 0.02) and turn times also not different (p = 0.87; ES, 0.01). Lower-body peak-power output pre-time-trial was not different between conditions (p = 0.40; ES, 0.04), though female values were ~2.2% higher (p = 0.03; ES, 0.23) 4 min post-time-trial in Combo.

Tcore increased by ~0.5 ± 0.1°C during the pool warm-up in each condition. It was unclear (p = 0.36; ES, 0.65) whether Combo (-0.12 ± 0.19°C; mean ± 90% confidence limits) elicited an improvement in Tcore maintenance within transition above that of Control (-0.31 ± 0.19°C) (Fig. 5A). Tskin increased within transition to a similar magnitude (p = 0.12; ES, 0.20) in both
Control (1.15 ± 0.44°C) and Combo (1.66 ± 0.58°C) (Fig. 5B). $T_{\text{skin}}$ immediately pre-time-trial was significantly higher ($p = 0.01$; ES, 0.70) within Combo (30.13 ± 0.94°C; mean ± standard deviation) compared to Control (29.11 ± 1.27°C). Upper-body temperature (measured via thermal camera) one min post time-trial was similar between conditions (Control: 31.70 ± 0.20°C, Combo: 31.83 ± 0.35°C, $p = 0.67$; ES, 0.38), with four min post time-trial values higher in comparison ($p$ value range = 0.01-0.09), though similar between conditions (Control: 33.70 ± 0.46°C, Combo: 33.60 ± 1.25°C, $p = 0.91$; ES, -0.14). Lower-body temperature (measured via thermal camera) one and four min post time-trial was similar for both conditions (Control: $p = 0.46$; ES, -0.05, Combo: $p = 0.73$; ES, 0.25). Completion of the dryland-based exercise routine elicited a 17 ± 10 bpm (mean ± 90% confidence limits) rise in HR ($p = 0.02$; ES, -1.85) and a 4 ± 3 point rise in RPE ($p = 0.01$; ES, 0.51) (Table 18). Lower and whole-body thermal sensation were similar between conditions up until the pre-dryland routine sample point after which values were substantially higher in Combo ($p$ value range = 0.00 - 0.04, ES range = -0.36-0.81).

**Fig. 5 Fluctuation in core ($T_{\text{core}}$) and skin ($T_{\text{skin}}$) temperature from pre-pool warm-up (baseline) to 4 min post 100 m time-trial, for the Control and Combo conditions. A) Core temperature. B) Skin temperature. Data are presented as mean ± standard deviation. Significantly different to Control * $p \leq 0.05$.**
Table 18. Heart rate (HR), lactate (La−) and upper and lower body surface temperature (as determined using a thermal imaging camera) values recorded immediately post pool warm-up and pre time-trial with calculated values sampled at 1 and 4 minutes post time-trial (peak post time-trial) presented.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Control</th>
<th>Combo</th>
<th>p value</th>
<th>Effect Size</th>
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<tr>
<td><strong>Post Pool Warm-Up</strong></td>
<td></td>
<td></td>
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<tr>
<td>HR (bpm)</td>
<td>115 ± 19</td>
<td>111 ± 19</td>
<td>0.65</td>
<td>-0.37</td>
</tr>
<tr>
<td>La− (mmol/L)</td>
<td>2.2 ± 1.4</td>
<td>2.4 ± 1.0</td>
<td>0.70</td>
<td>0.24</td>
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<td>Upper-body (°C)</td>
<td>29.5 ± 2.4</td>
<td>31.6 ± 0.8</td>
<td>0.76</td>
<td>1.01</td>
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<tr>
<td>Lower-body (°C)</td>
<td>29.7 ± 2.5</td>
<td>29.1 ± 1.0</td>
<td>0.60</td>
<td>0.34</td>
</tr>
<tr>
<td><strong>Pre Time-Trial</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HR (bpm)</td>
<td>83 ± 18</td>
<td>84 ± 14</td>
<td>0.83</td>
<td>0.68</td>
</tr>
<tr>
<td>La− (mmol/L)</td>
<td>1.4 ± 0.6</td>
<td>1.2 ± 0.3</td>
<td>0.17</td>
<td>-0.57</td>
</tr>
<tr>
<td>Upper-body (°C)</td>
<td>31.9 ± 1.4</td>
<td>31.1 ± 3.1</td>
<td>0.46</td>
<td>-0.35</td>
</tr>
<tr>
<td>Lower-body (°C)</td>
<td>30.0 ± 1.6</td>
<td>29.2 ± 1.5</td>
<td>0.39</td>
<td>0.35</td>
</tr>
<tr>
<td><strong>Peak Post Time-Trial</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HR (bpm)</td>
<td>160 ± 22</td>
<td>168 ± 19</td>
<td>0.02*</td>
<td>0.30</td>
</tr>
<tr>
<td>La− (mmol/L)</td>
<td>7.0 ± 2.8</td>
<td>8.0 ± 1.8</td>
<td>0.07</td>
<td>0.40</td>
</tr>
<tr>
<td>Upper-body (°C)</td>
<td>32.7 ± 1.1</td>
<td>32.7 ± 1.3</td>
<td>0.97</td>
<td>-0.13</td>
</tr>
<tr>
<td>Lower-body (°C)</td>
<td>27.7 ± 1.1</td>
<td>28.2 ± 1.9</td>
<td>0.61</td>
<td>-0.20</td>
</tr>
</tbody>
</table>

All data are mean ± standard deviation. * Significantly different between conditions p ≤ 0.05.

7.2.5 DISCUSSION

Pre-time-trial lower-body power output, sprint breaststroke start, turn and finish times were not enhanced following a combination of lower-body passive heating and dryland-based exercise completion during a 30 min transition phase, compared to Control. We have previously reported that freestyle swimmers experienced a substantial enhancement of Tcore maintenance and a ~1.1% improvement in sprint performance when using the Combo warm-up strategy. However we were unable to replicate this performance enhancement in breaststroke swimmers. Tskin was higher immediately prior to the commencement of the time-trial in Combo, though it appears that this alone was insufficient to overcome the lack of Tcore or Tskin maintenance within transition. Our findings in part concur with results showing an improvement in Tmuscle maintenance when heated tracksuit pants were worn by cyclists during transition, but without a concurrent improvement in Tcore maintenance.
It is possible the surface area covered by the heating elements was inadequate to elicit improvements in $T_{\text{core}}$ or $T_{\text{skin}}$ maintenance. The number of leg muscles covered by the heating elements was higher in an earlier study ($\text{six.leg}^{-1}$)\textsuperscript{35} versus the current study ($\text{three.leg}^{-1}$), though our heating elements were set $\sim 10^\circ \text{C}$ higher. Accounting for heat transfer via convection, it is possible swimmers experienced a similar level of heat transfer. However, swimmers complete their sport-specific warm-up while submerged in a $\sim 27^\circ \text{C}$ pool, which resulted in baseline $T_{\text{skin}}$ declining to a similar temperature to that of pool water $\sim 5$ min after swimmers began their pool warm-up. Therefore, swimmers have to overcome a large temperature gradient within the transition phase which takes time, evident by comparable lower- and whole-body thermal sensations for eight min (pre-dryland routine sample point) into the transition phase. Future research should investigate whether tracksuit pants with integrated heating elements covering a greater surface area improve $T_{\text{core}}$ and $T_{\text{skin}}$ maintenance throughout the transition phase. Alternatively, the combination of a low-heat ($\sim 37^\circ \text{C}$) heated tracksuit jacket and high-heat ($51^\circ \text{C}$) heated tracksuit pants may be required. Caution should be taken to limit adverse effects on a swimmer’s thermal tolerance.

The exercises completed within the dryland routine were designed to simulate common swimming movements, sequenced in such a way as to replicate the kinetic chain of the swim start.\textsuperscript{232} Enhancement of lower-body power output and subsequent freestyle swim start time has been demonstrated following dryland exercise completion.\textsuperscript{29} For breaststrokers it is important that muscles in both the upper and lower body are activated prior to an event as these swimmers rely equally upon their arms and legs for propulsion through the water.\textsuperscript{261} Although exercises designed to induce a postactivation-potentiation response (PAP) and enhance lower-body power output were included in the dryland routine, it appears the PAP response was not strong enough to carry through to the time-trial. Swim start time was also not faster in Combo compared to Control, which contrasts to previous results demonstrating an improvement in freestyle start performance following use of the Combo additional warm-up strategy.\textsuperscript{232} Improvements in power output are present $\sim 18.5$ min following a PAP stimulus,\textsuperscript{152} however exercises must be completed with additional load.\textsuperscript{152} The addition of load to the tuck jump exercise via a weight vest could be a practical alternative to improve lower-body power output and subsequently start time performance. A positive temperature-dependent relationship is also evident with high velocity movements (e.g. the swim start),\textsuperscript{32} so the failure to improve time-trial performance could be explained by a lack of enhanced $T_{\text{core}}$ and/or $T_{\text{skin}}$ maintenance.
7.2.6 CONCLUSIONS

Targeted lower-body passive heating and completion of dryland-based activation exercises within transition did not enhance sprint breaststroke performance despite eliciting elevated skin temperature immediately prior to time-trial commencement.
CHAPTER 8: Morning exercise enhances afternoon sprint swimming performance

8.1 Manuscript Information

In the previous three chapters, the influence of several additional warm-up strategies completed within the transition phase on subsequent swimming performance has been investigated. Although warming-up is the most commonly utilised preconditioning strategy on competition day, the use of a morning exercise bout to potentiate later day performance is being increasingly utilised. Previous research indicates that an exercise bout consisting of sport-specific and non-specific resistance or sprint activities can enhance performance for up to 6 hr.\textsuperscript{53-55} It is possible that an intra-day priming effect might be advantageous to competitive swimmers, particularly those qualifying for the final in sprint events such as the 50, 100 and 200 m where heats and semi-finals take place in the morning and afternoon/evening of day one and finals are swum in the afternoon/evening of day two. At the Olympics and World Championships, coaches of swimmers qualifying for the final in these sprint events must decide whether to prescribe a morning exercise bout prior to racing later that day or to simply rest. Therefore, the aim of the study discussed within the following chapter was to determine whether a swimming specific morning exercise bout completed alone or in combination with non-specific resistance exercises influences sprint freestyle performance completed later that same day.

8.1.1 Research Objectives

1. Determine if completion of a morning exercise bout consisting of swimming exercise alone, or in combination with dryland-based exercises, enhances afternoon sprint swimming performance later that same day.

2. Quantify the influence of a morning exercise bout on physiological variables such as body temperature, heart rate and stroke characteristics including swimming stroke rate and length.
8.2 Submitted Manuscript

8.2.1 ABSTRACT

An exercise bout completed several hours prior to an event may improve competitive performance later that same day. Objectives: To examine the influence of morning exercise on afternoon sprint swimming performance. Methods: Thirteen competitive swimmers (seven male, 19 ± 3 y; six female, 17 ± 3 y; mean ± SD) completed a morning session of 1200 m of varied intensity swimming (SwimOnly), a combination of varied intensity swimming and a resistance exercise routine (SwimDry) or no morning exercise (NoEx). Following a six hour break, swimmers completed a 100 m time-trial. Results: Time-trial performance was faster in SwimOnly (1.6% ± 0.6%; mean, ± 90% confidence limits, p < 0.01) and SwimDry (1.7% ± 0.7%; p < 0.01) compared with NoEx. Split times for the 25-50 m distance were faster in both SwimOnly (1.7% ± 1.2%; p = 0.02) and SwimDry (1.5% ± 0.8%; p = 0.01) compared to NoEx. First 50 m stroke rate was higher in SwimOnly (0.70 ± 0.21 Hz, mean ± standard deviation; p = 0.03) and SwimDry (0.69 ± 0.18 Hz, p = 0.05) compared to NoEx (0.64 ± 0.16 Hz). Before the afternoon session, core (0.2°C ± 0.1°C; mean, ± 90% confidence limits, p = 0.04), body (0.2°C ± 0.1°C, p = 0.02) and skin (0.3°C ± 0.3°C; p = 0.02) temperatures were higher in SwimDry compared to NoEx. Conclusions: Completion of a morning swimming session alone or together with resistance exercise can substantially enhance sprint swimming performance later the same day.

8.2.2 INTRODUCTION

Elite coaches, sport scientists and strength and conditioning coaches invest considerable time and effort in the lead up to major swimming competitions ensuring athlete’s training and recovery strategies are appropriate to ensure optimal performance is attained on competition day. However, on competition day itself there are additional opportunities in which event performance might be improved by utilizing various preconditioning strategies. One such strategy involves the completion of an exercise bout several hours prior to a competitive event. Previous research has indicated that an exercise bout consisting of specific/non-
specific resistance or sprint activities can enhance subsequent performance for up to six hours post exercise bout completion.\textsuperscript{53-56} For competitive swimmers, this strategy is highly relevant.

In order for swimmers competing in events over the 50, 100 and 200 m distances to participate in the event finals, firstly swimmers must swim the morning heat session to qualify through to the afternoon/evening semi-final later that same day. Swimmers who subsequently qualify for the final via their semi-final performance, then compete in the afternoon/evening event final the following day. On the morning of the final, swimmers and their coaches then have to decide whether to complete a morning exercise session or simply rest prior to the finals event later that day. Anecdotal evidence from our group indicates that a number of swimmers choose to complete a morning swimming session prior to competing in a finals event later that same day. It is plausible that this is due to the habitual nature of swimming training in which typically swimmers complete an initial early morning (e.g. 06:00-08:00) and a second afternoon (16:00-18:00) swimming session. Given the competition timeline outlined above, it is pertinent to determine if completion of a morning swimming bout positively enhances afternoon swimming performance above that of a no-swim or rest condition (control).

Completion of a resistance exercise bout has been demonstrated to acutely enhance subsequent performance.\textsuperscript{143} Recent evidence also suggests that completion of a morning resistance exercise bout can positively influence afternoon sprint and resistance exercise performance.\textsuperscript{53,54,56} A movement-specific effect was also proposed, with completion of a morning sprint session enhancing afternoon sprint but not strength performance.\textsuperscript{54} It is possible this intra-day priming effect induced via morning resistance exercise completion may be advantageous to competitive swimmers. Thus, it would be useful to determine if combining a movement-specific morning swimming session with a bout of resistance exercise elicits additional incremental performance benefits to afternoon swimming performance.

Acute free testosterone levels are predictive of ensuing physical performance\textsuperscript{217,218} and completion of a morning sprint or resistance exercise bout can offset the circadian decline in serum testosterone concentration.\textsuperscript{54,56} It is also plausible that previously reported improvements in afternoon exercise performance could have been due to the manipulation of body temperature and/or changes to circadian rhythms. The influence of circadian rhythms on
exercise performance has been well documented\textsuperscript{57,58}, with substantial alterations in anaerobic physical performance (e.g. force and power) reported at different times of the day.\textsuperscript{58} Core temperature ($T_{\text{core}}$)\textsuperscript{60} and heart rate (HR)\textsuperscript{60} also exhibit circadian rhythmicity, with an early morning nadir and a subsequent peak in the late afternoon.\textsuperscript{58} Importantly, entering an exercise task with an elevated $T_{\text{core}}$ can enhance repeat-sprint performance and lower-body power output.\textsuperscript{38} Specifically in swimming, wearing a heated tracksuit jacket and completing a dryland-based exercise routine within the 30 min transition phase prior to a competitive race can offset the typical decline in $T_{\text{core}}$, permitting swimmers to enter an event with higher a $T_{\text{core}}$ and improving (~1.1%) subsequent sprint swimming performance.\textsuperscript{232}

Therefore, the aim of this study was to determine whether in comparison to a no morning exercise condition, completion of a morning exercise bout consisting of swimming exercise alone, or in combination with resistance exercise, elicits substantial improvements to same-day afternoon 100 m swimming performance. To ensure swimmers were optimally prepared, a standardised pool warm-up was completed (as is normal practice prior to a competitive race\textsuperscript{262}) and swimmers wore a heated jacket and undertook a dryland exercise routine during the 30 min transition phase prior to the race-simulated 100 m event.

8.2.3 METHODS

Subjects

Thirteen national level swimmers (n = seven males: age 19 ± 3 y, stature 1.77 ± 0.08 m, 71.0 ± 7.3 kg; n = six females: 17 ± 3 y, 1.72 ± 0.10 m, 60.7 ± 7.0 kg; mean ± standard deviation) were recruited. Swimmers provided written informed consent to participate in the study (parent/guardian consent was also obtained for all participants < 18 yrs) after being informed of the benefits and risks of the study. All participants were currently competing at national age-group level or above and had completed a minimum of six swim training sessions per week for three years. This study was approved by the University of Canberra’s Human Research Ethics Committee (approval number 15-06).
Design

In a randomised cross-over design, each swimmer completed three trials (SwimOnly, SwimDry, NoEx) involving a morning exercise bout followed by a six hour break and an afternoon 100 m time-trial using their most competitive stroke (Fig 6). All trials were completed within a one week period, separated by 48 hr, with morning sessions (lasting ~1 hr) undertaken at 08:30, and afternoon sessions (lasting ~1.5 hr) at 14:30. Each swimmer acted as their control. Familiarisation with the experimental protocols and equipment was completed in the week prior to the first testing session.

Methodology

Morning Session

In the morning session, swimmers arrived at the pool and following baseline measurements, completed one of three exercise bouts in a randomised counterbalanced order. In NoEx, no exercise was undertaken; swimmers presented themselves for baseline measurements only. In SwimOnly, 1200 m of variable intensity swimming involving stroke drills, turns and start practice was completed (Table 19). In SwimDry, 1200 m of varied intensity swimming was completed followed by a 10 min break then a 10 min resistance exercise routine. The routine involved two sets of the following exercises: 3 x 10 m running sprints from a stationary start (30 sec rest), 4 x tuck jumps – 2 x with a weight vest (6.5 kg; 10 sec rest) and 2 x unloaded (10 sec rest); 5 x handstand push-ups against wall with partner holding legs (continuous), 3 x 10 sec simulated underwater butterfly kick in a streamline position holding a BodyBlade® (Mad Dogg Athletics Inc., California, USA) oscillation device above the head (10 sec rest) and 3 x 3 kg medicine ball throw downs (10 sec rest). All exercises were completed at maximum effort with two min rest observed between sets. The prescribed exercises were chosen and adapted for pool-deck use in accordance with previously described methods.54,56,232

Afternoon Session

Following a six hour break in which swimmers were requested to rest wherever possible and avoid physical exertion (naps were not permitted); swimmers arrived at the testing pool for
the afternoon session. The participants were all currently studying at secondary school or university and had attended classes during the six hour break. After baseline measures were taken, swimmers completed a standardized pool warm-up (Table 19), followed by a 30 min transition phase and a 100 m time-trial (most competitive stroke). To limit the decline in body temperature during the transition phase, each swimmer wore a heated tracksuit jacket (City heated jacket, Venture heated clothing, Melbourne, Australia) and completed a brief dryland-based exercise routine as described previously (although tuck rather than box jumps were completed) between 21-16 min prior to the start of the time-trial. On completion of post-time-trial measurements, the swimmers completed a standardized pool warm-down totaling 800 m. The warm-down was standardized to ensure the total work done on each trial day was kept consistent.

Swimmers were requested to maintain the same nutrition (abstain from caffeine in the 12 hr prior) and sleep routine prior to each testing session, and refrain from completing heavy exercise (in the pool or gym) within two days prior and on the day of testing. With the assistance of the coach involved in the study, training volume and intensity were also kept consistent throughout the study duration. Quantitative feedback on 100 m time trial swimming performance (e.g. times and stroke characteristics) was deferred until the end of the study.

**Fig. 6 Schematic of testing session design.**
Pool warm-ups and time-trial swims were completed in a 50 m indoor pool (pool temperature 26.9 ± 0.3°C, air temperature 26.4 ± 2.4°C, relative humidity 45 ± 4%; mean ± SD). Split (25 m) and overall times were manually recorded by a national coach. Digital video cameras (Canon Legria FS21, Tokyo, Japan) positioned at the 5, 15, 25 and 45 m marks were used to determine start and turn times as well as mid-pool swimming velocity (m.s⁻¹), stroke rate (Hz), stroke length (m) and stroke efficiency index (m².stroke⁻¹.s⁻¹) for both time-trial laps through established methods.

Table 19. Standardised pool warm-up used for morning swimming session and prior to afternoon 100 m time trial.

<table>
<thead>
<tr>
<th>Distance</th>
<th>Stroke Type</th>
<th>Intensity</th>
<th>Rest</th>
</tr>
</thead>
<tbody>
<tr>
<td>300 m</td>
<td>FR</td>
<td>&lt; 50% HR_{max}</td>
<td>NA</td>
</tr>
<tr>
<td>200 m (drill)</td>
<td>Best Stroke</td>
<td>60% HR_{max}</td>
<td>10 sec</td>
</tr>
<tr>
<td>4 x 50 m</td>
<td>FR</td>
<td>50-70% HR_{max}</td>
<td>15 sec</td>
</tr>
<tr>
<td>4 x 50 m (2 x pull, 2 x kick)</td>
<td>Best Stroke</td>
<td>50-70% HR_{max}</td>
<td>15 sec</td>
</tr>
<tr>
<td>4 x turns (from/to 15 m line)</td>
<td>Best Stroke</td>
<td>80-90% HR_{max}</td>
<td>1 min (cycle)</td>
</tr>
<tr>
<td>4 x 25 m dive</td>
<td>Best Stroke</td>
<td>90-100% HR_{max}</td>
<td>1 min (cycle)</td>
</tr>
<tr>
<td>100 m</td>
<td>FR</td>
<td>50% HR_{max}</td>
<td>NA</td>
</tr>
</tbody>
</table>

FR freestyle, Best Stroke (stroke to be used in time-trial either backstroke or breaststroke or butterfly or freestyle) HR_{max} Heart rate max, PB personal best time, SR stroke rate

Ingestion of a temperature sensor (CorTemp™, HQ Inc., Palmetto, USA) permitted measurement of T_{core}. Total body temperature (T_{body}), capillary blood lactate concentration (La⁻¹, Lactate Pro, Arkray, Shiga, Japan), T_{core} and skin temperature (T_{skin}) were monitored and calculated according to established methods. Changes in swimmers HR were monitored via using Polar RS400 equipment (Polar Electro Oy Kempele, Finland). Using a thermal imaging camera (SC660, FLIR Systems, Inc., Oregon, USA), changes in surface heat patterns were assessed via images taken of each swimmer’s right trapezius muscle and right rectus femoris muscle (marked by a 50 mm by 50 mm square reference point). Subjective ratings of perceived exertion (RPE, Borg 6–20 scale) were taken following the pool warm-up, dryland routine and time-trial. We deemed it important to monitor each swimmer’s affective response to the morning priming and afternoon warm-up tasks, as positive affective responses are associated with improved subsequent uptake. The Feeling Scale is an 11-point scale (+5 very good, -5 very bad) used to assess affective valence and was used to record swimmer’s affective response to the tasks completed in the morning and afternoon testing sessions.
Statistical Analysis

Statistical analysis was performed using SPSS software (version 21; SPSS Inc., Chicago, USA) with significance set at $p \leq 0.05$. A sample size of 13 participants was deemed adequate for a post-only cross-over design assuming a smallest worthwhile change in time-trial performance of 0.40% for highly trained swimmers,\textsuperscript{242,243} a typical error of hand-timing of 0.36%\textsuperscript{256} and values of 5% and 75% for type I and II errors respectively. Effect size (ES) was calculated using Cohen d (value ranges of 0.2–0.6, 0.61–1.19 and > 1.20 were deemed small, medium and large effects, respectively). Precision of estimation was indicated with 90% confidence limits. To limit the effect of noise (from the different strokes used) when determining the differences in performance time, all raw time-based performance data was normalised against NoEx and analysed using a one-way within-subject analysis of variance (ANOVA) comparing the two intervention conditions (SwimOnly, SwimDry) relative to NoEx. Mean stroke characteristics were analysed using a one-way within-subject ANOVA. 

\[ T_{body}, T_{core}, T_{skin}, \bar{L}, HR, \text{RPE and swimmer's perceptual feelings} \] were analysed using a two-way repeated-measures ANOVA accounting for timing and condition.

8.2.4 RESULTS

Morning Session

There was no substantial difference between conditions in initial morning baseline measurements of $T_{body}$, $T_{core}$, $T_{skin}$, HR or thermal imaging values. Following completion of the morning pool session, $T_{core}$ was higher in SwimOnly ($0.9°C ± 0.4°C$; mean ± 90% confidence limits; $p < 0.01$, ES, 3.09) and SwimDry ($1.0°C ± 0.1°C$, $p < 0.01$, ES, 3.39) in comparison to NoEx. There was no significant difference between SwimOnly and SwimDry post pool session $T_{core}$ values ($p = 0.73$, ES, 0.11). After the resistance exercise routine was completed in SwimDry, $T_{core}$ values were also greater ($0.7°C ± 0.2°C$, $p < 0.01$, ES, 2.35) compared to NoEx. As the pool sessions were completed in “cold” water ($26.9 ± 0.3°C$, mean ± standard deviation), $T_{skin}$ values post pool session were lower compared to baseline values in both SwimOnly ($32.1°C ± 0.7°C$ versus $28.5°C ± 0.4°C$) and SwimDry ($32.3°C ± 0.6°C$ versus $28.3°C ± 0.6°C$). However, $T_{skin}$ increased by $1.9°C ± 0.7°C$ (mean ± 90% confidence
limits) following the resistance exercise routine in SwimDry. At the completion of the morning exercise bouts, SwimDry $T_{\text{skin}}$ values were significantly higher ($1.6^\circ C \pm 0.7^\circ C$, $p = 0.01$, ES, 3.39) in comparison to SwimOnly.

The swimming exercise elicited a ~2.3 mmol/L increase in La$^{-}$ and a ~50 beats per min (bpm) rise in HR in both the SwimOnly and SwimDry conditions. Capillary blood La$^{-}$ then declined by $0.7 \pm 0.3$ mmol/L (mean ± standard deviation) during the 10 min break between the swimming exercise and the start of the resistance exercise routine in SwimDry. Completion of the resistance exercise routine yielded a $0.5 \pm 0.1$ mmol/L increase in La$^{-}$ and a $37 \pm 6$ bpm rise in HR. Thermal imaging upper-body values were ~2°C higher following completion of the swimming exercise in SwimOnly and SwimDry in comparison to NoEx, with values still ~2°C higher than the NoEx condition after the resistance exercise was completed in SwimDry. Swimmers rated the pool session at ~12 points (“somewhat hard”) on the RPE scale and the resistance exercise routine as ~13 points (“somewhat hard”). Following completion of the swimming session in SwimOnly and completion of the resistance exercise routine in SwimDry, swimmers perceived feelings were similar, with swimmer’s reporting feeling “fairly good” to “good” on the scale.

Afternoon Session

Of the thirteen swimmers who participated in the study eight used freestyle for their 100 m time-trial, four utilized butterfly and one swimmer completed the time-trial using breaststroke. Afternoon time-trial performance was faster in SwimOnly ($1.6\% \pm 0.6\%$; mean ± 90% confidence limits, $p < 0.01$, ES, -0.73) and SwimDry ($1.7\% \pm 0.7\%$, $p < 0.01$, ES, -0.76) compared to NoEx. Split times for the 25-50 m distance were faster in both SwimOnly ($1.7\% \pm 1.2\%$, $p = 0.02$, ES, -1.16) and SwimDry ($1.5\% \pm 0.8\%$, $p = 0.01$, ES, -0.27) compared to NoEx, with 50-75 m splits also faster in SwimOnly ($1.6\% \pm 0.8\%$, $p < 0.01$, ES, -1.16) and SwimDry ($1.6\% \pm 0.7\%$, $p < 0.01$, ES, -0.79 (Fig. 7). Start times ($p$ value range: 0.36-0.44, ES range:-0.16-0.18) and turn times ($p$ value range: 0.29-0.39, ES range:-0.11-0.18) were similar between conditions. Stroke rate was higher in the first 50 m of the time-trial in the SwimOnly condition ($0.70 \pm 0.21$ Hz, mean ± standard deviation; $p = 0.03$, ES, 0.35) and SwimDry condition ($0.69 \pm 0.18$ Hz, $p = 0.05$, ES, 0.42) compared to NoEx ($0.64 \pm 0.16$ Hz). Greater mid-pool swimming velocity was detected within the first 50 m of the time-trial in SwimDry ($2.1 \pm 0.2$ m.s$^{-1}$) compared to NoEx ($1.9 \pm 0.2$ m.s$^{-1}$, $p = 0.03$, ES, 0.69) and
SwimOnly (1.8 ± 0.1 m.s⁻¹, p < 0.01, ES, 1.49). In the second 50 m of the time-trial, mid-pool velocity was also higher in SwimDry (1.9 ± 0.2 m.s⁻¹, p = 0.04, ES, 0.71) in comparison with NoEx (1.7 ± 0.2 m.s⁻¹).

Prior to the afternoon session, higher readings for Tcore (0.3°C ± 0.2°C mean ± 90% confidence limits; p = 0.03, ES, 1.03), Tskin (0.7°C ± 0.3°C, p = 0.01, ES, 0.78) and Tbody (0.2°C ± 0.1°C, p < 0.01, ES, 1.74) were recorded in the NoEx trial compared with morning baseline measurements. Substantially higher pre-afternoon session readings were recorded for Tcore (0.2°C ± 0.1°C, p = 0.04, ES, 0.60), Tbody (0.2°C ± 0.1°C, p = 0.02, ES, 0.69) and Tskin (0.3°C ± 0.3°C, p = 0.04, ES, 0.52) in SwimDry compared to NoEx. Pre-afternoon session SwimDry Tcore (0.1 ± 0.2°C, p = 0.15, ES, 0.49), Tbody (0.3 ± 0.2°C, p = 0.04, ES, 0.69) and Tskin (0.4 ± 0.3°C, p = 0.03, ES, 0.73) readings were also higher in comparison with SwimOnly values. The Tcore values were also substantially higher immediately prior to the time-trial in SwimDry (0.6°C ± 0.3°C, p = 0.03, ES, 1.83) in comparison with NoEx (Fig. 8A).

HR values were higher following the pool warm-up in SwimDry (11 ± 6 bpm, p = 0.01, ES, 0.63) compared with NoEx. No difference in HR values between conditions was recorded prior to the time-trials. Thermal imaging upper-body values rose by ~0.7°C and lower-body values by ~0.5°C when the dryland routine was completed in all three conditions prior to

**Fig. 7** 25 m split times recorded throughout the 100 m time-trial. Data are presented as mean ± standard deviation. Significantly different to NoEx *p ≤ 0.05.
entering the simulated marshalling period. Swimmer’s perceived feelings prior to the afternoon session and the 100 m time-trial were similar between conditions, with swimmer’s reporting feeling “fairly good” to “good” on the scale.

![Graph showing changes in core and skin temperature](image)

**Fig. 8** Changes in core (A) and skin (B) temperature from morning baseline to pre 100 m time-trial, for the NoEx, SwimOnly and SwimDry conditions. Data are presented as mean ± standard deviation. SwimDry condition significantly different to NoEx condition * p ≤ 0.05.

### 8.2.5 DISCUSSION

Afternoon sprint swimming performance was enhanced when a morning exercise bout consisting of swimming exercise alone (~1.6%) or in combination with dryland-based resistance exercises (~1.7%) was undertaken. Elevations in swimming stroke rate and
velocity during the initial stages of the time-trial as well as higher body temperatures prior to the afternoon session likely contributed to the improved performance time. Inclusion of a morning exercise bout comprising either swimming alone, or swimming in combination with resistance-exercise, should be considered for a swimmer’s competition day preparations.

Overall time-trial performance was marginally faster in SwimDry compared to SwimOnly. One possible explanation for this finding is that mid-pool swimming velocity was ~0.2 m.s\(^{-1}\) higher in SwimDry in comparison to SwimOnly in the first 50 m of the time-trial. Proficient technical swimming ability is associated with optimal high-intensity performance.\(^{260}\) Swimming velocity is the product of stroke rate and the distance travelled with each stroke cycle\(^{235}\) and higher stroke rates are typically associated with increases in swimming velocity.\(^{199}\) Therefore, the higher stroke rates recorded during the first 50 m within the SwimOnly and SwimDry trials and the second 50 m within SwimDry, may partially explain the faster overall time-trial performances recorded in these conditions. These outcomes support recent work demonstrating a movement-specific priming effect following same-day prior exercise completion, with a morning sprint exercise bout reported to enhance afternoon sprint though not strength performance.\(^{54}\)

Completion of the SwimOnly and SwimDry morning exercise bouts yielded a ~1°C increase in \(T_{\text{core}}\). This outcome is consistent with a report that a 1300 m pool warm-up elicits a ~0.7°C increase in \(T_{\text{core}}\).\(^{232}\) Physiological markers such as \(T_{\text{core}}\) also exhibit circadian rhythmicity with an early morning nadir and a subsequent peak in the afternoon. Our data also showed a similar pattern with \(T_{\text{body}}\) (~0.2°C), \(T_{\text{core}}\) (~0.3°C) and \(T_{\text{skin}}\) (~0.7°C) readings higher in NoEx prior to the afternoon session compared to morning baseline measurements. Within the SwimDry condition, \(T_{\text{body}}\), \(T_{\text{core}}\) and \(T_{\text{skin}}\) were substantially higher prior to the afternoon session in comparison to NoEx.

Metabolic rate can remain elevated by ~9% for up to 15 hr following exercise,\(^{266}\) with a dose-response relationship reported between the intensity and the duration of the exercise bout completed and the subsequent increase in metabolic rate.\(^{267}\) Elevated muscle temperature (\(T_{\text{muscle}}\), is also partially responsible for increases reported in recovery energy expenditure.\(^{268}\) Although \(T_{\text{muscle}}\) was not able to be measured, given the inclusion of high-level swimmers, changes in \(T_{\text{core}}\)\(^{16}\) and \(T_{\text{skin}}\)\(^{8}\) have been correlated with changes in \(T_{\text{muscle}}\). Thus, the swimming and resistance exercise completed in the morning within the SwimDry
condition may have elicited an increase in metabolic rate which possibly continued to remain elevated throughout the day, providing a plausible explanation for the higher $T_{body}$, $T_{core}$ and $T_{skin}$ readings recorded prior to the afternoon session. Importantly, $T_{core}$ remained elevated throughout the afternoon session in the SwimDry condition, with $T_{core}$ still higher immediately prior to the 100 m time trial in SwimDry compared to NoEx. The difference in $T_{core}$ readings between the SwimDry and NoEx conditions prior to the time-trial was ~0.6°C which is practically significant given undertaking an exercise task with only a slightly elevated $T_{core}$ (~0.3°C) can improve peak power output as well as repeat-sprint performance.\(^{38}\)

Interestingly, although overall performance times were similar between the SwimOnly and SwimDry conditions, $T_{body}$, $T_{core}$ and $T_{skin}$ values were all higher prior to the afternoon session in SwimDry. Therefore it is plausible that alterations in body temperature may not be the sole mechanism contributing to the faster performance times recorded in the SwimOnly and SwimDry conditions. Completing a postactivation potentiation (PAP) stimulus can improve subsequent performance by enhancing motor unit recruitment.\(^{269}\) However, the effects of this traditional PAP-associated mechanism may diminish 8 min following a PAP stimulus.\(^{143}\) Secondary mechanisms such as hormonal changes and lowered anxiety though may contribute to enhanced performance over a longer timeframe.\(^{54,55}\) Salivary testosterone concentration has been highly correlated with sprint performance ($r = -0.87$) in elite strength athletes.\(^{218}\) Testosterone levels typically peak in the early morning before slowly decreasing throughout the day.\(^{57}\) Completion of a morning sprint or resistance exercise bout can offset the circadian decline in serum testosterone concentration and enhance lower-body power output and repeat-sprint performance for up to 6 hr post bout.\(^{54,56}\) However, from this preliminary work it remains unclear whether such hormonal changes are directly related to subsequent afternoon performance improvements or are merely reflective markers.

The participating swimmers had experience in preparing for afternoon/evening finals races and they habitually trained twice per day, in the morning and in the afternoon. However the participating swimmer’s chronotype was not assessed nor was the female participant’s time of the month with regards to the menstrual cycle monitored. We acknowledge these are limitations of the present study and future studies should consider both of these factors. Further research is also required to fully elucidate the physiological mechanisms (e.g. changes in testosterone concentrations) responsible for the enhancement of afternoon sprint
swimming performance. It would also be of interest to assess whether completion of a
morning exercise bout positively influences afternoon lower and upper body power output
responses and in turn swim start characteristics (e.g. horizontal velocity), which are known to
be acutely enhanced following a resistance exercise bout.\textsuperscript{29} The influence of a morning swim,
or early afternoon swim, on evening performance also requires investigation given the finals
of most international competitions are held between 17:00-21:00.

8.2.6 CONCLUSIONS

Swimming coaches can be advised that completion of a morning exercise bout consisting of
swimming exercise alone, or in combination with dryland-based resistance exercises, can
enhance competitive sprint performance later that same day by \textasciitilde1.6-1.7\%. Enhancement of
stroke rate and swimming velocity during the initial stages of the time-trial as well as higher
body temperatures prior to the afternoon session likely contributed to the improvement in 100
m time trial performance.

8.2.7 PRACTICAL APPLICATIONS

Swimmers who qualify through to the afternoon/evening final must decide whether to
complete a morning training session or simply rest without any exercise. It is also common
for high-level swimmers to train twice per day, with benchmark time-trials and high-intensity
training sets typically completed in the afternoon session. We have presented preliminary
evidence which suggests that completion of a swimming only or swimming and resistance
exercise bout 6 hr prior to a sprint swimming event can substantially improve performance
above that of a no morning exercise condition.
CHAPTER 9: Discussion, practical outcomes, future directions, limitations and conclusions

9.1 DISCUSSION

This thesis investigated the influence of competition day preconditioning strategies on sprint performance in high-level swimmers. Analysis of current elite swimming coach warm-up practices and situational challenges faced by high-level swimmers and their coaches within the competition environment was used to inform a number of experimental investigations. The duration of the transition phase was identified as a major factor which could potentially eliminate some of the benefits of current pool warm-ups. A number of new warm-up strategies were developed to ensure that the elevated body temperature and muscle activation achieved through pool warm-up completion was maintained during the transition phase. The wearing of heated tracksuit jackets and completion of dryland-based exercise routines during the transition phase significantly improved sprint freestyle performance in both junior (~1.1%) and senior elite (~0.8%) swimmers. However a similar combination additional warm-up strategy utilising heated tracksuit pants and dryland-based exercise routines did not improve elite senior breaststroke performance. Preliminary evidence was also presented demonstrating that completion of a morning exercise bout consisting of swimming exercise alone (~1.6%), or in combination with dryland-based resistance exercises (~1.7%), can enhance sprint swimming performance completed later that same day. The major findings of this thesis are summarised in Fig 9.

9.1.1 Current warm-up practices utilised by elite swimming coaches

Elite swimming coaches identified four key objectives of the pre-competition warm-up: 1) To increase body temperature and muscle activation (physiological preparation), 2) To increase swimmers “feel” of the water and familiarise swimmers with start blocks and walls (kinaesthetic/tactile preparation), 3) To practice race-pace (tactical preparation), and 4) To improve focus and reduce anxiety (mental preparation), with the first two deemed the most important.
**Fig. 9 Summary of thesis findings**

<table>
<thead>
<tr>
<th>Preconditioning Strategy Type</th>
<th>Preconditioning Strategy Details</th>
<th>Performance Benefits (versus control)</th>
<th>Physiological Benefits (versus control)</th>
<th>Biomechanical Benefits (versus control)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Morning Exercise Bout</strong></td>
<td>1160 m of varied intensity swimming including stroke-specific drills + a set of 4 x 15 m out/back turns + 4 x 25 m dive race-pace efforts</td>
<td>OT 1.6%, 25-50m 1.7%, 50-75m 1.6% faster</td>
<td>Morning T-core 0.9°C higher</td>
<td>1st 50 m SR 0.6 Hz + SV 1.8 m.s(^{-1}) higher</td>
</tr>
<tr>
<td>(completed 6 hr prior to time-trial)</td>
<td><strong>SwimOnly</strong></td>
<td></td>
<td>Morning La 2.5mmol higher</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>SwimDry</strong></td>
<td>OT 1.7%, 25-50m 1.5%, 50-75m 1.6% faster</td>
<td>Morning T-core 1.0°C higher</td>
<td>1st 50 m SR 0.5 Hz + SV 2.1 m.s(^{-1}) higher</td>
</tr>
<tr>
<td></td>
<td>Pool exercise as per SwimOnly + Resistance exercise routine: running sprints, weighted/un-weighted tuck jumps, push-ups, simulated butterfly kick, MB throw downs</td>
<td></td>
<td>Afternoon T-core 0.2°C higher</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Pool Warm-Up</strong></td>
<td></td>
<td>Afternoon T-skin 0.3°C higher</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100 m: ~1400 m varied intensity swimming including stroke-specific drills + 3 x 25 m dive race-pace efforts</td>
<td>Race-pace rehearsal</td>
<td>Increased body temperature + muscle activation</td>
<td>Increased tactile “feel of water”</td>
</tr>
<tr>
<td></td>
<td>200 m: ~1650 varied intensity swimming including stroke-specific drills + 4 x 50 m dive race-pace efforts</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>400 m: ~1900 varied intensity swimming including stroke-specific drills including 4 x 100 m dive race-pace efforts</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Dryland Warm-Up</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Routine completed on pool-deck involving various exercises such as skipping, core activation exercises, jumps, arm/leg swings, upper-body stretch cord exercises</td>
<td></td>
<td>Increased body temperature + muscle activation</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Additional Warm-Up Strategies</strong> (completed during 30 min transition phase)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Passive</strong></td>
<td>JF: OT 0.4%, Start 0.2%, 25-50m 0.5%, Turn 1.2% faster</td>
<td>JF: T-core limited to 0.6°C decline in transition, T-skin 0.9°C higher pre TT</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Initial active, 1160-1350 m pool warm-up including 2-4 x 25 m dive race-pace efforts + heated tracksuit jacket worn during transition</td>
<td>JF: SI 0.2 m(^2).stroke(^{-1}).s(^{-1}) higher</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Dryland</strong></td>
<td>JF: OT 0.7% faster, Turn 1.3% faster</td>
<td>JF: T-core limited to 0.2°C decline in transition</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pool exercise as per Passive + 3 x: medicine ball throw downs, 10 sec simulated butterfly kick, box/tuck jumps, completed prior to 15 min marshalling</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Combo</strong></td>
<td>JF: OT 1.1%, Start 0.4% faster</td>
<td>JF + SF: T-core limited to 0.1-0.2°C decline in transition. SF: tHb=51 µM higher, T-core 0.3°C higher pre TT. SB: T-core=0.1°C decline in transition (p=0.36), T-skin 1.0°C higher pre TT.</td>
<td>SF: LB PPO = similar pre TT (p=0.84), SB LB PPO: similar (p=0.4)</td>
</tr>
<tr>
<td></td>
<td>Pool + Dryland exercise as per Passive + Dryland</td>
<td>SF: OT 0.8%, Start 1.5% faster</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Heated tracksuit jacket (freestyle) or pants (breaststroke) worn during transition</td>
<td>SB: OT = similar (p=0.55)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Results in reference to control condition*
There is good evidence\textsuperscript{3,3,223} that athletes competing in sprint and short (< 2 min) sustained high-intensity events are likely to obtain an advantage from a warm-up-induced increase in body temperature. However the tactile preparation afforded to swimmers completing a pool-based warm-up is likely to be useful for swimmers competing over all distances. This is could be one explanation as to why the surveyed swimming coaches stated they preferred to prescribe pool-based warm-ups over dryland exercises to provide swimmers with an opportunity to gain a “feel” for the water and familiarise themselves with the start blocks and walls.

Everyday activities such as eating and sleeping can cause slight miscalibration of the human body’s sensorimotor network.\textsuperscript{270} Undertaking of specific-sport-skill practice can restore the network to its previous level of expertise.\textsuperscript{270} Therefore, completion of a pool warm-up may enable swimmers to recalibrate their sensorimotor networks back to the level of expertise required for optimal performance. The coaches also prescribed a set of race or near race-pace efforts towards the end of the pool warm-up to permit swimmers to gain a feel for the pacing to be used in the upcoming race. Completion of at least one set of race-pace efforts during the pool warm-up is necessary to sufficiently prime swimmers for an upcoming sprint swimming event.\textsuperscript{5,163}

The structural template of the dryland and pool warm-ups provided by the elite coaches was similar regardless of the race distance to be swum (100, 200 or 400 m freestyle). Initially, a dryland-based warm-up consisting of leg/arm swings, single-arm rows using stretch cords, skipping, core activation exercises and jumps was prescribed prior to the pool-based warm-up. A dryland-based warm-up consisting of heavy resistance exercises such as lunges, YoYo squats,\textsuperscript{44} and back squats\textsuperscript{29} resulted in faster\textsuperscript{44} or similar\textsuperscript{29} swimming performances to that of a pool-based warm-up. However, completing these heavy resistance exercises within a competition setting is likely un-feasible. Combinations of ballistic-exercises such as calisthenics and skipping\textsuperscript{19} or skipping, vertical jumps and swimming wall push-offs\textsuperscript{28} can produce similar subsequent performances to that of a pool-based warm-up. Given that the surveyed coaches stated the dryland warm-up was typically completed on pool deck, competitive swimmers require the prescription of specific exercises that satisfy the aims of the pre-competition warm-up, involve minimal equipment, and can easily be completed within a confined area. These situational factors are important considerations for strength and conditioning coaches consulting with high-level swimming squads.
Following the dryland warm-up, the surveyed coaches prescribed a pool warm-up entailing a period of continuous, low-intensity swimming, a set of specific stroke drills, one-two sets of increasing intensity efforts and finally, several race or near-race pace efforts. Total pool warm-up volume varied with race distance with ~1400 m prescribed for the 100 m distance ~1650 m for the 200 m and ~1870 m for the 400 m distance. A pool warm-up totalling ~1000-1500 is sufficient for achieving optimal swimming performance in 100-400 m events, with longer warm-ups reported to negatively impact sprint performance.

Presumably, to ensure sprint performance was not compromised, coaches reported that sprint swimmers were required to perform fewer and shorter efforts throughout the warm-up. For example, coaches requested the set of race or near race pace efforts completed towards the end of the pool warm-up be shorter in length (25-50 m efforts) than those completed prior to the longer (200-400 m) race distances (50-100 m efforts).

Interestingly, the surveyed coaches reported that the race or near race-pace efforts completed towards the end of the pool warm-up were to be done from a dive start and not an in-pool wall push-off. This activity could partially fulfil the kinaesthetic objective of the pre-competition warm-up, increase muscle fibre recruitment and enhance mental preparedness. In cyclists, the high muscle fibre tension produced during performance of a standing start preferentiates the recruitment of type II muscle fibres. Improvements in central nervous system activation, such as enhanced motor recruitment are associated with enhanced short-duration-task performance following completion of a PAP stimulus. Increasing motor unit recruitment, such that the ‘strain’ placed on each individual muscle fibre is reduced, would potentially be of benefit to all swimmers, though in particular, sprint swimmers who possess a higher proportion of type II muscle fibres. Future research should investigate if race or near-race pace efforts completed from a dive start increase motor unit recruitment above that of an in-pool wall push-off and whether this increased motor unit recruitment leads to faster subsequent sprint swimming performance.
9.1.2 Challenges faced by elite coaches and their swimmers during the final race preparation phase

The surveyed coaches identified several issues which may compromise the benefits of the dryland and pool warm-ups. The first of these was the lengthy time required to don a race swimsuit. In the past 20 years race swimsuits have altered dramatically, primarily in a bid to reduce the drag (skin friction drag, pressure drag and wave drag) experienced by swimmers moving through the water. Loose fitting swimsuits can increase drag in comparison to tight fitting suits and thus due in part to enhancements in compression garment technology, racing swimsuits have become increasingly form fitting. As a result, these suits are difficult to put on, with the surveyed coaches reporting swimmers take ~10 min to get into their race swimsuit. Although there is evidence to suggest that swimming performance is not enhanced when these high-tech swimsuits are worn, there is anecdotal reports from swimmers stating they ‘feel’ faster when they wear these suits. Given the placebo effect is linked with substantial improvements in athletic performance, swimmers will likely continue to utilise these high-tech swimsuits. Therefore, swimming coaches must allow sufficient time (~10 min) following completion of the pool warm-up for their swimmers to don a race swimsuit. However, given the different swimsuits worn by male (shorts only) and female (combination of traditional swimsuit design and shorts) swimmers, males may require less time than females.

The second issue identified by the elite coaches was delays in the competition schedule. Though frustrating, it is difficult to predict when these delays will occur and how long they will last. Therefore, coaches and athletes must rely on their previous experience in an attempt to work around these delays. As an aside, for swimmers competing in multiple events within a heats or finals session, it may be possible to utilise passive heat maintenance strategies such as a heated tracksuit jacket to maintain elevated body temperature during breaks between races. Recently in rugby, wearing a blizzard survival jacket during a 15 min half-time break was shown to improve $T_{core}$ maintenance and subsequently enhance lower-body peak power output (~3.2%) and mean total repeat-sprint performance (~1.4%). Caution should be exercised though to ensure application of additional passive heat does not adversely affect swimmers’ thermal tolerance nor result in dehydration. Future research is required to
determine how long heated tracksuit jackets can be worn and the upper temperature setting that can be tolerated before swimming performance is negatively impacted.

The final issue identified by the surveyed coaches concerned the length of the marshalling period and the overall duration of the transition phase. Upon finishing the pool warm-up, swimmers change into their race swimsuit, receive any final coach communications and proceed to the marshalling area. The coaches reported that these activities typically take ~18 min with swimmers proceeding to marshalling, lasting ~15-20 min, immediately afterwards. Considering these lengthy marshalling periods and the time required to don a race suit (~10 min) as well as unexpected delays in the competition schedule, transition phases of ~30-40 min are not uncommon in competitive swimming. The coaches expressed their concern that as a consequence of these lengthy transition phases swimmers may “cool” down and/or begin to feel “flat”, subsequently resulting in a negative impact on swimming performance. Indeed $T_{\text{muscle}}$ can decline immediately following the cessation of exercise, with a marked reduction occurring ~15-20 min after exercise termination.\textsuperscript{16} In addition, transition durations of 7–10 min have been deemed optimal for eliciting peak power outputs in experienced individuals following a PAP stimulus.\textsuperscript{50-52} Therefore, it is critical that new practical methods are developed to assist swimmers to maintain elevated body temperature and muscle activation throughout lengthy transition phases. As was demonstrated within the experimental chapters within this thesis, swimmers can utilise strategies such as passive heat maintenance, via heated athletic garments, and additional dryland-based warm-up exercises during the transition phase, to mitigate the negative effects of lengthy transitions.

9.1.3 Additional warm-up strategies – Passive heat maintenance

Following completion of a pool warm-up, wearing a heated jacket during a 30 min transition phase was shown to limit the decline in $T_{\text{core}}$ to ~0.4°C compared to ~0.6°C when no additional passive heat was provided. Although the difference in the decline in $T_{\text{core}}$ within the heated jacket condition was not significantly less than that of the control (no jacket) condition, both start (~0.2%) and overall junior 100 m freestyle performance (~0.4%) were still marginally faster when the heated jackets were worn during transition. Given the swim start at the international competitive level contributes up to 30% of total race performance
time, using heated tracksuit jackets as passive heat maintenance devices during the transition phase appears to be a worthwhile strategy.

The $T_{\text{core}}$ and performance results reported in the junior freestyle study are consistent with previous work in professional rugby, demonstrating an improvement in lower-body peak power output and performance in a repeat-sprint task after blizzard survival jackets were worn during transition. However, the decline in $T_{\text{core}}$ within each of these studies was less (~0.1-0.2°C) than reported in the junior freestyle study when the heated jackets were worn (~0.4°C). One possible explanation for this outcome is that the transition phase duration used in the rugby studies was much shorter (15 and 20 min) in comparison with the 30 min transition phase used in the junior freestyle study.

Finally, in junior swimmers, $T_{\text{skin}}$ immediately prior to the 100 m time-trial was substantially higher (~0.9°C) when the heated jackets were worn within the transition phase. High-velocity movements (e.g. swim start) are more temperature-dependent than low-velocity movements with the rate of deterioration in muscle performance strongly associated with reductions in $T_{\text{muscle}}$. Changes in $T_{\text{skin}}$ are correlated with changes in $T_{\text{muscle}}$, and thus it is plausible that the heated jackets contributed to improved start times through elevated $T_{\text{muscle}}$ immediately prior to the time-trial.

### 9.1.4 Additional warm-up strategies – Dryland-based exercises

The impact of an additional dryland-based exercise routine was assessed in three experimental studies within this thesis. The exercises contained within the routine were designed in such a way as to mimic common swimming movements in a sequence replicating the kinetic chain of a swim start. The chosen exercises specifically targeted both the upper and lower-body and were designed to be completed in a small space using portable equipment. It was important to ensure the movements executed as part of these exercise tasks replicated as closely as possible those to be completed in the subsequent 100 m freestyle time-trial as a movement-specific relationship exists between exercises undertaken as part of a PAP protocol and those completed in a subsequent criterion task. This was recently exemplified in rugby players when a series of back squats was shown
to potentiate vertical jump but not sprinting nor sled pull performance. The routine was completed just prior to entering the marshalling period (15 min prior to time-trial start) and resulted in a smaller decline in $T_{core}$ during the transition phase, and a substantial improvement in junior sprint freestyle performance, in comparison to when the routine was not undertaken. This observation is consistent with data indicating that undertaking a dryland-based exercise routine during a football halftime break can attenuate $T_{core}$ decline. Completion of the dryland routine elicited a smaller decline in $T_{core}$ ($0.2^\circ C$ vs. $0.4^\circ C$) than that reported following passive heat maintenance (via the heated tracksuit jackets) and this translated to faster 100 m time-trial performance (dryland routine: $\sim0.7\%$, heated jackets: $0.4\%$, in comparison to a control condition).

Within the dryland routine, body weight box/tuck jumps were included in order to improve lower-body power output. An improvement in short-duration tasks (i.e. sprinting, jumping) has been shown when bodyweight CMJ and drop jumps or tuck jumps are completed during the warm-up. Improvements in lower-body power output are also associated with faster freestyle swim start times, though heavy-resistance exercises were used to induce a PAP response in that particular study. Although elite senior freestyle start time performance was faster when the dryland routine was completed in conjunction with the wearing of the heated jackets, an improvement in lower-body power output was not reported. There are two plausible explanations for this non-improvement in lower-body power output. First, the transition phase duration between dryland routine completion and time-trial start (15 min) may have blunted any PAP response that was induced. Secondly, the intensity (i.e. the load moved) of the lower-body exercises, box/tuck jumps, may not have been sufficient to induce a PAP response strong enough to be carried through to race start.

The inclusion of bodyweight tuck jumps into a dryland-based warm-up has been demonstrated to acutely enhance CMJ height, though only when a 5 min transition phase is observed. Anecdotal evidence from our group and others, and the information collected from the elite swimming coach survey presented within this thesis, suggest that the duration of the marshalling period is typically 15-20 min and swimmers are required to remain relatively inactive during this time. Therefore, although bodyweight tuck jumps can enhance subsequent performance and an 8 min transition phase is deemed optimal for transferring the benefits of a PAP stimulus, completion of activities within 15 min prior to racing (i.e. the marshalling period) in an actual swimming competition is not feasible. It was paramount
within the experimental studies contained within this thesis to ensure close replication with the competition timeline and as such a 15 min marshalling period was observed within the four intervention studies.

Improvements in power production can occur up to 18.5 min following a PAP stimulus, though warm-up exercises need to be completed with additional load. By increasing the load moved by the swimmers during the dryland routine, it may be possible to increase the magnitude of the PAP response induced such that any induced beneficial effects (e.g. enhanced central output to motor neurons, increased reflex electrical activity in the spinal cord and phosphorylation of myosin regulatory light chains) can be carried through a 15 min marshalling period and into an event. Tuck, drop and depth jumps completed while wearing a weight vest of 2-20% body mass prior to a 20 min transition phase can enhance, or at least limit the decline in lower-body power output and CMJ height. Therefore, in swimmers it may be possible to improve (or at least limit the decline which occurs during a transition phase) lower-body power output by ensuring the tuck jump exercise in the dryland routine is completed with a weight vest of up to 20% body mass.

9.1.5 Additional warm-up strategies – Combination, passive heat maintenance and dryland-based exercises

In junior freestyle swimmers the Combo additional warm-up strategy, passive heat maintenance (via heated tracksuit jackets) and completion the of a dryland-based exercise routine, was deemed the best strategy of those examined for improving $T_{core}$ maintenance during the transition phase and subsequently enhancing sprint swimming performance (by 1.1%). A similar outcome was also evident in senior elite freestyle swimmers with 100 m time-trial performance 0.8% faster following Combo strategy use. However, elite sprint breaststroke performance was not improved when a Combo additional warm-up strategy involving heated tracksuit pants and completion of a dryland-based exercise routine was undertaken within the transition phase.

To remain in contention for a medal, Olympic swimmers need to improve their performance by ~1% within the year prior to competition. Research suggests that various training
interventions are capable of eliciting at least a ~1% improvement in performance, but an additional ~0.3-0.4% improvement is needed to substantially increase a swimmer’s chances of winning a medal at the elite level. Thus, any interventions which yield performance improvements of the magnitude reported in the junior (~1.1%) and senior (~0.8%) freestyle studies discussed within this thesis could potentially alter the final race outcome.

When the Combo strategy was completed, the decline in T_core during the 30 min transition phase was ~0.1°C in junior swimmers and ~0.2°C in the senior swimmers. The decline in T_core following the Combo strategy was smaller than that reported when the heated tracksuit jackets were worn alone (~0.4°C), though similar to that recorded when the dryland routine was completed separately (~0.2°C) in the junior freestyle study. The magnitude of the decline in T_core during the transition phase was also slightly greater within the senior versus junior swimmers, possibly due to the senior swimmers completing their time-trials in an outdoor pool compared to an indoor pool used in the junior’s investigation.

The smaller decline in T_core elicited by the Combo strategy was also correlated with faster junior freestyle time-trial performance (R² = 0.91; p = 0.04). In addition, in elite senior freestyle swimmers although T_skin declined from pre to post pool warm-up in both conditions including Combo, the rise in T_skin during the transition phase was substantially greater in Combo (~2.2°C) in comparison to Control (~1.3°C). To date only one other study has investigated the influence of completing a combination additional warm-up strategy, passive heat maintenance plus additional dryland-based exercises, within the transition phase on rugby-related performance. The findings of this particular study were in line with those described in the junior and senior freestyle investigations, with completion of the additional warm-up strategies associated with only a ~0.1-0.2°C decline in T_core and the subsequent enhancement of CMJ and repeat-sprint performance.

Immediately prior to the time-trials completed by the junior and elite senior freestyle swimmers, T_core and T_skin were elevated (by ~0.3°C and by ~1.2-1.5°C respectively, in comparison to Control) when the Combo strategy was completed. As discussed previously, elevated body temperature immediately prior to a competitive event is beneficial for athletes competing in sprint and short-duration tasks. Although T_muscle was not measured within the studies contained in this thesis, due to the examination of high-level swimmers, changes in T_core and T_skin correlated with changes in T_muscle. Therefore, it is plausible that
the higher \( T_{\text{core}} \) and \( T_{\text{skin}} \) readings recorded immediately prior to the freestyle time-trial correlated with higher \( T_{\text{muscle}} \) readings and this in turn may have contributed to the faster start times recorded in Combo (~0.4% in juniors, ~1.5% in seniors).

An additional explanation for the improvement in start time performance recorded following Combo strategy completion may have stemmed from an enhancement in upper-body power output, given the inclusion of upper-body-focused exercises within the dryland routine (e.g. medicine ball throw downs). Within the freestyle stroke, the muscles of the upper-body are primarily responsible for driving a swimmer’s propulsion through the water.\(^{260,279}\) However this can only be speculated as upper-body power output was not measured in either the junior or senior freestyle studies.

In senior sprint freestyle swimmers, completion of the Combo strategy resulted in notably higher local (trapezius) \( \text{tHb} \) concentration and \( \text{Hb}_{\text{diff}} \) values throughout the transition phase, with substantially greater values recorded prior to the time-trial in comparison with Control. These outcomes coincided with the significant improvements in \( T_{\text{core}} \) maintenance and a substantial rise in \( T_{\text{skin}} \) within the transition phase in Combo. At higher body temperatures blood flow to working muscles is improved.\(^ {196,249}\) Changes in \( \text{tHb} \) concentration are also a gross representation of alterations in blood flow,\(^ {259}\) and thus higher local \( \text{tHb} \) concentrations may positively affect local tissue metabolism. Therefore, it is plausible that the greater local \( \text{tHb} \) and \( \text{Hb}_{\text{diff}} \) values prior to the time-trial in Combo may have positively influenced performance by ensuring a better \( O_2 \) supply to working muscles within the swimming time-trial.

In the junior and senior freestyle-focused studies, targeted upper-body passive heating via heated tracksuit jackets, combined with the completion of dryland-based exercises within a 30 min transition yielded substantially faster 100 m time-trial performance. Unlike freestyle swimmers who derive propulsion primarily from their arms,\(^ {260}\) breaststroke swimmers rely equally upon their arms and legs for propulsion through the water.\(^ {261}\) Previous research in cycling has revealed that combining an active cycle ergometer warm-up with the application of passive heat (via heated tracksuit pants) during a 30 min transition can improve \( T_{\text{muscle}} \) maintenance and power output during a subsequent sprint cycling task.\(^ {35,36}\) However, the outcomes of the breaststroke investigation are in opposition to these findings as well as those reported in both junior and senior sprint freestyle swimmers in this thesis.
Neither start nor overall 100 m breaststroke time-trial performance was faster when the Combo additional warm-up strategy (passive heating provided via heated tracksuit pants) was undertaken. It was unclear \((p = 0.36, ES, 0.65)\) whether the Combo strategy \((-0.1 \pm 0.2^\circ C; mean \pm 90\% confidence limits)\) elicited an improvement in \(T_{core}\) maintenance within the transition phase above that of the Control condition \((-0.3 \pm 0.2^\circ C)\). However, \(T_{skin}\) values immediately prior to the time-trial were higher \((\sim 1.0^\circ C)\) when the Combo strategy was completed, though this alone did not appear sufficient to elicit faster performance times in the Combo condition in comparison to Control. These temperature-related findings in part concur with results demonstrating that when heated tracksuit pants were worn by cyclists during a 30 min transition, \(T_{muscle}\) (known to follow a similar time course as \(T_{core}^{16}\) and \(T_{skin}^8\)) prior to a criterion task was elevated, though \(T_{core}\) was not maintained during the transition phase.\(^{35}\) Furthermore, application of heated tracksuit pants alone (i.e. not combined with a heated jacket) was also not shown to attenuate the decline in \(T_{muscle}\) during a 12.5 min transition phase in football players.\(^{280}\)

One possible explanation for the absence of an improvement in \(T_{core}\) maintenance within the transition phase in the breaststroke study is that the surface area covered by the heating elements was inadequate. The number of leg muscles covered by the heating elements was higher in an earlier study (six per leg)\(^{35}\) versus the breaststroke investigation (three per leg), though the heating elements within the breaststroke investigation were set \(~10^\circ C\) higher. Therefore, accounting for heat transfer via convection, it is possible the breaststroke swimmers experienced a similar level of heat transfer. However, swimmers have to overcome a large temperature gradient within the transition phase because their sport-specific warm-up is completed while submerged in a \(~27^\circ C\) pool. Therefore, a greater number of heating elements within the heated tracksuit pants may be required to overcome this large temperature gradient and subsequently enhance \(T_{core}\) maintenance within a 30 min transition phase.

Lower-body power output in breaststroke specialists was not enhanced following completion of the dryland-based exercise routine. This outcome may partially explain the non-improvement in start time performance recorded in the breaststroke study. However, as was suggested for freestyle specialists, it would be of interest to determine if additional load added to the tuck jumps exercise via a weight vest of up to 10% body mass, would elicit an improvement (or at least limit the decline during transition) in lower-body power output. A
positive temperature-dependent relationship is also evident with high velocity movements such as the swim start,\textsuperscript{32} and thus the lack of improvement in start time performance could also be explained by the failure to enhance $T_{\text{core}}$ maintenance.

### 9.1.6 Same day priming exercise bouts

Swimmers competing in only one event at a competition who qualify through to the evening final must decide whether to complete a morning training session or to simply rest. High-level swimmers also complete both morning and afternoon training sessions on a daily basis, with benchmark time-trials typically completed in the afternoon session throughout the year. Completion of an exercise bout consisting of sport-specific and non-specific resistance or sprint activities can enhance performance for up to 6 hr.\textsuperscript{53-55,136} Preliminary evidence was presented in the final experimental chapter of this thesis which demonstrated that completion of a morning exercise bout, consisting of swimming exercise alone, or a combination of swimming and dryland-based resistance exercise, can substantially enhance (~1.6-1.7\%) sprint swimming performance completed later that same day. These outcomes are useful to swimmers preparing for benchmark time-trials and subsequently, competitive races.

Proficient technical swimming ability is strongly associated with optimal high-intensity performance\textsuperscript{260,279,281} and higher stroke rates are associated with increases in swimming velocity.\textsuperscript{199} Within the first 50 m of the 100 m time-trial, higher stroke rates were recorded in the SwimOnly and SwimDry conditions. This outcome may partially explain the faster overall time-trial performances reported in these conditions. Furthermore, the improvement in first 50 m stroke rate (0.06Hz and 0.05Hz) relative to the NoEx condition was similar for both the SwimOnly and SwimDry conditions. It could be postulated that from a purely swimming-specific skills performance standpoint, the inclusion of the dryland resistance exercise circuit in the SwimDry condition appears to have had a minimal impact upon afternoon swimming-skill performance. These findings are also in line with recent work in rugby players demonstrating a movement-specific potentiating effect following same-day prior exercise completion, with the completion of a morning sprint exercise bout enhancing afternoon sprint, but not strength performance.\textsuperscript{54} Therefore it appears key when designing a
morning exercise bout for swimmers to ensure a portion of the session involves an in-water swimming-specific component.

Physiological markers such as $T_{\text{core}}$\textsuperscript{59,60} exhibit circadian rhythmicity with an early morning nadir and a subsequent peak in the afternoon.\textsuperscript{58} In support of this, higher $T_{\text{core}}$ (~0.3°C), $T_{\text{skin}}$ (~0.7°C) and $T_{\text{body}}$ (~0.2°C) readings were recorded prior to the afternoon session, in comparison to morning baseline measurements in the NoEx condition. Importantly, $T_{\text{core}}$ was substantially higher prior to the afternoon session in the SwimDry condition, compared to the NoEx condition. One possible explanation for these higher $T_{\text{core}}$ readings is that metabolic rate may have been affected by the morning exercise bouts. An increase in metabolic rate can be defined in two ways, an increase in heat production (measured via direct calorimetry) or an increase in oxygen consumption (indirect calorimetry).\textsuperscript{282} Metabolic rate can remain elevated by ~9% for up to 15 hr following exercise,\textsuperscript{266} with a dose-response relationship reported between the intensity and the duration of the exercise bout completed and the subsequent increase in metabolic rate.\textsuperscript{267} Elevated body temperature is also partially responsible for increases reported in recovery energy expenditure.\textsuperscript{268} Thus the swimming and resistance exercise completed in the morning within the SwimDry condition may have elicited an increase in metabolic rate which may have continued to remain elevated throughout the day, providing a plausible explanation for the higher $T_{\text{core}}$ readings recorded prior to the afternoon session.

Throughout the afternoon session, $T_{\text{core}}$ was greater in the SwimDry condition and prior to the 100 m time trial, $T_{\text{core}}$ was still higher in SwimDry compared to NoEx. The difference in $T_{\text{core}}$ readings between the SwimDry and NoEx immediately prior to the time-trial was ~0.6°C. This outcome is practically significant given that in this thesis, elite senior 100 m freestyle performance was reported to be faster when $T_{\text{core}}$ was marginally elevated (~0.3°C) immediately prior to a time-trial. An improvement in lower-body peak power output and repeat-sprint performance is also possible when criterion tasks are commenced with only a slightly elevated $T_{\text{core}}$ (~0.3°C).\textsuperscript{38} Furthermore, in comparison to the NoEx condition, $T_{\text{skin}}$ and $T_{\text{body}}$ were substantially higher in SwimDry prior to afternoon session commencement. Changes in $T_{\text{skin}}$ are associated with changes in $T_{\text{muscle}}$\textsuperscript{8} and although measurement of $T_{\text{muscle}}$ was not possible (given the inclusion of high-level swimmers) it is plausible that $T_{\text{muscle}}$ readings remained elevated throughout the afternoon session within the SwimDry condition.
Peak $T_{\text{core}}$ typically occurs at around 18:00, although hormones such as testosterone peak in the early morning. Maximal voluntary strength can increase in a dose-dependent manner with changes in testosterone concentration. This may be useful to sprint swimming performance, particularly within the initial start phase. However, the impact of completing an exercise bout upon circadian changes in testosterone is uncertain, with reports demonstrating an offset and no influence upon the circadian decline in testosterone concentration. One possible explanation for these different findings is the level of athlete examined. Elite athletes are known to have a highly predictive linkage of free testosterone to performance in comparison to their less experienced counterparts. Therefore, it would be useful in the future to determine whether completion of a morning swimming exercise bout, or combination swimming and dryland resistance exercise bout, influences the circadian changes in testosterone concentration and if such changes are correlated with improvements in junior and senior sprint swimming performance.

9.2 PRACTICAL OUTCOMES

The focus of this thesis was to determine the impact of various competition day preconditioning strategies on sprint swimming performance. The information gathered from the initial coach survey can be used to inform future intervention studies about the challenges faced by elite swimming coaches when finalising their swimmer’s competition preparation. The structure and content of the swimming and dryland warm-ups outlined could also be used to inform trainee swimming coaches about preparation requirements for elite athletes. A summary of the recommendations for competition day preparation strategies appears in Fig 10.

According to the information gathered in the coach survey, competitive swimmers observe lengthy transition phases during competition, typically lasting 20-40 min. Combining a swimmer’s pool warm-up with passive heating (via heated tracksuit jackets) and the completion of a short, dryland-based exercise routine during the transition phase was shown to be the best strategy for attenuating the decline in $T_{\text{core}}$ and increasing the rise in $T_{\text{skin}}$ during these lengthy transitions.
Fig. 10 Recommendations for competition day preparation strategies to enhance sprint (100 m) swimming performance. Concepts which have been demonstrated to improve performance in this thesis are presented in solid boxes. Concepts proposed for further investigation are presented in dashed boxes.

**Morning Exercise Bout**
- 6 hr break
- Swimming: ~1300 m varied intensity + 2 x 25 m race-pace efforts
- Resistance Exercises: weighted/un-weighted tuck jumps, running sprints, medicine ball throw downs

**Pool Warm-Up**
- ~1100-1400 m varied intensity swimming including stroke-specific drills + 2-4 x 25 m race-pace efforts

**30 min transition phase**

**15 min marshalling period**

**100 m race**

**Additional Warm-Up Strategies**
- Heated Jacket (freestyle)
- Dryland Warm-Up: medicine ball throw downs, simulated butterfly kick, bodyweight tuck jumps

**Heated Jacket + Pants OR heated tracksuit pants + additional heating elements (breaststroke)**
- Tuck jumps + weight vest (10% body mass)

**Combined**

**Separate or Combined**
These improvements in body temperature maintenance were associated with substantially faster start and overall time-trial performance in junior and senior freestyle swimmers. However, the application of these strategies may not always result in improvements in performance as was observed with breaststroke swimmers. At present, the majority of swimmers wear a standard tracksuit jacket while waiting to race and thus substituting this with a heated jacket should not present any logistical challenges, except perhaps cost. The dryland routine outlined within this thesis was also shown to enhance junior sprint swimming performance when performed as the lone additional warm-up strategy with a 30 min transition phase. Thus, if access to a heated jacket was not possible, completion of the dryland-based routine is a suitable alternative. Completing the dryland-based exercise routine within the competition environment should also not present a logistical challenge as the exercises contained within the routine were designed to be completed on pool deck, utilising minimal equipment and space which is crucial given the busy competition environment.

Finally, preliminary evidence was presented on the influence of same-day morning priming exercise on afternoon sprint swimming performance. Completion of a morning exercise bout consisting of swimming exercise alone or together with resistance exercise was demonstrated to substantially enhance sprint swimming performance completed later that same day. These outcomes should be useful to swimmers preparing for benchmark time-trials in training and competitive races.

9.3 LIMITATIONS

Within the study designs each of the investigations contained in this thesis, several limitations were evident. In the initial coach survey, primarily the responses from Australian coaches were gathered. When conducting research, it is important to ensure the sample participants are representative of the larger cohort. The coaches recruited for the survey were required to hold a minimum of a State-Level coaching licence, with the majority (32 out of 46) of coaches eventually recruited holding a National-level coaching licence or higher. Therefore, the coaches who participated within the initial survey study sufficiently represented the cohort of current elite level swimming coaches and thus the nationality of the surveyed coaches is largely irrelevant.
To limit the time burden placed upon the surveyed coaches and thus to potentially increase the questionnaire response rate, coaches were asked to provide specific pool warm-up details for only the 100, 200 and 400 m freestyle. Information pertaining to these particular events was requested as six (including freestyle and medley relays) of the sixteen Olympic pool-based swimming events require an individual to complete either a 100, 200 or 400 m freestyle effort. Therefore information was gathered on ~40% of all Olympic pool events.

In the four experimental studies, the principal limitation of these studies was the sample size. One explanation for the “small” sample sizes is that recruitment of high-level swimmers and, in particular elite swimmers, for intervention studies is often difficult, primarily because the number of swimmers classed as “elite” is so small. Access to these athletes is further hampered as a consequence of their busy training and competitive schedules. However, a power analysis was completed within the design phase of each study to ensure an adequate number of participants were recruited and participated in the studies to yield sufficient power during analysis. While separate analyses of the male and female results would have been preferable, the limited number of swimmers available within each of the experimental investigations did not permit this.

One of the important considerations for all four experimental studies was to ensure that all interventions could feasibly be directly implemented into real-world competition settings. To ensure the heated tracksuit jackets and pants could be made available to athletes immediately, (if positive results were obtained in the investigations) these items needed to be sourced commercially. There are very few commercial options for these items and thus limited scope to control where the heating elements were situated in the garments. It would be useful in future investigations to investigate the efficacy of garments containing different combination placements of heating elements on body temperature maintenance within the transition phase.

While heavy-resistance exercises such as lunges and YoYo squats have been demonstrated to enhance sprint swimming performance, it is unrealistic to expect swimmers to have access to the required facilities to complete these exercises at all competition venues. Therefore more practical ballistic-style exercises, such as bodyweight tuck jumps, which can improve performance in sprint swimming and other short-duration tasks, were included within the dryland and morning resistance exercise routines. Taking into account the information
gathered from the coach survey, all exercises included within these two routines were able to be completed in a small space, using minimal and easily transportable equipment.

In the three warm-up studies completed (studies 2, 3, 4), it would have been preferable to complete a PAP protocol in the pool in order to attain optimal movement specificity transfer. An example of this could have been attaching a swimmer to a weighted power rack and asking them to complete a series of wall-push offs. This particular exercise would simulate the end motion of a tumble turn and adding additional load to the power rack could increase the induced PAP response. However, exercises such as this are not feasible in the real-world competition environment for two logistical reasons. Firstly, swimmers must complete their pool warm-up at least 30 min prior to their race to ensure they have sufficient time to change into their race swimsuit (~10 min), have a final chat with their coach (~5 min) and ensure they are present in the marshalling area 15 min prior to their race. Secondly, gaining access to and utilising a power rack in a busy warm-up pool would be unrealistic within a competition setting. Therefore a compromise had to be reached, and in this case a dryland-based exercise routine was developed as an alternative.

Due to logistical constraints (only one NIRs unit was available), only local upper-body, specifically upper shoulder trapezius, blood flow characteristics were monitored in senior elite freestyle swimmers. This site was chosen as muscles in the upper-body contribute substantially during the propulsion phase within the freestyle stroke. However, other upper-body muscles such as latissimus dorsi as well as lower-body muscles are also involved during the propulsive phase in swimming. Therefore, it would be of interest to quantify the changes in blood flow characteristics at different body sites that may occur when swimmers wear heated garments and complete dryland-based exercise routines. Future research should also seek to monitor changes in blood flow characteristics at different body sites within different swim stroke specialists (e.g. backstroke swimmers) during completion of the Combo additional warm-up strategy.

The circadian decline in hormonal markers such as testosterone has previously been shown to be offset following completion of a morning resistance or sprint exercise bout. While it would have been interesting to ascertain if similar changes occurred following a morning swimming and/or resistance exercise bout, this was not a viable option due to logistical constraints.
Finally, a limitation of all four experimental studies was that only sprint, and not endurance, swimming performance was evaluated following the completion of the additional warm-up strategies or the morning priming exercise bouts. It was determined that sprint swimming performance would be examined as previous literature has demonstrated that athletes competing in sprint and short-duration tasks are likely to benefit from starting an event with elevated body temperature. Indeed elevations in $T_{\text{muscle}}$ are associated with faster ATP turnover, primarily via augmentation in the rate of PCr utilisation and H+ accumulation, as well as increases in anaerobic glycolysis and muscle glycogenolysis. Increases in subsequent exercise power production are considered the primary outcome of these changes.

9.4 FUTURE DIRECTIONS

The surveyed swimming coaches stated that transition phases of at least 30 min are common in competitive swimming events. The outcomes from the two freestyle-focused warm-up intervention studies in this thesis demonstrated that in the absence of additional warm-up strategies, transition phases of 30 min can negatively impact subsequent sprint swimming performance. It is important that any future work on competition day warm-up strategies utilise transition phases typically experienced by competitive swimmers. In addition, future investigations should determine if swimming coaches prescribe different pre-competition warm-ups for swimmers competing in the three form strokes, backstroke, breaststroke and butterfly, and in events of > 400 m in duration, in comparison to the warm-ups presented in the initial coach survey study.

One of the primary practical outcomes of this thesis was that additional passive and active warm-up strategies completed within the transition phase can mitigate some of the negative effects associated with lengthy transition phases. However, this finding was not observed in breaststroke swimmers. Given the absence of improved $T_{\text{core}}$ or $T_{\text{skin}}$ maintenance within the senior breaststroke investigation, it is possible the surface area covered by the heating elements contained within the heated tracksuit pants was inadequate. A long sleeve, blizzard survival jacket which fell to below the knee was shown to enhance $T_{\text{core}}$ maintenance during a 15 or 20 min transition phase leading to improvements in lower-body power-output.
Thus, a similar response may be possible in swimming. Future research should investigate whether tracksuit pants with integrated heating elements covering a greater surface area can improve $T_{\text{core}}$ maintenance during the transition phase. Alternatively, the combination of a low-heat ($\sim 37^\circ$C) heated tracksuit jacket and high-heat ($\sim 51^\circ$C) heated tracksuit pants may be required. Caution should be observed to limit the potential adverse effects on a swimmer’s thermal tolerance. In addition, further investigation is required to determine the optimum placement of the passive heat source on the body for both the backstroke and butterfly swim strokes. This could be achieved using thermal manikins. It would also be of interest to determine if these additional warm-up strategies, heated jackets and dryland-based activation exercises, can positively influence performance over different swimming distances such as the 200 and 400 m.

The additional warm-up strategies discussed within this thesis, in particular the heated athletic garments, may also be of interest to athletes competing in other sports. For instance, athletes competing in throws events in athletics typically wait long periods between competition throws and thus may “cool” down in between. Kayakers and rowers also have to wait in the boat on the water before racing for an extended period. Finally, team sport athletes such as hockey and football players, particularly those at the elite level, also experience lengthy transition phases following warm-up completion due to media commitments (e.g. opening addresses, singing of anthems). Team-sports such as hockey also permit unlimited player substitutions. In recent times, professional Australian Rules football teams have placed stationary bikes beside their substitution bench area for players to utilise while waiting to return to the playing field. While active re-warm-up during this period may be beneficial, completion of such activities results in the depletion of energy substrate stores. Players also typically only wait on the side-line for a short period of time ($< 10$ min), particularly in hockey, and thus passive heat maintenance via heated tracksuit jackets may be a more suitable alternative.

Lower-body power output was not shown to be significantly enhanced following completion of the dryland routine. It is possible that this was due to the 15 min recovery period observed between the dryland routine and time-trial start (which was used to simulate a typical competition marshalling period). Improvements in power output have been observed as long as 18.5 min following completion of a PAP stimulus, though additional load was utilised. Further attention is required to determine if additional load, via a weight vest for example,
added to the tuck jump exercise can elicit a greater PAP response than bodyweight tuck jumps and subsequently enhance lower-body power output. The surveyed swimming coaches also stated that it was common for their swimmers to practice their pool warm-ups in the final few weeks leading into a competition. Therefore, it may also be useful to determine whether practicing the dryland routine during the taper phase can improve swimmers’ familiarity with the exercises and subsequently result in further incremental performance gains.

Upper-body exercises included within the dryland routine, such as medicine ball throw downs, may have contributed to the faster performance times reported in the Combo condition in both the junior and senior freestyle studies given the substantial role these muscles play in the propulsion phase within the freestyle stroke. Future research should seek to clarify this and determine whether exercises such as medicine ball throw downs can elicit an improvement (or at least limit the decline during transition) in upper-body power output. The standing backward overhead medicine ball throw (BOST) test is a valid and reliable method for assessing explosive upper-body as well as total-body power output, and therefore may be an appropriate tool in this context. It would also be of interest to determine whether any upper-body PAP response induced via the medicine ball throw down exercise can be further enhanced through the alteration of the load moved and/or the number of repetitions completed. Finally, individual responses to PAP stimuli can occur. Therefore, future studies involving swimmers should seek to determine each individual athlete’s optimal pre-loading exercise intensity and transition duration as well as account for their predominant fibre type to maximise power generating capabilities in a subsequent exercise task.

The precise physiological mechanisms as to why afternoon swimming time-trial performance was enhanced following a morning exercise bout were not fully elucidated. Future swimming-focused investigations should seek to monitor changes in physiological markers such as testosterone and cortisol levels which have been shown to alter following a bout of morning exercise in rugby players. Monitoring changes in metabolic rate throughout the testing day may also provide additional useful information. It would also be of interest to assess if morning exercise completion influenced afternoon lower and upper body power output responses and in turn swim start characteristics (e.g. horizontal velocity). In addition, as has been reported with PAP, individual responses may occur and differences in the response to morning exercise may be present between sub-elite and elite athletes. Further
investigation is required to ascertain if such differences are present and if so how can the composition of the morning exercise bout be altered to optimise the afternoon performance response for each individual athlete.

Finally, although in swimming competitions heat sessions typically take place in the morning (~08:00-11:00) with finals sessions in the late afternoon/evening (~17:00-21:00), for the Olympic Games, these session times are often altered to fall in line with prime-time television viewing slots. For instance, at the upcoming Rio 2016 Olympic Games, heat sessions will commence at 13:00 and finals sessions at 22:00. Therefore, it would be of interest to investigate if completion of a priming bout later in the day, for example at 13:00-14:00, would elicit similar performance improvements in races completed in the later evening to those demonstrated in the final study presented within this thesis.

9.4 CONCLUSIONS

The results disseminated in this thesis provide support for the use of competition day preconditioning strategies such as morning exercise bouts and additional pre-event warm-up strategies to enhance competitive sprint swimming performance. The structural template of the contemporary pool and dryland-based warm-ups identified by the surveyed coaches is useful for coach education purposes. This information could be used to inform trainee swimming coaches, sport scientists and strength and conditioning coaches about the situational factors elite coaches and swimmers face within the competition environment. Swimming coaches can also utilise the presented information to review their personal warm-up practices and as a possible source for new components and designs.

Several factors such as the time required to don a race swimsuit (~10 min), delays in the competition schedule and lengthy marshalling periods were reported by the surveyed coaches to cause delays in the transition from warm-up to racing which may mitigate the benefits of previously completed dryland and pool warm-ups. Swimming coaches can be advised that utilising heated tracksuit jackets and completing dryland-based exercises in real-world competition settings can significantly enhance both junior and elite senior sprint freestyle performance. However, use of these additional warm-up strategies does not lead to
improvements elite sprint breaststroke performance. These outcomes highlight the importance of examining the responses of different swimming strokes to new interventions. Completion of a morning swim session or a combined swim and resistance exercise session was shown to enhance sprint swimming performance completed later that same day. The inclusion of either of these morning priming exercise sessions should be considered when planning a swimmer’s competition day preparations, though additional research is required to fully elucidate the physiological mechanisms responsible for the noted performance improvements.
APPENDIX
Summary of the performance, physiological and biomechanical changes following passive and active warm-up completion in swimming

Table 20. Performance, physiological and biomechanical changes following passive and active warm-up completion in swimming.

| Reference          | Participants | Warm-Up | In-Pool Volume (m) | Intensity Passive Dryland Changes Transition Criterion Test Performance Results Physiological Results Biomechanical Results |
|--------------------|--------------|---------|--------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Neiva et al. 2015 | 11T (M)      | WU1:150 | Breathe 5th Stroke | -               | HR, RPE: HR, RPE: similar; | 10   | 100 m | Overall time: WU2< WU1< WU3 | 2nd 50 m SL, SI: WU2>WU3 |
|                    |              | 2 x 100 | 25 m kick/high SL  | -               | WU1 + WU2> WU3 | 2nd 50 m SL, SI: WU2>WU3 |
|                    |              | 4 x 50  | 50 m drill/50 RP,25m RP/ easy | -               | TC: WU2> WU3 | 2nd 50 m SL, SI: WU2>WU3 |
|                    |              | 50      | Easy As above      | -               | As above        | 2nd 50 m SL, SI: WU2>WU3 |
|                    |              | WU2:300 |                    |                 |                 |                 |                 |                 |                 |
|                    |              | 4 x 100 |                    |                 |                 |                 |                 |                 |                 |
|                    |              | 8 x 50  |                    |                 |                 |                 |                 |                 |                 |
|                    |              | 100     |                    |                 |                 |                 |                 |                 |                 |
|                    |              | WU2:500 |                    |                 |                 |                 |                 |                 |                 |
|                    |              | 6 x100  |                    |                 |                 |                 |                 |                 |                 |
|                    |              | 12 x 50 |                    |                 |                 |                 |                 |                 |                 |
|                    |              | 100     |                    |                 |                 |                 |                 |                 |                 |
| Hancock et al. 2015 | 30T:15M, 15F | WU2:900 | “Resisted”         | -               | -               | 6               | 100 m | Overall time: WU2< WU1 | La: WU2>WU1 |
|                    |              | WU2:900 |                    |                 |                 |                 |                 |                 |                 |
|                    |              | 4 x 10  |                    |                 |                 |                 |                 |                 |                 |
| Sarramian et al. 2015 | 18T:10M, 8F | WU2:30 min | Swim, kick, “short sprints” | -               | WU2:15, WU2,10 < 4, 8 or 12 | 50 m | Overall time: WU1< WU2 | -                 |
|                    |              | WU2,3,4:15 min | Swim, kick, “short sprints” | -               | WU2,15, WU2,10 < 4, 8 or 12 | 50 m | Overall time: WU1< WU2 | -                 |
|                    |              |         |                    |                 |                 |                 |                 |                 |                 |

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### Table 20. continued

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<th>Reference</th>
<th>Participants</th>
<th>Warm-Up</th>
<th>In-Pool Volume (m)</th>
<th>Intensity</th>
<th>Passive</th>
<th>Dryland</th>
<th>Changes</th>
<th>Transition (min)</th>
<th>Criterion Test</th>
<th>Performance Results</th>
<th>Physiological Results</th>
<th>Biomechanical Results</th>
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<td>Cuenca-Fernandez et al. 2015</td>
<td>14T:10M, 4F</td>
<td>WU₁, WU₂, WU₃: 200 50 50 100</td>
<td>Easy 12.5 m “fast”/”smooth”</td>
<td>-</td>
<td>WU₁, WU₂, WU₃: Dynamic stretching WU₂:3 x lunge 85% 1RM WU₃:4 x max YoYo Squat</td>
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<td>15 m NS</td>
<td>Overall time: WU₃ &lt; WU₁; 5 m time: WU₃ &lt; WU₂ &lt; WU₁; Dive distance: WU₃ &gt; WU₂ &gt; WU₁</td>
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<td>-</td>
<td>WU₂:20 min sauna 80°C WU₁:10 min sauna 80°C</td>
<td>-</td>
<td>HR,RPE: WU₂ &gt; WU₁</td>
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<td>100 m Back, Breast, Free, Fly</td>
<td>Overall time: similar</td>
<td>HR,RPE: WU₁ &lt; WU₂</td>
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<td>20T: 10M, 10F</td>
<td>WU₁:0 WU₂:300 2 x 100 4 x 50 4 x 50 100</td>
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<td>-</td>
<td>NS</td>
<td>10</td>
<td>100 m Free</td>
<td>Overall, 50 m split time: WU₂ &lt; WU₁</td>
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<td>1st 50 m SL, SI: WU₂ &gt; WU₁</td>
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<td>13T: 9M, 4F</td>
<td>WU₁:365.8 4 x 91.4 4 x 45.7 4 x 22.8 WU₂:45.7 45.7</td>
<td>6 min Drill/swim 1.40 min Kick/swim 1 min 1 RP/1 easy 90% max 100% max</td>
<td>-</td>
<td>WU₂:1 min skip, 10 VJ, 365.8 m easy swim, 5 x push offs, 45.7 m kick/swim, 5 x push offs</td>
<td>HR: WU₂ &gt; WU₁</td>
<td>5</td>
<td>45.7 m Free</td>
<td>Overall time: similar</td>
<td>HR: similar</td>
<td>-</td>
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<tr>
<th>Reference</th>
<th>Participants</th>
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<th>Intensity</th>
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<th>Dryland</th>
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<th>Transition (min)</th>
<th>Criterion Test</th>
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<th>Biomechanical Results</th>
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<tbody>
<tr>
<td>West et al. 2013</td>
<td>8T: 4M, 4F</td>
<td>WU₁: 400</td>
<td>HR 40-60 bpm below HR&lt;sub&gt;max&lt;/sub&gt;</td>
<td>-</td>
<td>-</td>
<td>T&lt;sub&gt;core&lt;/sub&gt;, T₁&gt; T₂, La: similar</td>
<td>T₁: 20</td>
<td>200 m</td>
<td>Overall time: T₁ (~1.5%) &lt; T₂*</td>
<td>T&lt;sub&gt;core&lt;/sub&gt;, HR, RPE: similar; La: T₁ &gt; T₂*</td>
<td>SR: similar</td>
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<tr>
<td>Neiva et al. 2012</td>
<td>10T (M)</td>
<td>WU₁: 0</td>
<td>“Freely”</td>
<td>-</td>
<td>-</td>
<td>10</td>
<td>50 m</td>
<td>Free</td>
<td>Overall time: similar</td>
<td>La*, RPE: similar</td>
<td>-</td>
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<tr>
<td>Neiva et al. 2012</td>
<td>7T (F)</td>
<td>WU₁: 0</td>
<td>“Freely”</td>
<td>-</td>
<td>-</td>
<td>10</td>
<td>50 m</td>
<td>Free</td>
<td>Overall time: similar</td>
<td>La*, RPE: similar</td>
<td>SR, SL, SI: similar</td>
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<tr>
<td>Balilionis et al 2012</td>
<td>16T: 8M, 8F</td>
<td>WU₁: 0</td>
<td>“Freely”</td>
<td>-</td>
<td>-</td>
<td>10</td>
<td>50 m</td>
<td>Free</td>
<td>Overall time: similar</td>
<td>La*, RPE: similar</td>
<td>SR, SL, SI: similar</td>
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<tr>
<td>Dimitric et al 2012</td>
<td>12T: 8M, 4F</td>
<td>WU₁: 1500</td>
<td>40% max</td>
<td>-</td>
<td>-</td>
<td>3</td>
<td>45.7 m</td>
<td>Free</td>
<td>Overall time: WU₁ &lt; WU₂*</td>
<td>HR: WU₂ &lt; WU₃</td>
<td>Dive distance, SC, SR: similar</td>
</tr>
<tr>
<td>Neiva et al. 2011</td>
<td>10T (M)</td>
<td>WU₁: 0</td>
<td>“Freely”</td>
<td>-</td>
<td>-</td>
<td>10</td>
<td>30 sec</td>
<td>Free</td>
<td>Overall time, 1s 50 m: WU₁ + WU₂ similar, WU₂ &lt; WU₃*</td>
<td>F&lt;sub&gt;max&lt;/sub&gt;, F&lt;sub&gt;mean&lt;/sub&gt;: WU₂ &gt; WU₁</td>
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<tr>
<td>Kilduff et al. 2011</td>
<td>9T: 7M, 2F</td>
<td>WU₁: 300</td>
<td>Easy</td>
<td>-</td>
<td>-</td>
<td>NS</td>
<td>8</td>
<td>15 m</td>
<td>15 m start time: similar</td>
<td>PHF: WU₁ &lt; WU₂<em>PVF: WU₁ &lt; WU₂</em></td>
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<table>
<thead>
<tr>
<th>Reference</th>
<th>Participants</th>
<th>Warm-Up In-Pool Volume (m)</th>
<th>Warm-Up Intensity</th>
<th>Dryland Changes</th>
<th>Transition Time (min)</th>
<th>Criterion Test</th>
<th>Performance Results</th>
<th>Physiological Results</th>
<th>Biomechanical Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nepocaty et al. 2010 176</td>
<td>10M: 4M, 6F</td>
<td>WU1:400 45.7 m</td>
<td>90% VO₂max</td>
<td>WU₂:5 x 1 min</td>
<td>3</td>
<td>45.7 m</td>
<td>Overall time: similar</td>
<td>HR: WU₁ &gt; WU₂</td>
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<tr>
<td></td>
<td></td>
<td>WU₂:45.7</td>
<td>40% VO₂max</td>
<td>UBV (22Hz)</td>
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<td></td>
<td></td>
<td></td>
<td>90% VO₂max</td>
<td></td>
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<tr>
<td>Zochowski et al. 2007 15</td>
<td>10T: 5M, 5F</td>
<td>WU1:300 6 x 100</td>
<td>Easy</td>
<td></td>
<td>HR: T₁: 10</td>
<td>200 m</td>
<td>Overall time: T₁ (~1.4%)</td>
<td>HR: T₁ &gt; T₂</td>
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<tr>
<td></td>
<td></td>
<td>10 x 50</td>
<td>Pull/kick</td>
<td></td>
<td>T₂: 45</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>100</td>
<td>Easy</td>
<td></td>
<td></td>
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<tr>
<td>Bobo et al. 1999 26</td>
<td>23T (NS)</td>
<td>WU₁: 0</td>
<td>&quot;Moderate&quot;</td>
<td></td>
<td>5</td>
<td>5 x 91.4 m Free</td>
<td>Overall time: similar</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>WU₂: 731.5</td>
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<tr>
<td>Akamine &amp; Taguchi 1998 292</td>
<td>6T (M)</td>
<td>-</td>
<td>WU₁ Bath 36 °C, CO₂ 300ppm</td>
<td>-</td>
<td>10</td>
<td>4 min kick</td>
<td>HCT, WBC, PP, Chol:</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>20 min</td>
<td></td>
<td></td>
<td>(80% max)</td>
<td>WU₁ &gt; WU₂; HR, La, EMG:</td>
<td></td>
<td></td>
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<tr>
<td>Romney &amp; Nethery 1993 89</td>
<td>12T: 4M, 8F</td>
<td>WU₁: 0</td>
<td>RPE = 12</td>
<td>WU₂: 5 min:</td>
<td>3</td>
<td>91.4 m</td>
<td>Overall time: WU₂ &lt; WU₁</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>WU₂: 5 min: 10 x 22.9</td>
<td>Build to RP</td>
<td>skipping,</td>
<td></td>
<td>Free</td>
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<td></td>
<td></td>
<td>5 min</td>
<td></td>
<td>calisthenics, skipping</td>
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<tr>
<td>Mitchell &amp; Huston 1993 27</td>
<td>10T (M)</td>
<td>WU₁: 0</td>
<td>70% VO₂max</td>
<td></td>
<td>La: WU₃ &gt; WU₁ +</td>
<td>CT₁: 183 m Free</td>
<td>Overall times: similar</td>
<td>CT₁; HR: WU₁ &gt; WU₂</td>
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<tr>
<td></td>
<td></td>
<td>WU₂: 366</td>
<td>1 min rest,</td>
<td></td>
<td>WU₁ *</td>
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<tr>
<td></td>
<td></td>
<td>WU₂: 4 x 46</td>
<td>110% VO₂max</td>
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<table>
<thead>
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<th>Reference</th>
<th>Participants</th>
<th>Warm-Up</th>
<th>In-Pool Volume (m)</th>
<th>Intensity</th>
<th>Passive</th>
<th>Dryland</th>
<th>Changes</th>
<th>Transition (min)</th>
<th>Criterion Test</th>
<th>Performance Results</th>
<th>Physiological Results</th>
<th>Biomechanical Results</th>
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<tbody>
<tr>
<td>Houmard et al. 1991</td>
<td>8T (M)</td>
<td>WU1:0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5</td>
<td>365.8 m Free</td>
<td>HR, La: WU1 &gt; WU2,3,4</td>
<td>SL: WU3,4 &gt; WU1,2</td>
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<tr>
<td></td>
<td></td>
<td>WU2:4 x 45.7</td>
<td>95% VO2 max</td>
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<td>WU3:1371.6</td>
<td>65% VO2 max</td>
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<td></td>
<td>WU4:1188.7</td>
<td>65% VO2 max</td>
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<td>4 x 45.7</td>
<td>95% VO2 max</td>
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<td>Robergs et al 1990</td>
<td>8T (M)</td>
<td>WU1:0</td>
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<td>WU2:400</td>
<td>82% VO2 max Kick, 45% VO2 max</td>
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<td>4 x 50</td>
<td>111% VO2 max</td>
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<td>De Vries et al. 1959</td>
<td>13T (M)</td>
<td>WU1:0</td>
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<td></td>
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<td>WU2:457.2</td>
<td>“Moderate”</td>
<td>WU1:10 min massage WU4:6 min HS</td>
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<td>WU4:</td>
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<td>Thompson 1958</td>
<td>60UT (M)</td>
<td>WU1:0</td>
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<td>WU2:110</td>
<td>“Moderate”</td>
<td>WU4:5 Calisthenics Circuit</td>
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<td>WU3:2.5 min</td>
<td>75% VO2 max</td>
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<td>Carlile et al. 1956</td>
<td>10 (NS)</td>
<td>WU1:0</td>
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<td>WU2:8 min HS</td>
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<td>Muido 1946</td>
<td>2T (M), 1UT (M)</td>
<td>Warm-Up</td>
<td>Physiological Results</td>
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<td>Changes</td>
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<td>Criterion Test</td>
<td>Performance Results</td>
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<tr>
<td></td>
<td></td>
<td>WU₁:0</td>
<td>-</td>
<td>WU₂: 15-18 min HB</td>
<td>WU₄: 10 min cycle</td>
<td>WU₅: 10 min jogging</td>
<td>WU₂: -1°C</td>
<td>CT₁: Overall time: WU₁ &lt; WU₂ (2%)</td>
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<td>WU₂: 40-43°C</td>
<td>WU₃: 10°C</td>
<td>WU₅: 0.6°C</td>
<td>WU₅: 2.2°C</td>
<td>-</td>
<td>WU₂: 10°C</td>
<td>WU₁ &lt; WU₂ (0.6-2.2%)</td>
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<td>WU₃: SWD</td>
<td>0°C</td>
<td>WU₅: 0.6°C</td>
<td>WU₅: 2.2°C</td>
<td>-</td>
<td>WU₅: 10°C</td>
<td>CT₂: Overall time: WU₂ &lt; WU₃ (1.8-1.9%)</td>
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<tr>
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<td></td>
<td>WU₄: 1°</td>
<td>WU₅: 0°C</td>
<td>WU₅: 2.2°C</td>
<td>WU₅: 2.2°C</td>
<td>-</td>
<td>WU₅: 10°C</td>
<td>WU₁ &lt; WU₂ (1.4-2.6%)</td>
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</table>

1RM 1 repetition maximum, * denotes p < 0.05.
Study 1 Swimming Coach Warm-Up Questionnaire

These questions pertain to the warm-up strategies you provide to your athletes during competition.
Please select the most applicable option(s)

1. How long have you been coaching swimming? _______ years

2. Were you a swimmer yourself? ☐ Yes ☐ No
   If yes, what was the highest level you competed at?
   ☐ State Age ☐ State Open ☐ National Age ☐ National Open ☐ International Age
   ☐ International Open

3. What formal coaching qualifications do you hold? E.g. Bronze, Silver, Gold, Platinum Coach

4. Do you specialise in coaching any particular events? (Please tick any that apply)
   ☐ Sprint: 50-100m ☐ Middle-Distance: 200-400m ☐ Long-Distance: 800-1500m
   ☐ Medley: 200-400m ☐ Open Water

5. What is the highest level of competitor you coach on a regular basis?
   ☐ State Age ☐ State Open ☐ National Age ☐ National Open ☐ International Age
   ☐ International Open

6. What is the typical age of your squad?
   ☐ 12-15yrs ☐ 15-18yrs ☐ 18-21yrs ☐ 21-25yrs ☐ 25-30yrs ☐ 30yrs+

7. What is the typical length of the warm-up you advise your athletes to complete prior to a race? _______ metres

8. In the tables below, please outline the competition warm-up you usually prescribe before 100/200/400m Freestyle races. Please use more space as required.

<table>
<thead>
<tr>
<th>Example</th>
<th>Warm Up Stage</th>
<th>Distance (metres)</th>
<th>C= continuous B= build S= sprint</th>
<th>% Intensity Effort</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>700</td>
<td>C</td>
<td>50%Effort</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>300</td>
<td>B</td>
<td>50-70%Effort</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3 x 25m</td>
<td>C + S</td>
<td>80,90%Effort</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>100m</th>
<th>Warm Up Stage</th>
<th>Distance (metres)</th>
<th>C= continuous B= build S= sprint</th>
<th>% Intensity Effort</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td>%Effort</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td></td>
<td></td>
<td>%Effort</td>
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<td>3</td>
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<td>%Effort</td>
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<tr>
<td></td>
<td>4</td>
<td></td>
<td></td>
<td>%Effort</td>
</tr>
</tbody>
</table>
9. During the warm-up, how long are the rest intervals that you prescribe between sprint efforts?
☐ 10-15secs  ☐ 15-30secs  ☐ 30-60secs  ☐ 1-2min  ☐ Other _______

10. Do you consider the issue of exercise intensity in assigning warm-ups? If yes, how do you monitor/measure intensity? E.g. Time, Heart rate, Feel, Stroke Rate

___________________________________________________________________________
___________________________________________________________________________

11. During the warm-up, do you ask your athletes to use any specific devices?
☐ Kickboard  ☐ Pull Buoy  ☐ Snorkel  ☐ Other-please list below

___________________________________________________________________________
___________________________________________________________________________

12. Do you prescribe any dryland-based exercises for your athlete’s warm-up?
☐ Leg/Arm Swings  ☐ Stretch cords  ☐ Jumps  ☐ Static Stretching  ☐ Hot Shower
☐ Other-please list below

___________________________________________________________________________
___________________________________________________________________________

If so, what number of reps/sets and rest times between sets do you prescribe?

___________________________________________________________________________
___________________________________________________________________________

13. Do you feel that the length of time between the warm-up and the start of the race is important to consider? If so, what do you feel is the optimal recovery period?
☐ 5min  ☐ 10min  ☐ 15min  ☐ 20min  ☐ 25min  ☐ 30min  ☐ 30min+
14. A warm-up may not go according to plan. What external influences affect the recovery time between the end of the warm-up and the start of the race?

___________________________________________________________________________

15. Following completion of their warm-up, what do your athletes typically do before the race?
☐ Sit  ☐ Listen to Music  ☐ Put on a Tracksuit  ☐ Hot Shower  ☐ Other-please list below

How long approximately do they participate in these activities?
☐ 5min  ☐ 10min  ☐ 15min  ☐ 20min  ☐ 25min  ☐ 30min  ☐ 30min+

16. What do you believe are the primary benefits of the warm-up? E.g. Physical, Mental, Tactical Preparation

___________________________________________________________________________

___________________________________________________________________________

17. Do you get your athletes to practice using their competition warm-up in training sessions?  ☐ Yes  ☐ No
If yes, please describe the circumstances with which they practice using them under e.g. time-trials

___________________________________________________________________________

___________________________________________________________________________

18. Do you have any further comments regarding competition warm-up strategies?

___________________________________________________________________________

___________________________________________________________________________

Are you interested in receiving any additional follow-up information regarding warm-up strategies?
If yes, please provide your contact details below
Email: ____________________________________________________________

Phone: ___________________________________________________________
Study 2 Athlete Questionnaires

Start of Testing Block Questionnaire
Name: __________________________
Date: __________________________

1. How important is warming-up in the pool before a race to you?
Not Very Important Not Important Somewhat Important Important Very Important

2. Why do you think it is important to warm-up before a race?
Helps me swim faster Helps me get ‘in the zone’ Injury prevention Because my coach says it is

3. Do you think warming-up before a race helps you to swim faster?
Definitely No Mostly No Maybe Mostly Yes

4. Do you think that warming-up in a pool is the best way to prepare for your race?
Definitely Not Probably Not Probably Yes Definitely Yes

5. If for some reason you could not warm-up before your race, would you swim slower?
Definitely Not Probably Not Probably Yes Definitely Yes

6. How important is the warm-up process to you in terms of getting you focused on the race ahead and ‘in the zone’?
Not Important Not Very Important Somewhat Important Important Very Important

7. Does the way in which you currently warm-up before your races help you to mentally focus on the upcoming race and get ‘in the zone’?
Never Not Really Sometimes Most of the Time All of the Time

8. Does the way in which you currently warm-up before your races physically prepare you to swim fast?
Never Not Really Sometimes Most of the Time All of the Time

9. Does how you feel in yourself prior to your race affect your performance?
Yes No
10. Do you think you swim faster if you feel good in yourself prior to your races? Or does it not matter how good/bad you feel?

Yes  No  Doesn’t Matter

11. Please rank the warm-up strategies from 1-4 in terms of how well you think they will prepare you to race fast in the time-trials. i.e. place a 1 in the box for the strategy you think will prepare you best and so on

☐ Control  ☐ Passive  ☐ Dryland  ☐ Combo

- **Control** = Swimmers will perform their normal pool warm-up, towel off, put on their tracksuit and then be directed to a simulated marshalling area to wait until they compete
- **Passive** = Swimmers will perform their normal pool warm-up, towel off and then put on a tracksuit with heat filaments sewn in which will help keep them warm whilst they wait in the simulated marshalling area before they compete
- **Dryland** = Swimmers will perform their normal pool warm-up, towel off, put on their tracksuit and then perform a simple 5 min routine involving box jumps, medicine ball throws (2-3kg) and arm swings before being directed to the simulated marshalling area where they wait to compete
- **Combo** = Swimmers will perform their normal pool warm-up, towel off and then put on a tracksuit with heat filaments sewn in which will help keep them warm whilst they perform a simple 5 min routine involving box jumps, medicine ball throws (2-3kg) and arm swings before being directed to the simulated marshalling area where they wait to compete
Pre-Testing
Name: ________________________________
Date: ________________________________

1. How are you feeling today?
Terrible Not Good Ok Good Very Good
Excellent

2. How recovered are you from your last workout?
Not recovered at all Pretty Recovered Recovered Very Recovered

3. How many hours sleep did you get last night?

4. And the night before?

5. How tired are you feeling today?
Very Tired Moderately Tired A little Bit Tired Not Tired at all

6. How motivated are you for your time-trial today?
Not motivated Somewhat Motivated Fairly Motivated Very
Motivated

7. How confident are you that the warm-up strategy you have been assigned with
today will help you swim fast in your time-trial?
Not Confident At All Somewhat Confident Fairly Confident Very
Confident
Post-Testing
Name: ____________________________
Date: ____________________________

1. How much effort did you put into your time-trial?

| %  | 60% | 65% | 70% | 75% | 80% | 85% | 90% | 95% | 100% |

2. How comfortable did you feel after you completed both your pool and out of pool warm-ups?

Not Very Comfortable Somewhat Comfortable Fairly Comfortable Very Comfortable

3. How tired did you feel after you’re out of pool warm-up?

Very Tired Moderately Tired A little Bit Tired Not Tired at all

4. How physically prepared did you feel to swim fast in your time-trial after you completed both your pool and out of pool warm-ups?

Very Unprepared Somewhat More Prepared Fairly Prepared Very Prepared

5. How mentally prepared did you feel to swim fast in your time-trial after you completed both your pool and out of pool warm-ups?

Very Unprepared Somewhat More Prepared Fairly Prepared Very Prepared

6. How fast did you think you swam in your time-trial?

Not Very Fast Somewhat Fast Pretty Fast Very Fast Personal Best Time

7. Do you think the warm-up strategy you completed prior to your time-trial helped you to swim fast?

Definitely No Mostly No Maybe Mostly Yes Definitely Yes

8. Do you think there is anything you could have done extra or done less of in your pool warm-up, or you’re out of pool warm-up, to help you swim faster?

________________________________________

________________________________________

________________________________________

172
End of Testing Block

Name: ______________________

1. Please rank the warm-up strategies from 1-4 in terms of how well you think they prepared you to race fast in the time-trials. I.e. place a 1 in the box for the strategy you thought prepared you best and so on.

☐ Control  ☐ Passive  ☐ Dryland  ☐ Combo

2. Did any of the warm-up activities make you feel uncomfortable? Please circle any activities that did.

Pool Warm-Up  Hot Jackets  Dryland Warm-Up  Hot Jackets + Dryland
Exercise

Please explain briefly why you felt uncomfortable:

_________________________________________  _________________________________________

_________________________________________  _________________________________________

_________________________________________  _________________________________________

_________________________________________  _________________________________________

3. Would you consider using any of the new warm-up strategies (passive, dryland or combo) in an actual competition?

Yes  No

If yes, which strategy(s) would you consider using and why do you think it would be beneficial?

_________________________________________  _________________________________________

_________________________________________  _________________________________________

_________________________________________  _________________________________________

Checklist:

- **Control** = Swimmers will perform their normal pool warm-up, towel off, put on their tracksuit and then be directed to a simulated marshalling area to wait until they compete
- **Passive** = Swimmers will perform their normal pool warm-up, towel off and then put on a tracksuit with heat filaments sewn in which will help keep them warm whilst they wait in the simulated marshalling area before they compete
- **Dryland** = Swimmers will perform their normal pool warm-up, towel off, put on their tracksuit and then perform a simple 5 min routine involving box jumps, medicine ball throws (2-3kg) and arm swings before being directed to the simulated marshalling area where they wait to compete
- **Combo** = Swimmers will perform their normal pool warm-up, towel off and then put on a tracksuit with heat filaments sewn in which will help keep them warm whilst they perform a simple 5 min routine involving box jumps, medicine ball throws (2-3kg) and arm swings before being directed to the simulated marshalling area where they wait to compete
Study 3 and 4 Thermal Comfort and Thermal Sensation Scales

THERMAL COMFORT SCALE – POINT TO 1 NUMBER

+3 Very Comfortable
+2 Comfortable
+1 Slightly Comfortable
0 Neutral
-1 Slightly Uncomfortable
-2 Uncomfortable
-3 Very Uncomfortable

THERMAL SENSATION SCALE – POINT TO 1 NUMBER

+4 Very Hot
+3 Hot
+2 Warm
+1 Slightly Warm
0 Neutral
-1 Slight Cool
-2 Cool
-3 Cold
-4 Very Cold
Study 3 and 4 Athlete Questionnaires

Start of Testing Block
Name: ____________________________
Date: ____________________________

1 How important is warming-up before a race to you?
   Not Very Important   Not Important   Somewhat Important   Important   Very Important

2 Do you think warming-up before a race helps you to swim faster?
   Definitely No   Mostly No   Maybe   Mostly Yes   Definitely Yes

3 Do you think that warming-up in a pool is the best way to prepare for your race?
   Definitely Not   Probably Not   Neutral   Probably Yes   Definitely Yes

4 How important is the warm-up process to you in terms of getting you focused on the race ahead and ‘in the zone’?
   Not Important   Not Very Important   Somewhat Important   Important   Very Important

5 Does the way in which you currently warm-up before your races help you to mentally focus on the upcoming race and get ‘in the zone’?
   Never the Time   Not Really   Sometimes   Most of the Time   All of the Time

6 Does the way in which you currently warm-up before your races physically prepare you to swim fast?
   Never the Time   Not Really   Sometimes   Most of the Time   All of the Time
# Pre-Testing Session

Name: _____________________________  
Date: _____________________________

1. **How are you feeling today?**

<table>
<thead>
<tr>
<th>Not Good</th>
<th>Ok</th>
<th>Good</th>
<th>Very Good</th>
<th>Excellent</th>
</tr>
</thead>
</table>

2. **How recovered are you from your last workout?**

<table>
<thead>
<tr>
<th>Not recovered at all</th>
<th>A little Recovered</th>
<th>Pretty Recovered</th>
<th>Recovered</th>
<th>Very Recovered</th>
</tr>
</thead>
</table>

3. **How tired are you feeling today?**

<table>
<thead>
<tr>
<th>Very Tired</th>
<th>Moderately Tired</th>
<th>Tired</th>
<th>A little Bit Tired</th>
<th>Not Tired at all</th>
</tr>
</thead>
</table>

4. **How motivated are you for your time-trial today?**

<table>
<thead>
<tr>
<th>Not motivated</th>
<th>Somewhat Motivated</th>
<th>Motivated</th>
<th>Fairly Motivated</th>
<th>Very Motivated</th>
</tr>
</thead>
</table>

5. **How confident are you that the warm-up strategy you have been assigned with today will help you swim fast in your time-trial?**

<table>
<thead>
<tr>
<th>Not Confident At All</th>
<th>Somewhat Confident</th>
<th>Confident</th>
<th>Fairly Confident</th>
<th>Very Confident</th>
</tr>
</thead>
</table>
Post-Testing Session

Name: __________________________
Date: __________________________

1. How much effort did you put into your time-trial?

60%               65%               70%               75%               80%               85%               90%               95%

100%               

2. How comfortable did you feel after you completed both your pool and out of pool warm-ups?

Not Very Comfortable  Somewhat Comfortable  Comfortable  Fairly Comfortable  Very Comfortable

3. How tired did you feel after you’re out of pool warm-up?

Very Tired  Moderately Tired  Tired  A little Bit Tired  Not Tired at all

4. How physically prepared did you feel to swim fast in your time-trial after you completed both your pool and out of pool warm-ups?

Very Unprepared  Somewhat More Prepared  Prepared  Fairly Prepared  Very Prepared

5. Do you think the warm-up strategy you completed prior to your time-trial helped you to swim fast?

Definitely No  Mostly No  Maybe  Mostly Yes  Definitely Yes

6. Did any of the warm-up activities such as the pool warm-up, hot pants/hot jacket or dryland routine distract you from performing at your best in the time-trial? If yes, please briefly explain why they distracted you.

7. Do you think there is anything you could have done extra or done less of in your pool warm-up, or you’re out of pool warm-up, to help you swim faster? If yes, please briefly explain.
1. Did any of the warm-up activities make you feel uncomfortable? Please circle any activities that did.

Pool Warm-Up  Hot Jackets  Hot Pants  Dryland
Warm-Up

Please explain briefly why a specific/several specific warm-up activities made you felt uncomfortable:

________________________________________________________________________

________________________________________________________________________

________________________________________________________________________

________________________________________________________________________

2. Would you consider using any of the new warm-up strategies (hot jackets/hot pants/dryland routine) in an actual competition?

Yes  No  Perhaps

If yes, which strategy(s) would you consider using and why do you think it would be beneficial?

________________________________________________________________________

________________________________________________________________________

________________________________________________________________________
### Study 5 Perception Scale

**FEELING PERCEPTION SCALE – POINT TO 1 NUMBER**

<table>
<thead>
<tr>
<th>Number</th>
<th>Feeling</th>
</tr>
</thead>
<tbody>
<tr>
<td>+5</td>
<td>Very Good</td>
</tr>
<tr>
<td>+4</td>
<td></td>
</tr>
<tr>
<td>+3</td>
<td>Good</td>
</tr>
<tr>
<td>+2</td>
<td></td>
</tr>
<tr>
<td>+1</td>
<td>Fairly Good</td>
</tr>
<tr>
<td>0</td>
<td>Neutral</td>
</tr>
<tr>
<td>-1</td>
<td>Fairly Bad</td>
</tr>
<tr>
<td>-2</td>
<td></td>
</tr>
<tr>
<td>-3</td>
<td>Bad</td>
</tr>
<tr>
<td>-4</td>
<td></td>
</tr>
<tr>
<td>-5</td>
<td>Very Bad</td>
</tr>
</tbody>
</table>
Published Manuscripts
Appendix – Published Manuscript

This appendix has been removed due to copyright restrictions.

This appendix is available as:


Links to this chapter:

| Print | http://webpac.canberra.edu.au/record=b1924806~S4 |
| DOI | 10.1016/j.jsams.2014.11.333 |

**Abstract**

Only limited scientific evidence is available on the “best practices” for competition warm-up design in elite swimming. Given the recent occurrence of several major technical and technological changes in elite swimming competitions, coaches are left to draw upon outdated guidelines when designing athlete’s warm-up strategies. The aim of the present study was to describe current warm-up practices and identify contemporary issues faced by elite swimming coaches within the competition environment.
Appendix – Published Manuscript

This appendix has been removed due to copyright restrictions.

This appendix is available as:


Links to this chapter:

| Print | http://webpac.canberra.edu.au/record=b1924806~S4 |
| UC Online subscribed content | n/a |
| DOI | 10.1007/s40279-015-0376-x |

Abstract

It is widely accepted that warming-up prior to exercise is vital for the attainment of optimum performance. Both passive and active warm-up can evoke temperature, metabolic, neural and psychology-related effects, including increased anaerobic metabolism, elevated oxygen uptake kinetics and post-activation potentiation. Passive warm-up can increase body temperature without depleting energy substrate stores, as occurs during the physical activity associated with active warm-up. While the use of passive warm-up alone is not commonplace, the idea of utilizing passive warming techniques to maintain elevated core and muscle temperature throughout the transition phase (the period between completion of the warm-up and the start of the event) is gaining in popularity. Active warm-up induces greater metabolic changes, leading to increased preparedness for a subsequent exercise task. Until recently, only modest scientific evidence was available supporting the effectiveness of pre-competition warm-ups, with early studies often containing relatively few participants and focusing mostly on physiological rather than performance-related changes. External issues faced by athletes pre-competition, including access to equipment and the length of the transition/marshalling phase, have also frequently been overlooked. Consequently, warm-up strategies have continued to develop largely on a trial-and-error basis, utilizing coach and athlete experiences rather than scientific evidence. However, over the past decade or so, new research has emerged, providing greater insight into how and why warm-up influences subsequent performance. This review identifies potential physiological mechanisms underpinning warm-ups and how they can affect subsequent exercise performance, and provides recommendations for warm-up strategy design for specific individual and team sports.
Appendix – Published Manuscript

This appendix has been removed due to copyright restrictions.

This appendix is available as:


Links to this chapter:

| Print | http://webpac.canberra.edu.au/record=b1924806~S4 |
| DOI | 10.1016/j.jsams.2015.04.012 |

Abstract

Objectives

The lengthy competition transition phases commonly experienced by competitive swimmers may mitigate the benefits of the pool warm-up. To combat this, we examined the impact of additional passive and active warm-up strategies on sprint swimming performance.

Design

Counterbalanced, repeated-measures cross-over study.

Methods

Sixteen junior competitive swimmers completed a standardised pool warm-up followed by a 30 min transition and 100 m freestyle time-trial. Swimmers completed four different warm-up strategies during transition: remained seated wearing a conventional tracksuit top and pants (Control), wore an insulated top with integrated heating elements (Passive), performed a 5 min dryland-based exercise circuit (Dryland), or a combination of Passive and Dryland (Combo). Swimming time-trial performance, core and skin temperature and perceptual variables were monitored. Time variables were normalised relative to Control.
Results

Both Combo (−1.05 ± 0.26%; mean ± 90% confidence limits, \( p = 0.00 \)) and Dryland (−0.68 ± 0.34%; \( p = 0.02 \)) yielded faster overall time-trial performances, with start times also faster for Combo (−0.37 ± 0.07%; \( p = 0.00 \)) compared to Control. Core temperature declined less during transition with Combo (−0.13 ± 0.25 °C; \( p = 0.01 \)) and possibly with Dryland (−0.24 ± 0.13 °C; \( p = 0.09 \)) compared to Control (−0.64 ± 0.16 °C), with a smaller reduction in core temperature related to better time-trial performance (\( R^2 = 0.91; p = 0.04 \)).

Conclusions

Dryland-based exercise circuits completed alone and in combination with the application of heated tracksuit jackets during transition can significantly improve sprint swimming performance. Attenuation in the decline of core temperature and a reduction in start time appear as likely mechanisms.

Keywords

Core temperature;
Swim performance;
Passive heating
REFERENCES


