The Swimming Start: Measurement, Importance and Enhancement through Pre-Race Interventions

Helen Rachel Parrott

Submitted to Swansea University in fulfilment to the requirements for the Degree of Doctor of Philosophy

Swansea University

2023

Summary

The Swimming Start: Measurement, Importance and Enhancement through Pre-Race Interventions

The swimming start is underpinned by horizontal velocity, which is determined by power output on the block and can be enhanced through pre-race interventions. This thesis aimed to determine the accuracy of start times measured using a single panning camera analysis system, to quantify start times to total race time and investigate pre-race interventions to enhance start and countermovement jump performance. Study one determined the accuracy and reliability of a single panning camera analysis system to measure start time and within the context of a predetermined smallest worthwhile change (≥ 0.187 s). Systematic error and 95% limits of agreement were lower than the smallest worthwhile change for all start times. Study two quantified start time as a percentage of total race time. Start time was found to contribute up to 26.07% of total race time, with males having a lower start contribution than females, and differences between nationalities also identified. Study three assessed how isometric and ballistic postactivation potentiation conditioning activities impact start and countermovement jump performance. Ballistic postactivation potentiation elicited significantly higher countermovement jump height ($p = 0.045$) and peak power output ($p = 0.004$) values compared to the control. No significant differences were found for isometric postactivation potentiation compared to the control. Study four investigated the differences between an insulated, foil lined heat garment and trousers with heat elements across the thighs and calves. No significant changes in performance were found ($p > 0.050$) despite significantly higher muscle temperatures following active heat maintenance. Peak power output was significantly different following passive heat maintenance compared to the control ($p = 0.047$). This thesis suggests that coaches with sprint athletes should seek opportunities to enhance start performance, which can contribute a large proportion of total race time. Ballistic postactivation potentiation and passive heat maintenance can significantly increase peak power output and potentially start time, although this is on an individual basis. Pre-race interventions should be trialled within training and can be accurately monitored using a single panning camera analysis system to identify significant changes.

Keywords: Start performance, pre-race interventions, postactivation potentiation, muscle temperature

Declarations and Statements

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

[redacted]...

Date 22/03/2023

This thesis is the result of my own investigations, except otherwise stated. Other sources are acknowledged by footnotes giving explicit references. A bibliography is appended.

[redacted]...

Date 22/03/2023

I herby give consent for my thesis, if accepted, to be available for electronic sharing

[redacted]..

Date 22/03/2023

The University's ethical procedures have been followed and, where appropriate, that ethical approval has been granted.

[redacted]...

Date 22/03/2023

Table of Contents

Acknowledgements

First, I would like to thank my supervisors Prof Liam Kilduff and Prof Neil Bezodis for their advice and guidance over the past four and a half years. It has been a great experience learning off you both, and I would like to particularly thank Neil for being a listening ear, and Liam, for always providing honest feedback.

I would also like to thank Prof David Shearer for letting me use so much of your time to understand the minefield that is mixed modelling. Your expertise has been a great help to me.

Thank you to Swim Wales for funding my PhD and providing me with an incredible five years which has enabled me to attend the Commonwealth Games, an experience I will never forget. Thank you to Ross Nicholas for supporting me through this time, as well as Adam Baker, Graham Wardell and Stuart McNarry. Spencer Fuge, your knowledge of sports science will never cease to amaze me. Thank you for listening to my ideas and rants, as well as helping out during the PAP study.

Everyone who helped out during the data collection sessions, especially Dan Cunningham for being so ‘on it’ with the force data, as well as the swimmers at the Swansea and Cardiff High Performance Centres for completing the studies and being so enthusiastic throughout the process.

Of course, thank you to my friends. In particular, Dalia for always listening to me and telling me that I can do this, Katie and Anna in the “fun office” and Dan, your support has meant everything throughout this final year.

Thank you to my entire family for their unwavering support.

Finally, thanks mum. I honestly could not have done this without you. Thank you for believing in me when I didn’t, encouraging me when I needed it the most and being a constant rock in my life. I hope I’ve made you proud.

List of Figures

List of Tables

List of Abbreviations

ADP - Adenosine diphosphate

AHM – Active heat maintenance

ANOVA – Analysis of variance

ATP – Adenosine triphosphate

CMJ – Countermovement jump

CON - Control

EIMD – Exercise induced muscle damage

FINA – Fédération Internationale de Natation

ICC – Intraclass correlation coefficient

m – Metres

Min - Minute

MVC – Maximal voluntary contraction

PAP – Postactivation potentiation

PCr – Phosphocreatine

PHM – Passive heat maintenance

RM – Repetition maximum

PPO – Peak power output

RFD – Rate of force development

RPE – Rate of perceived exertion

s – Seconds

SD – Standard deviation

SWC – Smallest worthwhile change

TC – Thermal comfort

T_m – Muscle temperature

$T_{mBaseline}$ – Baseline muscle temperature

T_{mFinal} – Final muscle temperature

T_{mWU} – Warm-up muscle temperature

TS – Thermal sensation

VO_2 – Volume of oxygen

WU – Warm-up

Chapter 1. General Introduction

Competitive swimming involves participants covering a predetermined distance in the shortest time possible (Arellano et al., 2001) and has been part of the Modern Olympic Games since its inception in 1896. Thereafter, pool-based swimming at the Olympic Games has evolved, with 28 individual men's and women's races ranging between 50 metres (m) and 1500 m at the Tokyo 2020 Olympic Games. These races included backstroke, breaststroke, butterfly, freestyle and individual medley, but as the fastest stroke for most swimmers, front crawl is favoured within freestyle events (Maglischo, 2003). Seven relay events were also included during the Tokyo Olympic Games, totalling 35 medal opportunities within the pool, which equated to 10% of medal opportunities for the entire Tokyo Olympic Games. Small variations between finishing positions are also evident within the pool. For example, the difference between first and second place for the men's 100 m backstroke at the Tokyo Olympic Games was 0.02 seconds (s), which equated to 0.04% of total race time.

To minimise total swim time, thus improving medal likelihood, a swimmer must maximise their horizontal velocity through the water, a component dependent on power output and drag reduction (Barbosa et al., 2010; Toussaint & Beek, 1992). During the free-swimming segment of the race, horizontal velocity is determined by distance per stroke and stroke rate (Craig & Pendergast, 1979); however, a swimmer's initial velocity is generated during the dive, referred to as the swimming start. The start is defined as the time from the initial moment of the starting signal to the moment the swimmer's head reaches 15 m (Cossor & Mason, 2001). As outlined by the Fédération Internationale de Natation (FINA, 2017), free-swimming must begin by the 15 m mark in all strokes except breaststroke to avoid disqualification, therefore, the start cannot be longer than 15 m. The start begins on a starting block or in the water using a backstroke wedge for backstroke. Swimmers dive into the water and complete an independent number of underwater fly kicks (except during breaststroke), an undulatory movement designed to increase propulsion through the water (Lyttle et al., 2000; von Loebbecke et al., 2009) before resurfacing and beginning their stroke; because water density is substantially higher than air density (Fukuda et al., 1994), swimmers can achieve dive velocities that are twice the size of velocities attainable within the water (Kiuchi et al., 2010; Lyttle & Blanksby, 1988). Theoretically, if a swimmer can generate a high horizontal velocity whilst diving, this should transfer into the water and result in a greater horizontal velocity, providing the underwater fly kicks are efficiently performed, than those who cannot generate high horizontal velocities whilst diving.

Since medal likelihood in swimming can sometimes be determined by small time margins, coaches and practitioners seek opportunities to manipulate a swimmer's horizontal velocity with the aim of decreasing total race time. As the start dictates the velocity transferred into the water, improving this segment of the race can become a key component of the training cycle for sprint swimmers (< 200 m), where the start can make up to 26% of total race time for 50 m events (Cossor & Mason, 2001; Slawson, 2010); however, this percentage finding was concluded before the back plate on the starting block was introduced, which may have impacted the start's contribution. Similar to the overall race, previous research has established horizontal velocity at dive take-off as the underpinning contributor to start performance (Tor et al., 2015c). Velocity is the product of acceleration and time, and as acceleration is derived from force and mass, Newton's second law of motion, which states force is the product of mass and acceleration, requires consideration to enhance start performance (Nguyen et al., 2014; West et al., 2011). External power output, the product of external force and velocity, can therefore be used as a measure to observe the transference of force and horizontal velocity into the start (Turner et al., 2020). Peak power output (PPO) can be measured through integrated force platforms on the block, but these are costly, so access may be restricted. Countermovement jump (CMJ) PPO has been correlated with start time ($r = -0.73$; West et al., 2011), as both are considered explosive movements which are underpinned by power output, with greater lower-body power outputs theoretically enabling increases in CMJ height, dive distance and decreases in start time (Cossor et al., 2011). As CMJ PPO can be measured using portable force platforms, which are more readily accessible, the CMJ is regularly monitored to observe changes in PPO and monitor any improvements, when necessary, across the swim season.

During start and CMJ performance, muscles contract when myosin heads bind with parallel actin binding sites based on the sliding filament theory, which, when stimulated, rotate, causing the muscle fibres to slide across each other, thus eliciting a muscular contraction and limb movement (Folland & Williams, 2007; Powers & Howley, 2012). Therefore, with a greater frequency of actin-binding sites and myosin heads, muscles can contract more forcefully and at a higher velocity, thus increasing external power output. Increasing the recruitment of motor units stimulates more muscle fibres to contract and enables a greater force output during contractions permitting a greater external power output during the muscular contraction, based on the sliding filament theory above (Grimby & Hannerz, 1977; Henneman, 1957).

Additionally, power output is enhanced through increased muscle temperature (T_m) and hormone concentration (DeFreitas et al., 2004; Gray et al., 2008; Hansen et al., 2001; Sargeant, 1987; Stienen et al., 1996). Regular strength training can chronically increase power output through muscle hypertrophy from heightened testosterone and cortisol concentrations (Powers & Howley, 2012; Vingren et al., 2010), and technical changes, such as leg positioning on the block (Carradori et al., 2015), can also enable power output to increase during the start. Unfortunately, physiological adaptations and skill acquisition require a substantial amount of time and chronic adaptations are unachievable during the competition period due to scheduling and training availability during this time ahead of heat and final swims (DeFreitas et al., 2011; Williams & Hodges, 2005). As a result, coaches and practitioners have investigated pre-race interventions, which, if utilised correctly, can provide acute increases in PPO and performance, and impact medal likelihood and podium position due to minor improvements in overall swim time, as outlined above.

One popular pre-race intervention is postactivation potentiation (PAP) which is underpinned by increased motor unit recruitment and the phosphorylation of myosin regulatory light chains, which increases cross-bridge formation to enhance power output (Blazevich & Babault, 2019; Manning & Stull, 1982; Sale, 2004; Xenofondos et al., 2010). PAP is induced within the muscles following a high-intensity effort conditioning activity involving a similar movement to the subsequent performance (Hancock et al., 2015). A sufficient recovery time to overcome fatigue and maximise the PAP response within the muscles is also essential (Dello Iacono et al., 2018; Wilson et al., 2013). Research has detailed how PAP can improve start time (Cuenca-Fernández et al., 2015, 2019; Kilduff et al., 2011) and CMJ performance (Beato et al., 2019; Young et al., 1998) and how the PAP response is impacted by strength level (Tillin & Bishop, 2009) and muscle fibre type (Hamada et al., 2000). Although most PAP literature has used weight-lifting equipment to increase the conditioning activity intensity, ballistic PAP, which uses body mass as resistance, may be more favourable within the competition environment because of the limited equipment required (Desmedt & Godaux, 1977). Unfortunately, despite research supporting ballistic PAP within CMJ performance (Hester et al., 2017), limited research has been conducted to assess its use within swimming to enhance start performance. One limitation associated with eccentric and concentric activities is exercise-induced muscle damage (EIMD) which can be detrimental to power output and performance but is thought to be reduced following isometric exercise (Clarkson & Sayers, 1999). Esformes et al. (2011) found no PPO differences in ballistic bench press throw between eccentric, concentric, ballistic and isometric PAP conditioning activities, suggesting isometric PAP is an effective protocol to elicit a PAP response whilst reducing EIMD. Swimming competitions can last for six days, which increases the accumulation of EIMD, particularly if PAP is included as a pre-race intervention before each event. Therefore, isometric PAP may prove more beneficial to performance throughout swimming competitions, as it will reduce EIMD throughout the week whilst also achieving a PAP response and therefore increased PPO. Despite these potential benefits of isometric PAP, particularly within swimming, no known research has been completed assessing its use to enhance start performance.

Another component of the pre-race routine regularly utilised is the warm-up (WU), which aims to offer an acute performance enhancement by increasing T_m and elicit a structural and biochemical change within the muscles, such as increased metabolic reaction rate and decreased viscosity, permitting a more efficient internal environment for muscular contractions (Shellock, 1983). For example, Bergh & Ekblom (1979) found that power output, sprint time and jump performance improved when T_m increased. When the muscles contract, heat is generated as a by-product of metabolic reactions, dissipated into the bloodstream, and stimulates a rise in core and T_m (Gleeson, 1998). After approximately 15 minutes (min) of exercise cessation, T_m, and its associated mechanisms for increased power output, return to baseline values (McGowan et al., 2015), which is problematic within the competitive swimming environment because swimmers are often needed within the call room up to 20 min before their race. As a result, heat maintenance has become an additional pre-race intervention following the WU to reduce T_m decay throughout the transition period and ensure the WU adaptations enhance power output when racing begins.

Research has supported the use of heat maintenance garments in a variety of sports, and the garments have included additional warm layers, such as hooded tops and gloves (Galbraith & Willmott, 2018), and survival garments with foil linings to insulate the muscles (Beaven et al., 2018; Kilduff et al., 2013; Williams, 2012). More recently, garments with heated panels have been introduced to actively warm the muscles and promote an increase in T_m, and additional findings have supported their use throughout a swimming transition period (McGowan et al., 2016; Wilkins & Havenith, 2017). These heat maintenance garments could be more beneficial throughout the transition period if they can increase T_m, as the underlying mechanisms will be sustained more effectively than a heat maintenance garment which only delays heat decay. Nevertheless, no known research has investigated the differences between passive and active heat maintenance garments and their impact on swimming start and CMJ performance, both power-based movements.

To summarise, the start is a power-based movement that comprises a considerable amount of total race time and small improvements during this phase of the race could substantially impact podium position and medal likelihood. The CMJ is another power-based movement with an established relationship with start performance, and improvements in CMJ performance are likely to be transferred to the start. Therefore, the CMJ may be able to be used as a more direct measure of acute changes in PPO following interventions compared to the start, as potential variability in underwater fly kicking technique can impact overall start performance. Motor unit recruitment, T_m and hormone concentrations are factors that can influence PPO, and therefore require consideration when investigating changes in start and CMJ performance. To maximise performance on race day, swimmers may utilise pre-race interventions to enhance power output acutely and increase medal likelihood by manipulating their underlying mechanisms. PAP is a pre-race intervention which involves a high-intensity conditioning activity (> 75% maximum effort) to recruit higher-order motor units and thus increase power output during subsequent performance, if a sufficient recovery time is provided. PAP has been used throughout multiple sports, but ballistic PAP may be more favourable within the competition environment as it requires limited equipment. Isometric PAP is thought to reduce EIMD compared to alternative PAP modes, which can accumulate throughout swimming competitions. Heat garments have also become a popular pre-race intervention and aim to increase or maintain T_m generated during the WU. These garments may be passive or active, but regardless, research has supported their use within sport. Despite PAP offering an enhancement of power-based movements, no known research has compared the use of ballistic and isometric PAP to enhance start performance. Likewise, passive and active heat maintenance garments have gathered some traction since their introduction, but their impact on start performance has not knowingly been investigated.

Based on the above, and considering the current gaps within the literature, the aim of this thesis was to determine the accuracy of start times measured using a single panning camera analysis system, to quantify start times to total race time and investigate pre-race interventions which could enhance start performance. In order to achieve this aim, the following specific research objectives were devised:

- Establish the validity of the current single, panning camera analysis system used by Swim Wales to measure start time.

- Re-evaluate the quantification of start time from 2010 onwards to establish the impact equipment changes have had on start performance and the start’s contribution to total race time.

- Investigate the effectiveness of ballistic and isometric PAP conditioning activities to improve start time and enhance CMJ height and PPO within a group of national-level swimmers.

- Assess changes in start time and CMJ height and PPO when active and passive heat maintenance garments are utilised during the transition phase by a group of national-level swimmers.

The next chapter (2) will review the relevant literature to the specific objectives outlined above. The following chapter (3) will address the first objective, including a reliability assessment of the single panning camera. The second objective will also be addressed within the same chapter (3) and will encompass all events, sexes, and various competitions and nationalities. The following chapter (4) will focus on the third objective and investigate worthwhile changes within individuals. The proceeding chapter (5) will address the fourth objective and, similarly to the above, will investigate worthwhile changes within individuals following the interventions.

Chapter 2. Review of Literature

2.1 Introduction

This review of literature aims to discuss some of the previous research conducted to understand the determinants of the swimming start, and the considerations necessary to enhance start performance. To achieve this aim, this review has been split into four sections. Section 2.2 discusses the swimming start, detailing the start's contribution to overall swimming performance and how this may have changed as technological advancements within the sport have been made, before discussing how start time can be measured.

Section 2.3 outlines the physiological and biomechanical underpinnings of the start and the close relationship between power output, the CMJ and start performance. Various methodologies are detailed for measuring power output, as well as additional CMJ measures, such as flight time and jump height, focussing on the accuracy and reliability of each measure. The physiological mechanisms of muscular power and how power output can be increased are discussed towards the end of the section.

Section 2.4 reviews the theory supporting the first pre-race intervention explored within this thesis – PAP. The mechanisms underpinning PAP are explored, relating back to the power underpinnings in Section 2.3, and the necessary variables that require consideration for PAP to enhance start performance.

Finally, Section 2.5 evaluates the second pre-race intervention examined within this thesis – heat maintenance. The physiological adaptations that are elicited when T_m increases and the performance benefits that previous research has found are outlined and methods for measuring muscle and skin temperature are critiqued and their accuracy and application to the elite sporting world are discussed, as well as the current heat maintenance strategies available.

2.2 The swimming start

The swimming start is typically characterised as the first 15 m of the race and is defined as the moment from the starting signal to when the centre of the swimmer's head crosses the 15 m mark (Slawson et al., 2013). Although the backstroke start differs from the dive used within the other three strokes, the same definition applies. The start is typically broken into the block, flight, and underwater phases (Tor et al., 2014). The block phase can be defined as the first instance of the starting signal to the last moment of contact with the swimmer's foot on the block/backstroke wedge (Ruschel et al., 2007). The flight phase can be defined as the last moment of contact with the swimmer's foot on the block/backstroke wedge to when the centre of the swimmer's head enters the water (Tor et al., 2014). The underwater phase can be defined as the moment the centre of the swimmer's head enters the water to when the swimmer begins free-swimming at an undefined distance (Slawson et al., 2011; Vantorre et al., 2014). Research has considered the underwater phase the most important because of its duration and ability to determine the efficiency of start performance (Tor et al., 2015d), yet this is contradictory as each start phase is dependent upon its predecessor (Barlow et al., 2014; Ruschel et al., 2007). Therefore, despite the underwater phase being the longest within the start, all three start phases warrant consideration to improve start performance.

2.2.1 Swimming start performance and equipment changes within swimming

Swimming races range from four different strokes across 50 m to 1500 m and are composed of the start, free-swim and finish (last 5 m) segments; turns are also a component in long-course races of 100 m or above (Arellano et al., 2001). Sprint events are 200 m or less (Currie et al., 2018) and can be completed using all four strokes, whereas front crawl is predominantly used during distance events (≥ 400 m) as this is the fastest of the four strokes (Maglischo, 2003), demonstrated through the world record times (FINA, 2022b).

Understanding the start's contribution to total race time can help coaches and swimmers determine whether technical or physiological interventions that manipulate the start are worth pursuing to influence overall performance and increase medal likelihood. For example, Mason & Cossor (2000) quantified start time and its impact on performance through correlation analysis for the top 16 sprint swimmers and top eight distance swimmers at the 1999 Pan Pacific Championships. Start time significantly correlated with total race time for all events except the women's 200 and 800 m freestyle, 200 m butterfly and 200 m breaststroke (Table 2.1). For individual medley, only the women's 200 m significantly correlated with start time. Additional work by Lyttle & Benjanuvatra (2005) calculated the proportion of the start for each race distance, finding the initial 15 m makes up 30% for 50 m races, and 1% for 1500 m races. Although Lyttle & Benjanuvatra (2005) gave insight into the start's contribution for each distance, due to water's higher density, propulsion within the water is restricted by increased resistance compared to propulsion within the air (Maglischo, 2003), allowing swimmers to achieve a velocity during the dive that is typically twice as great as their velocity when free-swimming (Connaboy et al., 2010; Kiuchi et al., 2010). As the dive velocity is transferred into the water, this enables swimmers to complete the start with higher velocities, thus the start’s contribution to total race time is likely to be less compared to other segments of the race because it can be completed faster before drag cause deceleration.

Slawson (2010) averaged start times at the 2008 Beijing Olympic Games for the 50, 100 and 200 m women's freestyle. The maximum contribution for start time to total race time was 26% during the 50 m freestyle, and as race distance increased, the contribution from the start to total race time was stated to have decreased, although actual values were not reported. Within the same study, race time was altered to account for a 1% improvement in start time to investigate the importance of start time within the women's sprint freestyle events, which led to a podium switch between the first and second-place swimmers. Although these results were limited to one stroke within women's swimming, the results support how small improvements in start time can have a considerable effect on performance, medal likelihood and podium position. For the purpose of this thesis, the author conducted a similar analysis using results from the 2020 Tokyo Olympic Games and accounted for a smallest worthwhile change (SWC) value for start time (0.187 s), for the men's and women's sprint freestyle events (FINA, 2022a). The SWC value was subtracted from the final finishing times for second, third and fourth place to assess how a worthwhile change for start time could have impacted podium position and medal likelihood for the top four finishers (Table 2.2). Achieving a SWC in start time during the 50 m freestyle resulted in a switch between second and third place for men and women, and fourth place would have become second place for the men's 50 m freestyle if the SWC had been achieved. Second and fourth place during the men's 100 and 200 m freestyle would have increased by one finishing position (i.e. second place would have become first place) if the start time SWC had been achieved. These recent results are similar to the work of Slawson (2010) and support small improvements in start performance to significantly alter podium position and medal likelihood.

Table 2.1 The significant Pearson Product Moment Correlations (r) between start time and total race time for backstroke, breaststroke, butterfly, freestyle and individual medley races (extracted from Mason & Cossor, 2000).

Distance	Gender	Backstroke	Breaststroke	Butterfly	Freestyle	Individual Medley
50 m	Male				0.84**	
50 m	Female				0.84**	
100 m	Male	0.68**	0.59*	0.53*	0.50*	
100 m	Female	0.59*	0.76**	0.77**	0.73**	
200 m	Male	0.61**	0.62**	0.65**	0.74**	
200 m	Female	0.55*				0.58*
400 m	Male				0.72*	
400 m	Female				0.68*	
800 m	Female					
1500 m	Male				0.87**	

** indicates 0.01 level of significance and * indicates 0.05 level of significance

Table 2.2 The top four sprint freestyle finishers at the Tokyo 2020 Olympic Games with their finishing times, and a smallest worthwhile change time (0.18 s subtracted from finishing time) for second, third and fourth position to identify any changes in podium position if a smallest worthwhile change was achieved for start time (results extracted from FINA, 2022a).

	1st Place	**2nd Place**		**3rd Place**		**4th Place**	
	Finishing time (s)	Finishing time (s)	Smallest worthwhile change time (s)	Finishing time (s)	Smallest worthwhile change time (s)	Finishing time (s)	Smallest worthwhile change time (s)
Women's 50 m	23.81	24.07	23.89	24.21	24.03⁺	24.30	24.12⁺
Women's 100 m	51.96	52.27	52.09	52.52	52.34	52.59	52.41⁺
Women's 200 m	1:53.50	1:53.92	1:53.74	1:54.70	1:54.52	1:55.01	1:54.83
Men's 50 m	21.07	21.55	21.37	21.57	21.39⁺	21.6	21.42⁺⁺
Men's 100 m	47.02	47.08	46.90⁺	47.44	47.26	47.72	47.54
Men's 200 m	1:44.22	1:44.26	1:44.08⁺	1:44.66	1:44.48	1:44.68	1:44.50⁺

⁺ Indicates an increase in one podium position, e.g. second place becomes first place
⁺⁺ Indicates an increase in two podium positions, e.g. third place becomes first place

The percentage contributions identified by Slawson (2010) were supported by Argüelles-Cienfuegos & De La Fuente-Caynzos (2014), who measured start times during the semi-finals and finals at the 2013 World Swimming Championships. The average start contribution for 50 m events was 24% for the men's races and 25% for the women's, similar to Slawson (2010). For 100 m events, the start contributed 11% for men's races and 12% for women's races. Although start contribution was not published for the 200 m and 400 m events, it was outlined that the contribution decreased as race distance increased, with 800 m races having a 1% contribution for both sexes. More recently, Morais et al. (2018) published start time as a percentage of total race time for all four strokes during the 100 m finals at the 2016 European Swimming Championships which showed start time contributed 15% to total race time for males and females during 100 m events. No other distances were covered within the analysis.

Based on the studies above, it is clear that the start is a key component of sprint swimming, and even small changes in start time can significantly impact medal likelihood. However, despite the start being previously concluded as an important consideration for sprint swimming, it has since been directly impacted by several equipment changes within the elite swimming world which could alter the start's contribution to total race time and overall importance within sprint swimming.

One change was the introduction of a back plate on the start block in 2009 (Figure 2.1A), which has resulted in an evolution in start technique, noted through the set-up position swimmers can achieve with the new start block. Before 2009 swimmers would predominantly perform a track start, however, with the new back plate including an adjustable back plate, the kick start has become a favourable set-up. As a result, research has been conducted to assess changes in force production between the kick start (Figure 2.1A) and the track start (Figure 2.1B). For example, Ozeki et al. (2012) investigated kinematic differences in the two start techniques within 11 male elite college swimmers and found start time was 2% faster for the kick start. Block time was also 5% shorter, and horizontal velocity was 3% greater during the kick start than the track start. Further research has supported the use of the kick start to improve start time and horizontal velocity (Honda et al., 2012), which has led to the adoption of the kick start within the swimming world. Since the acceptance of the kick start and the velocity and power advantage of using the back plate, research has been completed to further enhance the start, including assessing leg positioning (Kibele et al., 2015), weight distribution (Barlow et al., 2014; Welcher et al., 2008) and position of the back plate (Takeda et al., 2012).

Another new change in start set-up is the backstroke wedge, introduced in 2014. Research has found significantly faster start times by 0.8% with the wedge compared to starts without the wedge. Jump distance also increased, and a smaller entry hole diameter was created when the backstroke wedge was used (Sinistaj et al., 2015). As outlined above, increasing jump distance enables the swimmer to have a longer flight phase and travel at a faster velocity for longer, as velocity decreases upon water entry as air resistance is less than water resistance (Thng et al., 2020; Tor et al., 2015a). Deceleration can be reduced by creating a smaller entry point during the start, as water resistance is limited when the entire body enters the water through the same hole because there is less contact with the water (Takeda et al., 2014). These results demonstrate how the new backstroke wedge can significantly increase horizontal velocity during the flight and underwater phases, which can enhance start time, providing additional technical considerations, such as angles of descent and ascent, are efficiently practised.

There have been two major developments within swimming that have had a direct impact on the start. The new back plate on the start block enables swimmers to achieve a greater power output and horizontal velocity off the block, supported by decreases in start time compared to the old set-up technique. Similarly, the backstroke wedge has improved start time by increasing horizontal velocity and creating a smaller entry hole. There is an abundance of research establishing the technical interventions through the new start blocks and backstroke wedge, but no known research has aimed to investigate how these developments have altered the contribution of the start to total race time, with the majority of start contribution research completed before these interventions were introduced. Therefore, further research is needed to fully understand the start’s current contribution to total race time. Until such research is completed, coaching decisions are made using out-of-date research which may no longer apply to the elite swimming world.

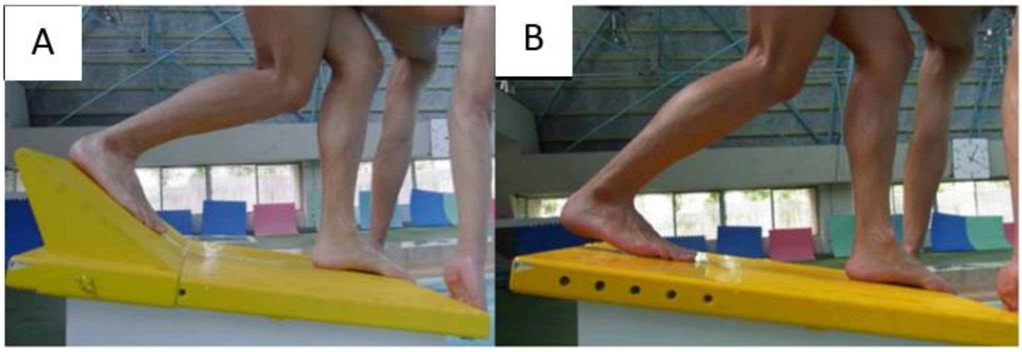

Figure 2.1 The kick start (A) and the track start (B). Notice the addition of the back plate enabling a raised position of the back foot in the kick start. (Extracted from Ozeki et al., 2012).

Although some research has only estimated the contribution of the start to the overall race based on distance, other studies have furthered this research by assessing the time contribution of the start to total race time and found that start time varies between strokes and sex. No known research has assessed the start's contribution to total race time across all distances, strokes, and sexes since the new equipment, which directly impacts the start was introduced. A current update of the importance of the start to each event, including distance events (> 400 m) enables coaches to continue making informed decisions of whether interventions should be pursued to enhance start time and therefore overall performance and medal likelihood. However, until a current study quantifies start time across all events and between sexes, coaching decisions remain based on estimates rather than accurate data.

2.2.2 Measuring start time

Race analysis through video footage has become a popular process within swimming as it can detail a swimmer's performance and offer insight into race components where worthwhile changes can be made during training (Veiga et al., 2013) or other interventions. However, for race analysis to positively impact performance, coaches, athletes, and support staff must have assurance that the data is valid and reliable, and in most applied instances this means ensuring that the camera set-up is accurate, and capable of monitoring and measuring worthwhile changes in swim time (Barris & Button, 2008).

Mooney et al. (2015) completed a systematic review assessing the various camera set-ups previously used for race analysis within swimming. Of the 30 papers reviewed, 97% of the video analysis methods were completed within the sagittal plane of motion, 20% measured swim performance above the water, 37% of papers measured swim performance with underwater cameras and 27% used both above water and underwater cameras. The set-up and camera configuration were discussed in detail within the review and maximising the swimmer within the camera view, as well as the distance of the camera from the swimmer were concluded to help reduce perspective error. The review also discussed the use of a single, panning camera to conduct video analysis compared to a multi-camera set-up, which places a camera perpendicular to each key distance being measured within the analysis, and the potential benefits and consequences of each method.

One of the consequences of using a single, panning camera is the possible presence of parallax error, which impacts video analysis because objects closer to the camera lens appear to travel shorter distances than those further away (Martin et al., 2020). Therefore, depending on the lane filmed within the pool, parallax error may lead to inaccurate measurements of start time compared to other lanes. Consistently using the same lane throughout training when interventions are being investigated can minimise the effects of this error, and placing the camera perpendicular to, but as far back as possible from 25 m ensures that any parallax error on either side of this distance is equal. However, if only one distance is being measured (e.g. 15 m for analyses focussing on just the start) within the analysis, having a camera which is perpendicular to this distance will reduce the parallax error substantially, regardless of the distance away from the pool.

Despite the reduced parallax error, a multi-camera set-up is often unrealistic within the applied setting, as restrictions are often enforced within the competition environment for analysis equipment, limiting the available camera positions and operators. A single, panning camera is more realistic within a competition environment where race analysis is often time-sensitive because coaches and swimmers require analysis reports from morning heats ahead of evening finals. Using multiple cameras requires synchronisation for race analysis to be completed, thus increasing the processing time and affecting the ability to complete race analysis within sufficient time, despite being the most accurate method to reduce parallax error (Stephens et al., 2019). Processing time is substantially reduced when using a single camera, making it a favourable analysis method when used within the applied setting, providing the method has been validated beforehand, and users have completed a reliability check.

The validity of using a single, panning camera to complete race analysis was conducted by Kelley (2014) during a domestic swim meet. Times to 5, 10, 15, 25, 35, 40 and 45 m were measured using a single panning camera at 25 m and multiple cameras placed perpendicular to each predetermined distance. All strokes and distances up to 400 m were recorded for both sexes and frame rates were all set to 50 frames per second. The times to each predetermined distance were compared between the two cameras to produce a mean error value, and limits of agreements and confidence intervals were also calculated. Distances further away from 25 m had greater mean error values; for example, the 45 m distance had a mean ± standard deviation (SD) of -0.133 ± 0.137 s. The 25 m distance had the smallest mean error (0.006 ± 0.045 s). The mean error for 15 m time was -0.047 (± 0.076 s), with butterfly having the largest mean error range across the four strokes, outlining the differences between strokes and the potential caution that should be considered when each stroke is analysed. Kelley (2014) discussed a SWC value and defined it as an improvement in one finishing position during the race, but a SWC value was only provided for turn time (15 m off the wall), as this was the main focus of the paper. A 0.47% improvement in turn time was calculated as the SWC needed to improve finishing position by one place, based on results from the 2012 London Olympic Games and the SWC required to make an Olympic Final (Table 2.3). Despite this description, the SWC referenced throughout the paper was 0.2 s, based on anecdotal evidence from the coaching and performance analysis team, which based on the results in Table 2.3, predominantly applies to 100 m performance. Nonetheless, the single, panning camera set-up was deemed valid for use within a race analysis setting as the mean error for all distances were lower than 0.2 s. As this SWC value was based on turn times and anecdotal evidence, the relevance to other distances, and whether these additional distances can be accurately measured using the single panning camera set-up is questionable. Therefore, an additional validation focussing on error differences between the two camera set-up methods for start time is necessary, accompanied by a pre-determined SWC value for start time. Nonetheless, the results of Kelley (2014) support the use of a single, panning camera to obtain race analysis within an applied setting when cameras perpendicular to each set distance cannot be used based on set-up restrictions.

Table 2.3 The freestyle world record, 0.47% of the world record and this 0.47% improvement divided by the number of turns (extracted from Kelley, 2014).

Distance	**100 m**	**200 m**	**400 m**	**800 m**	**1500 m**
World Record (s)	46.91	102	220.07	452.12	871.02
0.47% improvement (s)	0.22	0.48	1.03	2.12	4.09
Improvement per turn (s)	0.22	0.16	0.15	0.14	0.14

To summarise, parallax error is a potential consequence of conducting race analysis with a single panning camera and can lead to inaccurate start times, however it is a more realistic method to use within the applied environment where set-up and travel restrictions can reduce the number of cameras and operators available. The lower processing time enables feedback to be delivered to coaches and swimmers faster for any necessary changes to be made between heats and finals. Nonetheless, further work is necessary to establish the accuracy of a single panning camera within the context of a SWC for start time, rationalised by previous research where significant improvements in start time have been identified, instead of anecdotal evidence. Provided that mean errors for start time are smaller than the SWC, and there is a high user reliability, this would further support the use of a single panning camera set-up as an accurate, time effective method for determining start time within swimming.

2.2.3 Summary

The start is a key component of sprint swimming and can contribute up to 30% of total race time (Lyttle & Benjanuvatra, 2005). However, due to equipment changes within the last two decades, such as the introduction of the back plate on the start block in 2009, there is some discrepancy over the contribution of the start to total race time, with no known research offering a more recent quantification of start time across all events and between both sexes. Measuring start time during competitions can be beneficial to observe how training and interventions impact start performance, providing there is a SWC which has been predetermined through previous literature. Although a multi-camera set-up is desirable because of the reduced parallax error, a single, panning camera is often more realistic within the applied setting but should be validated in advance to ensure accurate start times are measured and confident decisions can be implemented based on the results.

2.3 The determinants and underpinning factors of start performance

2.3.1 Deterministic model of start performance

As outlined above, the start is a key element of overall sprint swimming performance and can contribute up to 26% of total race distance (Slawson, 2010). As a result, start research has been conducted to understand how technical changes can enhance start performance, including underwater fly kick frequency (Yamakawa et al., 2017), underwater trajectory (Tor et al., 2015d) and foot positioning on the backstroke wedge (de Jesus et al., 2013).

Additional research has aimed to establish the biomechanical and physiological underpinnings of a successful start. For example, Tor et al. (2015) analysed 52 dives performed by Australian national swimmers on the Wetplate analysis system. This system had previously collected a range of above-water and underwater kinetic and kinematic variables, including horizontal velocity at take-off, entry velocity, peak horizontal and vertical forces, underwater velocity and start time. Factor analysis determined the impact each variable had on start performance, and based on these results, regression analysis was conducted to understand which variables contributed to predicting start performance. Block time and horizontal velocity at take-off were identified as key above-water parameters. However, horizontal velocity at take-off was the only significant predictor of start performance. The underwater parameters included time in underwater descent and ascent and time to 10 m, and all three were significant within the regression analysis to predict start time (Table 2.4). Ruschel et al. (2007) also found significant correlations with start performance and average underwater velocity, flight distance, angle of entry and descent distance.

Table 2.4 Multiple regression outputs identifying the significant block and underwater parameters which significant contribute to start time. Note the importance of horizontal velocity at take-off to improve start performance (extracted from Tor et al., 2015).

On block parameters

Parameter	**B**	***R***	***P***	**Full model**	
Constant	12.31		0.00*	R	0.90
Take-off horizontal velocity	-1.42	-0.90	0.00*	R^2	0.81
Time on block	1.07	0.50	0.13	P	0.00

Full equation
Time to 15 m = 12.21-1.42 (Take-off horizontal velocity)

Underwater parameters

Parameter	**B**	***R***	***P***	**Full model**	
Constant	0.51		0.01*	R	0.98
Time to 10 m	1.50	0.05	0.00*	R^2	0.96
Time underwater in ascent	0.05	0.02	0.06*	P	0.00
Time underwater in descent	0.12	0.04	0.01*		

Full Equation
Time to 15 m = 0.51 + 1.50 (time to 10 m) + 0.05 (time in underwater ascent) + 0.12 (time in underwater descent)

*Significant for $P < 0.05$

Both Ruschel et al. (2007) and Tor et al. (2015) established horizontal velocity at take-off as the key underpinning of the start and suggest that if start performance is to improve, horizontal velocity at take-off must be increased. Although additional factors contribute to start performance as outlined above, because the time taken to cover a given distance is directly determined by the average velocity, obtaining a higher horizontal velocity enables swimmers to travel the start distance (15 m) in less time (Barbosa et al., 2010), providing drag and therefore deceleration is reduced during the underwater phase. Therefore, faster start times can improve overall performance and contribute to medal likelihood (Table 2.2). As a result of horizontal velocity underpinning start performance, a deterministic model was developed by the researcher for the purpose of this thesis (Figure 2.2) to offer a holistic approach to enhancing horizontal velocity throughout the start, with this variable being directly impacted by the block phase (power output) and the underwater phase (reducing drag). Considering some of the physiological, biomechanical and psychological variables that underpin power output, drag reduction, and resultant horizontal velocity, this should enable an enhancement in start time, which, even if marginally improved, can significantly impact overall performance and medal likelihood.

Research has aimed to establish how increasing horizontal velocity during the block and flight phase can enhance start performance, providing drag is minimised during the underwater phase. Figure 2.2 outlines some factors that can contribute to horizontal velocity and included technical considerations throughout the start and the physiological properties that affect muscular contractions. Within this deterministic model, one of the immediate underpinnings of horizontal velocity during the start is drag, which depends on take-off and entry angles and the underwater fly kicks. The other immediate underpinning of horizontal velocity during the start is power output, which can be manipulated through pre-race interventions and the block phase (Figure 2.2).

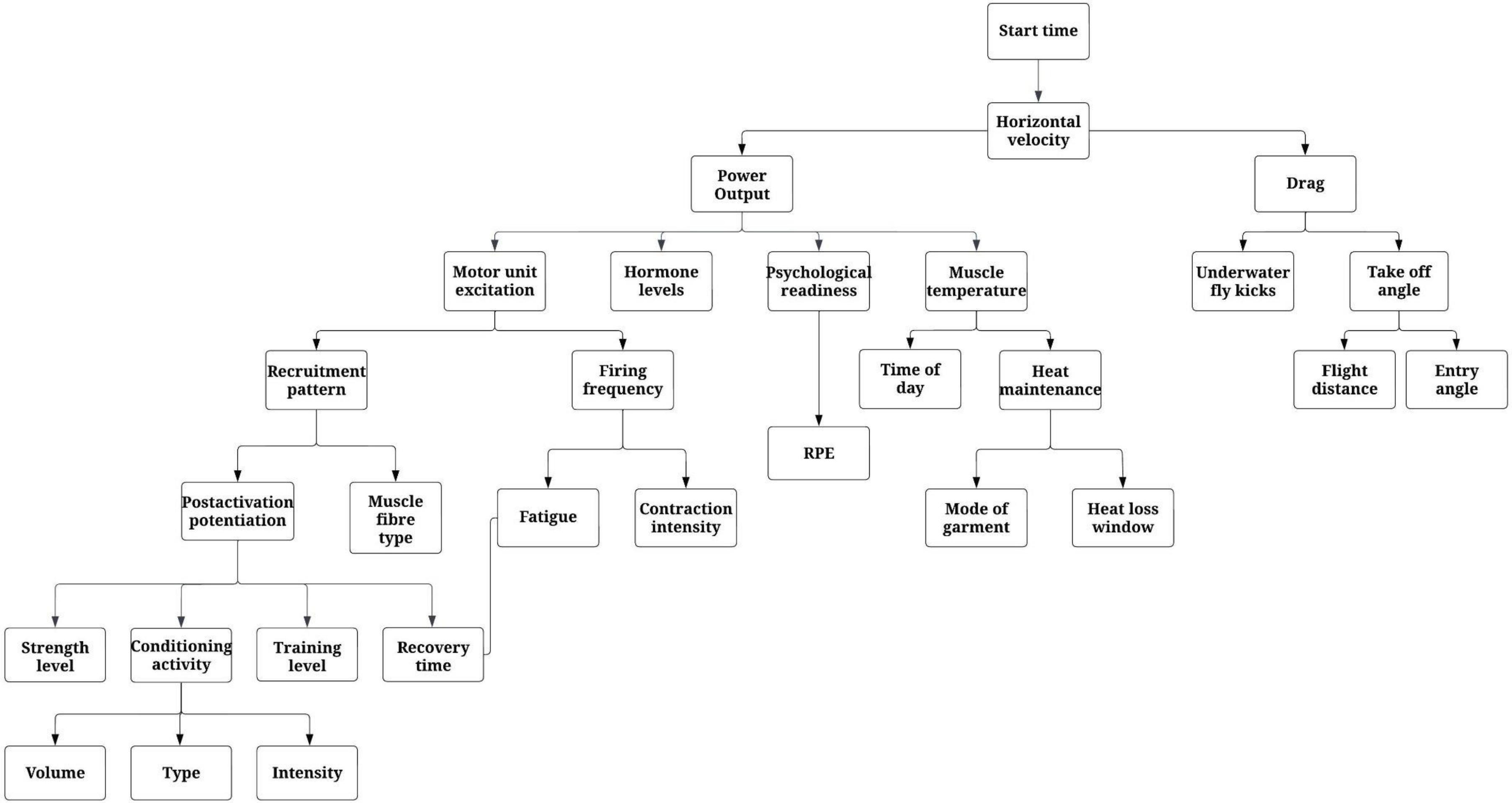

Figure 2.2 A deterministic model outlining the variables that contribute to start time, predominantly from a biomechanical and physiological perspective.

The variables within Figure 2.2 have been selected based on results from previous research which has aimed to enhance horizontal velocity and start performance, outlined at the beginning of this section. As this thesis aims to investigate pre-race interventions, this is the primary focus of Figure 2.2, and therefore the variables within the model relate directly to those interventions which might impact power output. Their potential contribution to enhancing power output, and therefore start performance, are further discussed in Sections 2.4 and 2.5. However, it is important to note that this is a theoretical model, and changes in one component of the model could positively or negatively impact start time. Other factors should therefore be considered when power output off the block is being measured. For example, increased power output may enhance horizontal velocity, but could alter entry angle and increase the drag experienced by the swimmer, therefore negatively impacting start time. Nonetheless, Figure 2.2 outlines the variables that can affect start time that will be discuss throughout the remainder of this thesis and is not an extensive list of the factors that can influence the start.

2.3.2 External power output and horizontal velocity

The start is a multi-joint movement which requires a swimmer to effectively coordinate and produce a large horizontal velocity off the block/backstroke wedge and maintain this velocity underwater by minimising drag, as outlined above (Figure 2.2). Variation in start performance is often observed, particularly within the underwater phase, the longest phase of the start where the largest variance typically occurs (Tor et al., 2015d). External power output is the product of external force production and velocity of the centre of mass, and can be measured and monitored through kinetic data using force platforms (Noffal & Lynn, 2012); therefore, external power output can be used as a measure of a swimmer's ability to produce a large horizontal velocity over a relatively short period of time and of overall start performance. For the remainder of this thesis, "power" and "power output" will refer to external power and external power output, unless otherwise stated.

To understand the relationship between power output and horizontal velocity, Newton's first law of motion, which describes how a body will remain in a constant state of rest or motion until an external force acts upon it, must first be considered

(Santavy, 1986). Force is generated within the muscles through an intricate series of neural and metabolic pathways, which result in muscle shortening and tension developing within the muscle (Powers & Howley, 2012); Section 2.4.2 provides a more detailed outline of how muscular contractions occur. Based on these events, muscles can contract and produce force, which, if large enough, can overcome inertia and result in movement depending on muscle shortening velocity (Figure 2.3; Itza-Ortiz et al., 2004; Jaric, 2015). When the force generated by the muscles is applied by the foot to the starting block/backstroke wedge, based on Newton's third law of motion, an equal and opposite force is applied back onto the foot, enabling a swimmer to propel themselves forward/backwards. Once the swimmer begins to initiate movement, power is generated (Turner et al., 2020) based on the equation below:

$$Power = \frac{Work}{\Delta Time}$$

Increasing lower-body power output during the block phase to improve start performance has been supported by West et al. (2011), who measured start time, 3 repetition maximum (RM) squat strength and CMJ performance within 11 international sprint swimmers. CMJs were performed on a force platform to obtain CMJ height and power output and starts were performed on a start block with an integrated force platform to determine peak vertical and horizontal forces. Significant negative correlations were found between start performance and CMJ height and relative power. Additionally peak vertical and horizontal force significantly correlated with start time, 1RM strength and peak power. These results support lower-body PPO as an underpinning to horizontal velocity, as shown through the significant correlations between power output and start performance, as well as demonstrating the relationship between force production and power output. The correlations found by West et al. (2011) also suggest that lower body strength levels are an essential component to increase power production, a principle later discussed in Section 2.3.5. Therefore, providing the additional start variables, such as entry angle and underwater technique remain consistent, lower-body PPO can be manipulated through physiological principles to enhance start performance (Figure 2.2).

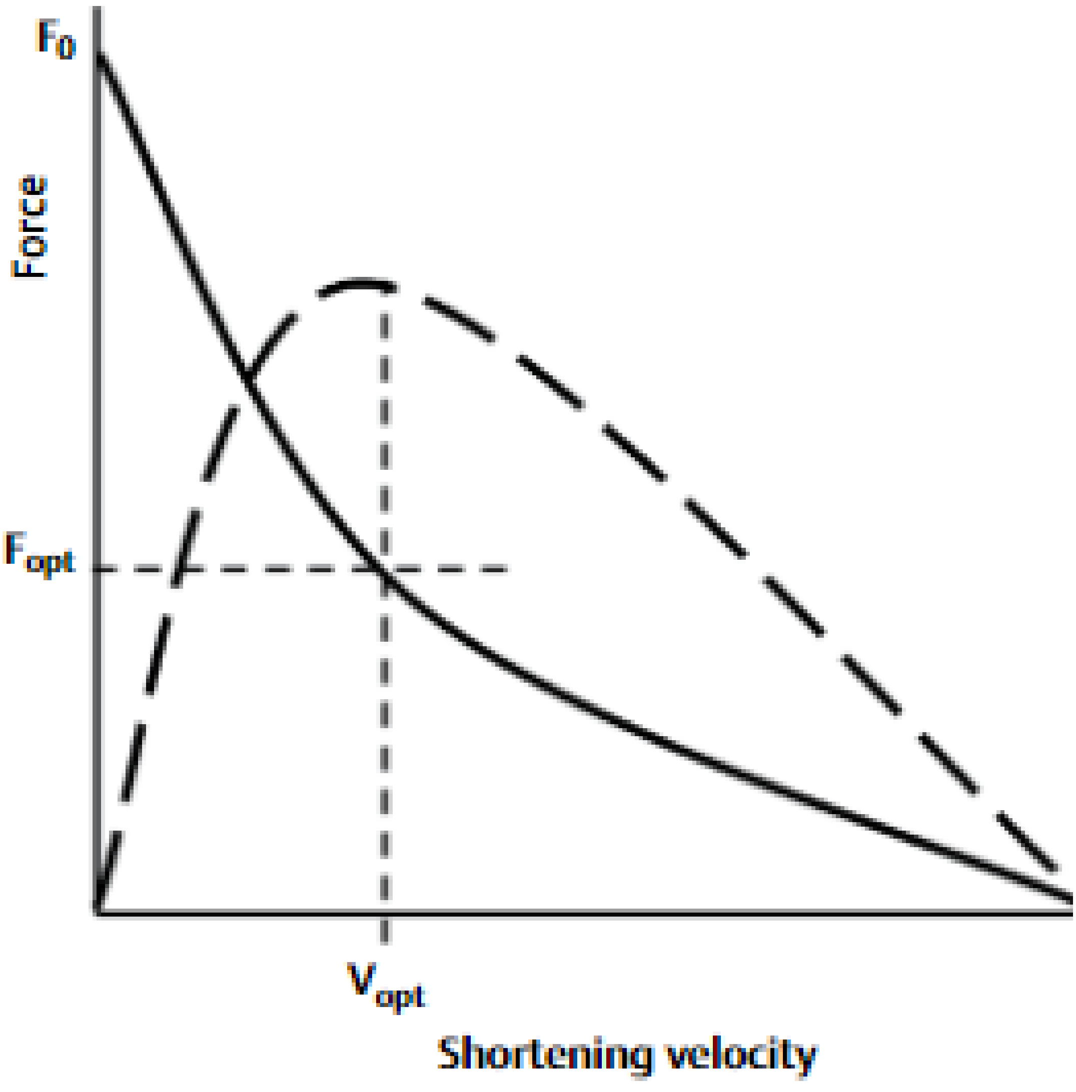

Figure 2.3 Typical force-velocity (solid line) and the corresponding power-velocity (dashed line) relationship obtained from a hypothetical muscle or muscle group. F_{opt} corresponds to the muscle force that overcomes the optimal external load that results in the optimum shortening velocity for maximising power (extracted from Jaric, 2015).

2.3.3 Countermovement jump and the swimming start

Although increased lower-body power output is fundamental for increasing horizontal velocity off the block and enhancing start performance, which can be measured through 15 m time, start performance is influenced by several technical considerations throughout the underwater phase (Figure 2.2). Ideally, power output would be measured during the block phase to understand how effective an intervention is at enhancing start performance. Unfortunately, measuring power output during the block phase can be unrealistic within the applied setting due to the availability of start blocks with an integrated force platform. Therefore, an alternative land-based measure is required to give insight into a swimmer's power output and ability to generate force within the lower-body, ideally, that could transfer across to start performance.

Jump testing is often completed alongside measuring start performance to understand a swimmer's ability to effectively produce power, especially when this cannot be directly measured during the start. Several jump tests have been used within previous swimming studies. For example, Thng et al. (2020) found concentric impulse during a squat jump was significantly correlated with start time for males ($R^2 = 0.746$) and females ($R^2 = 0.651$), with higher impulses on the block eliciting shorter start times. Despite this support for the squat jump, the CMJ is most investigated within swimming research and its relationship to start performance, and the remainder of this section supports this relationship. Likewise, the participants within Chapters 3 – 5 of this thesis regularly completed CMJs throughout the training season as this assesses their fundamental ability to forcefully and powerfully extend their legs, irrespective of the different global body orientations which may be used to satisfy the demands of different sporting tasks. Therefore, investigating the relationship between CMJ and the start is more comparable to previous swimming literature, and has a greater real-world application to the elite swimming population.

West et al. (2011) investigated the relationship between CMJ and start time within 11 international sprint swimmers to understand whether improvements in CMJ performance can be transferred to the start. They found significant negative correlations between start time and CMJ height and power output, measured using a force platform. Peak vertical and horizontal forces measured on a force platform during the block phase also significantly correlated with CMJ height and power output, establishing a relationship between the CMJ and start performance and enabling CMJ performance to become an alternative measure of start performance when start blocks with an integrated force platform are unavailable, as can often be the case within the elite sporting world. The results of West et al. (2011) also suggest that as well as horizontal velocity, peak force and power output are important considerations for determining start performance, which is anticipated because of the relationship between force, power and velocity (Section 2.3.2). Monitoring PPO changes through start time can only be identified if all additional variables which contribute to start performance (Figure 2.2) remain consistent across all trials. As a result, monitoring CMJ performance can give a direct insight into how interventions impact PPO, which is likely transferred to the start based on the correlations by West et al. (2011).

Cossor et al. (2011) also studied the relationship between CMJ and start performance within six international male swimmers whilst accounting for the potential change in block set-up position because of the new back plate on the start block (Section 2.2.1). Participants performed a start at maximum effort, and three CMJs were completed on a force platform, one with both feet next to each other, one with the right foot in front, and one with the left foot in front to replicate the position a swimmer adopts when performing the start. When the right foot was in front, significant relationships between peak vertical jump force and block time and peak horizontal and vertical force and start time were found. A significant correlation was found when the left foot was in front for peak vertical jump height and peak vertical force. These results support the transference of CMJ performance to start time, particularly when one foot is in front of the other, as is the case during the swimming start. Although start time was not included within the correlation analysis, Cossor et al. (2011) isolated the block and flight phases, thus removing any technical variables which can influence start time throughout the underwater phase, the phase where the largest variance within start performance occurs (Tor et al., 2015d). However, as start performance is dependent on the horizontal velocity achieved on the block (as well as the deceleration which occurs when the swimmer enters the water), isolating the block and flight phase can provide a direct measure of the swimmer’s ability to produce power and increase horizontal velocity. Therefore, although start time was not measured by Cossor et al. (2011), the results still support the use of CMJs to monitor start performance when assessing power off the block, particularly as the block phase impacts the subsequent start phases (Barlow et al., 2014), and an increase in power output on the block can enhance horizontal velocity, and therefore start time, providing deceleration is minimised when the swimmer enters the water (Section 2.3.2).

The relationship between CMJ and the start was more recently supported by García-Ramos et al. (2016), who assessed relationships between start time, CMJ and squat jump performance in 20 international female swimmers. Significant correlations were found for jump take-off velocity and 5 m time. A significant correlation was also found for relative PPO and 5 m and 10 m times; no jump variables significantly correlated with start time. As 5 m time is less dependent on the underwater phase, these findings continue to support the use of CMJs to monitor start performance and reemphasise the importance of power generation on the block to reach 5 m and 10 m faster. Unfortunately, because the study failed to specify the event the participants specialised in, generalising the findings to other elite swimmers cannot be achieved. For example, suppose the majority of the sample were distance swimmers. In that case, because PPO is less of a determinant in distance swimming, as this variable is not sustainable during distance events (Rodriguez & Mader, 2010), PPO is likely to be less than if sprint swimmers were used. Nonetheless, as 5 m time significantly correlated with relative PPO, this supports CMJ performance as a monitoring method for start performance when PPO cannot be directly measured during the block phase.

As well as significant correlations between CMJ and start performance, Sammoud et al. (2019) investigated the effects of plyometric jump training and whether improvements in CMJ performance can be transferred to the start. A group of 26 male, prepubertal swimmers either completed an eight-week plyometric jump training programme alongside swim training, or just swim training. CMJ and start performances were performed before and after the intervention. Following the eight weeks, CMJ height increased by 10%, and start time decreased by 5% for those who had completed the plyometric jump training. The control group had a decrease in CMJ height by 3%, but start time decreased by 2%. Therefore, although start time can improve through swim training alone, faster start times have been found when improvements in jump performance are also sought, thus establishing the CMJ as a land-based measure to monitor start performance.

Significant correlations have been found between start time and CMJ performance, suggesting that CMJ performance can be monitored throughout training to ensure physiological adaptations are induced to enhance power output when this cannot be directly measured during the start. Correlations have identified significant relationships between lower-body PPO and start time, suggesting that if any change in CMJ performance were to occur, they would likely transfer to the start. CMJ can therefore be considered a performance measure which provides a direct insight into PPO and removes any additional variables which may impact start performance, enabling coaches and practitioners to confidently identify changes in PPO. Although take-off angles during the start and CMJ are different because of their set-up, recent research has found significant correlations between dive distance and CMJ height (Calderbank et al., 2020). Therefore, if translated correctly, enhancing CMJ height and PPO can be associated with a heightened horizontal velocity at take-off which is sustained for longer because dive distance is increased. These enhancements during the block and flight phases benefit swimmers as this prolongs the time they travel their fastest throughout the race, before deceleration occurs due to drag forces (Kiuchi et al., 2010; Rago et al., 2018).

2.3.4 Measuring peak power output

An accurate and reliable method to measure PPO during the start and CMJ increases the confidence of coaches and support staff that improvements in power output are transferred to the start and are not a systematic error within the method used to record CMJ height and PPO. Currently, multiple methods are available to monitor CMJ performance, all with varying financial, accessibility and validity considerations. Inertial measurement units are easily portable, require minimal set-up and although research has supported inertial measurement units to accurately and reliably determine CMJ height (Picerno et al., 2011; Toft Nielsen et al., 2019) through accelerometers, gyroscopes and magnetometers (Ahmad et al., 2013), it has been suggested that an alternative method should be used to accurately determine PPO (Rantalainen et al., 2018). Additionally, jump-mats can offer instantaneous CMJ height and flight time results based on the time between take-off and landing, determined through contact with the mat (Klavora, 2000), but these are not valid compared to other methods (Dobbin et al., 2017).

Force platforms provide highly accurate force readings and are the gold standard method for measuring external ground reaction forces. Body weight can be measured through the vertical force applied to the force platform during quiet standing, and mass can be determined from this by accounting for the magnitude of acceleration due to gravity. Following this, centre of mass acceleration can be derived through Newton's second law of motion (Section 2.3.2), and velocity and displacement of the centre of mass can then be calculated through various integration methods (Buckthorpe et al., 2012; Owen et al., 2014); jump height can be accurately calculated using take-off velocity (Moir, 2008)

There are multiple considerations when recording CMJ performance using a force platform, which can all impact the validity of the final CMJ height and PPO results, and several protocols exist to determine these measures. For example, CMJ height can be calculated using flight time, total centre of mass displacement, or take-off velocity, which can provide different results (Moir, 2008). This lack of consistency between definitions and calculations of CMJ performance using a force platform was addressed by Owen et al. (2014), who aimed to establish a protocol to measure lower-body PPO when 15 male rugby union players completed a maximal CMJ on a force platform. Within the study, differences were investigated for the vertical force range, sampling frequency (100, 500 and 1000 Hz), method of numerical integration (Simpson’s rule and the trapezoidal rule) and identification of the initiation of the CMJ (when force is greater than bodyweight ± 5 SD minus 90 – 30 ms), as these are important considerations when calculating CMJ height and PPO. Each variable was reviewed, and the recommended criterion method is presented in Table 2.5. Therefore, despite a range of variable considerations available when measuring CMJ height and PPO, the process described by Owen et al. (2014) should be followed, when possible, due to the thorough validation completed.

Force platforms are capable of providing highly accurate CMJ results and are considered the gold standard for collecting force data. Through Newton's laws of motion, equations can determine many dependent variables, such as jump height, flight time and PPO. As a result of their reliability, practitioners can have confidence that changes in CMJ performance are a result of training adaptations rather than the systematic error from the force platform (Beckham et al., 2014). Although, various methods are available and method consistency is crucial for monitoring CMJ performance, force platforms, whose models have been previously validated, should be utilised to ensure the accuracy and reliability of the data is maximised where possible.

Table 2.5 Criterion method specification for the measurement of peak mechanical power in a CMJ by the criterion force platform method (bodyweight ± 5 standard deviations; extracted from Owen et al. 2014).

Variable	**Criterion method specification**
Vertical force range and resolution	5.6 × bodyweight of higher at 16-bit resolution
Sample frequency	1000 Hz
Integration frequency	1000 Hz
Method of integration	Simpson’s rule of trapezoidal rule
Determination of body weight	Mean ground reaction force measured for 1 s of the stationary stance phase immediately before the signal to jump
Determination of initiation of jump	The instant that bodyweight ± 5 SD is exceeded after the signal to jump has been given minus 30 ms

2.3.5 Physiological and biochemical underpinnings of power output

Pre-race interventions are regularly implemented within a swimmer's race preparation, as they can be designed to enhance power output and sprint performance. An understanding of the physiological and biochemical processes within the body is necessary when designing pre-race interventions, as these properties require manipulation for subsequent performance to be enhanced through increased power output.

Hormones

Hormones are secreted from the endocrine glands and are transported in the blood to the desired tissues or organs. Hormones react to environmental changes to maintain homeostasis within the body and elicit specific responses through biochemical reactions, including growth and development, metabolism and reproduction (Hiller-Sturmhöfel & Bartke, 1998).

Testosterone has received much attention because it promotes protein synthesis while simultaneously reducing protein degradation and eliciting muscle hypertrophy (Vingren et al., 2010). Additional hormones, including growth hormone and cortisol, are released in response to exercise to maintain glucose levels or promote tissue repair following intensive exercise (Birzniece et al., 2011; Powers & Howley, 2012). The hormonal response of growth hormone, cortisol and testosterone to isometric strength training was assessed by Hansen et al. (2001) in 16 untrained males before (pre) and after (post) a nine-week strength training programme. Eight participants completed a one-sided arm-only programme, and the other eight completed a one-sided leg and arm programme. Significant acute changes in hormone plasma concentrations were found for testosterone for the leg and arm group for pre and post-blood concentrations. The leg and arm group had a significant increase in cortisol during pre; the arm-only group had no significant increases in cortisol concentrations during pre or post. Growth hormone was lower during post for the leg and arm group compared to pre, but the arm-only group had higher growth hormone plasma concentrations at post compared to pre, although this was not significant. It was concluded that training larger muscle groups elicits a larger anabolic hormone response, thus increasing strength levels to a greater extent than when smaller muscle groups are trained in isolation.

Hormones are released into the bloodstream in response to various factors, including exercise. They encourage muscle hypertrophy, which can lead to chronic increases in power output. Although there are acute hormonal responses to exercise, it is unclear whether this leads to acute increases in power output and the possible impact on subsequent performance. As some hormones elicit a growth and development response within the muscle, the impact on acute power production is likely minimal, with more influence on chronic power production. Therefore, measuring blood hormone levels may only offer insight into the effectiveness pre-race interventions have at eliciting a hormonal response, rather than the impact hormone concentrations have on immediate power output.

Motor unit recruitment

Motor units are present within the muscle and are stimulated to perform muscular contractions through synaptic inputs transferred from the central nervous system; motor units are composed of motor neurons and their adjoining muscle fibres (Powers & Howley, 2012; Wakeling et al., 2006). The more motor units stimulated, the greater the force production, as more myosin heads are bound to the actin binding sites; therefore, the central nervous system directly influences force production and power output (Dideriksen et al., 2022). However, the ability to stimulate more motor units within the contraction is more comprehensive and relies on motor unit recruitment.

Since motor units can dictate force magnitude during a muscular contraction, previous research has sought to identify how motor unit recruitment is organised and the variables that impact the number of motor units stimulated. The work of Henneman has provided breakthroughs in the knowledge of motor unit recruitment. Henneman (1957) assessed how different electrical stimulations impact the reflex response magnitude within the ipsilateral sciatic nerve of cats. When the stimulation voltage was raised, an increase in firing frequency and reflex discharge amplitude was also observed. For example, a 10.0 v stimulation elicited a discharge amplitude which was twice the size of the discharge amplitude during the 5.0 V stimulation. Therefore, it was concluded that motor units are recruited in order of size, with smaller contractions requiring less stimulation and, therefore, fewer motor units and vice versa. It was suggested that this size principle resulted from the excitability of smaller motor units compared to larger motor units, supporting the need for increased motor unit recruitment to elicit stronger, more powerful contractions.

Once recruited, research has found the magnitude of the synaptic input is less to maintain force production than initiating a muscular response. Gorassini et al. (2002) sought to investigate the synaptic input of motor units throughout voluntary and reflexive contractions. Motor unit activity (recruitment and de-recruitment) from the tibialis anterior and soleus of 11 participants was measured through intramuscular electrodes and surface electromyography during contractions at 2 to 5% maximal voluntary contraction (MVC). Results found that once a motor unit was recruited following voluntary contractions, it would continue firing during subsequent contractions regardless of the intensity. Therefore, for power output to increase during the start, higher-order motor units need recruiting, a process which can be achieved through pre-race interventions and will be discussed further in Section 2.4.

Power output is directly impacted by motor unit recruitment and firing rate, with a greater proportion of motor units eliciting a greater force output from the muscles. Motor unit recruitment can be altered by preceding contractions and relies on the excitation of the synaptic nerve to stimulate motor unit activation and, therefore, muscular contraction. Motor unit recruitment is reviewed again in Section 2.4.2, detailing how conditioning activities can elicit earlier recruitment of motor units, aiding subsequent power output and performance.

2.3.6 Summary

There is a clear connection between power output and horizontal velocity, with greater power production within the muscle typically leading to an increase in horizontal velocity, enabling swimmers to obtain faster start times, providing the underwater phase is efficient at reducing drag. Although PPO during the start can be difficult to measure within the applied setting, research has found a strong relationship between CMJ and start performance. CMJs can be monitored through several methodologies, but force platforms are considered the gold standard because of their high accuracy and reliability. There are several physiological and biochemical underpinnings of muscular power, with hormones eliciting muscle hypertrophy, which can enhance power output in the long term. For an acute increase in power output, motor unit recruitment needs to be maximised to ensure all motor units within the muscle are activated and able to increase power within the muscle.

2.4 Postactivation potentiation as a pre-race intervention

During training, coaches and practitioners utilise different physiological stimuli and technical changes with the aim of maximising the athlete's competition performance. However, chronic changes cannot be achieved during competition because of the time requirements for physiological adaptations and skill acquisition (Williams & Hodges, 2005). Therefore, coaches and support staff investigate pre-race strategies to provide athletes with acute performance enhancements at competition. Amongst all sports, WUs have been widely accepted as an effective method for preparing athletes, both physiologically and psychologically (Hedrick, 1992; McGowan et al., 2015). However, additional pre-race interventions can be utilised to maximise performance alongside the traditional WU; one of these is PAP. PAP is a pre-race intervention where athletes complete a conditioning activity shortly before competing to enhance performance. PAP is considered to improve the performance of strength and power-based movements within the muscles, providing the conditioning activity and the subsequent movements are biomechanically similar (Gołaś et al., 2016; Kilduff et al., 2011; Sale, 2002).

2.4.1 Postactivation potentiation and swimming and countermovement jump performance

A vast amount of research has assessed the effectiveness of PAP across multiple sports, including rugby (Bevan et al., 2009; Kilduff, Bevan, Kingsley, et al., 2007; Kilduff et al., 2013), basketball (Gołaś et al., 2016; Sygulla & Fountaine, 2014), and athletics (Gołaś et al., 2016; Lim & Kong, 2013). However, this section of the review will focus on PAP within swimming and CMJ performance, a movement which previous research has found reflects start performance (Section 2.3.3).

Before 2011, only a handful of studies had been conducted investigating PAP within swimming. Interestingly, this coincides with new equipment being introduced into the sport, including the back plate on the start block and the backstroke wedge (Section 2.2.1). As the swimming start is dependent on horizontal velocity, which is determined by power output (Figure 2.2), it can be considered that PAP will have a positive effect on start and overall swimming performance, something researchers have since aimed to quantify.

Sarramian et al. (2015) assessed differences in 50 m freestyle swim times of 18 national level swimmers following a traditional 30 min swim WU, a lower-body PAP conditioning activity, an upper-body PAP conditioning activity and a combined upper- and lower-body PAP conditioning activity. All PAP conditioning activities were preceded by a 15 min swim WU and 10 min changing period. The traditional swim WU had significantly faster 50 m times than upper-body PAP by 1%. Although no other significant differences were identified, results showed that the traditional race WU had faster 50 m times than any PAP condition (Figure 2.4). Despite these results indicating that PAP is not beneficial at enhancing overall swim performance, other studies have presented conflicting results. Hancock et al. (2015) found an improvement in 100 m swim performance after four dynamic 10 m sprints whilst attached to a power rack. Swims were completed after a 6 min recovery time. Overall, swim times were significantly faster after the conditioning activity by 0.9%, rather than those who had only completed a 900 m standardised WU (Table 2.6). Both 50 m split times were also faster after the conditioning activity by 0.9% and 0.8%, respectively, although these were not significant. Blood lactates showed a 7% increase after the conditioning activity. The variation between the findings of Sarramian et al. (2015) and Hancock et al. (2015) may be explained through the recovery time between the conditioning activity and performance. Sarramian et al. (2015) used 4, 8 and 12 min recovery times based on individual strength testing. However, these times may have been too dispersed, unlike the 6 min recovery time set by Hancock et al. (2015). Variation in recovery time will be discussed further within Section 2.4.4 of this review. However, the dynamic sprints designed by Hancock et al. (2015) are more biomechanically similar to the proceeding swim, compared to the conditioning activities implemented by Sarramian et al. (2015), another important consideration when maximising the effectiveness of PAP. The results of Hancock et al. (2015) are also further supported by McGowan et al. (2016), who assessed different WU strategies on 100 m freestyle swim times using 16 national junior swimmers. The conditioning activity comprised four different activation exercises repeated twice over 5 min, followed by a 100 m maximum effort swim from a dive. Swim time was significantly faster after the conditioning activity compared to the standardised WU by 0.7%, and although start times were not significantly faster, turn times were also quicker following the conditioning activity. Despite some similarity between Hancock et al. (2015) and McGowan et al. (2016), some uncertainty remains surrounding the effectiveness of PAP within swimming and the most appropriate conditioning activity protocol and recovery times necessary for proceeding performance to be enhanced.

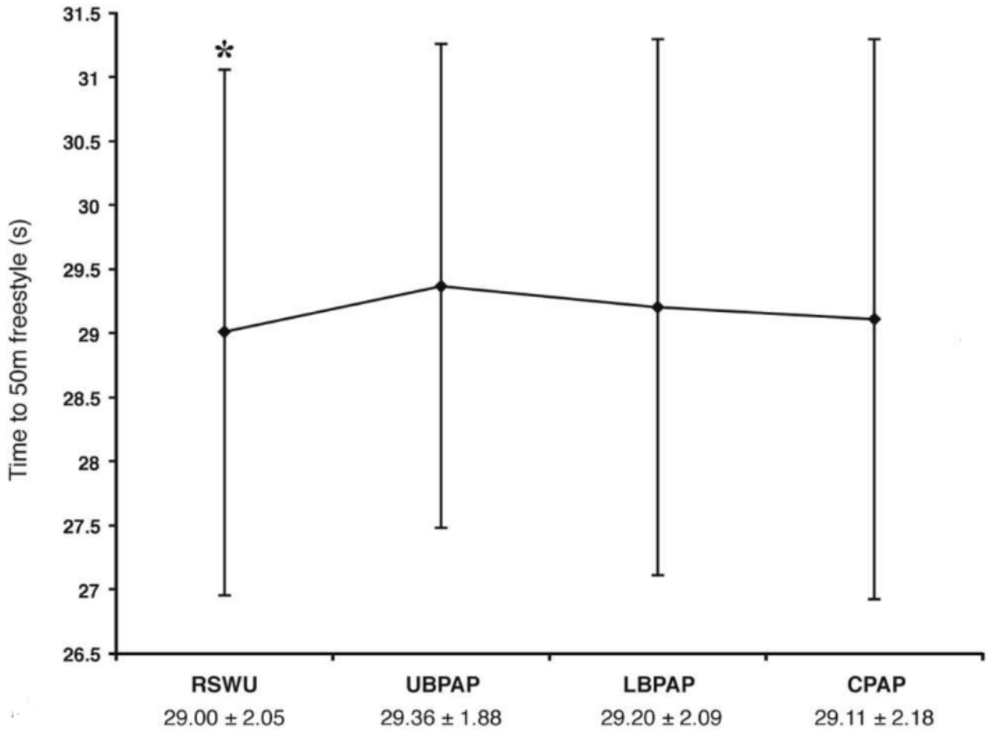

Figure 2.4 Mean times to 50 m freestyle after traditional swim warm-up (RSWU), upper-body PAP (UBPAP), lower-body PAP (LBPAP) and combined upper- and lower-body PAP. * denotes a significant decrease in 50 m time compared to UBPAP ($p < 0.05$). Please note the Y-axis starts at 26.5 s as presented by Sarramian et al., (2015).

Table 2.6 Swimming performance for 100 m and 50 m splits for all participants (extracted from Hancock et al., 2015).

Distance	Control time (mean ± SD (s))	PAP time (mean ± SD (s))	*p*
100 m	63.45 ± 5.37	62.91 ± 5.06	0.029
1st 50 m	29.78 ± 2.48	29.52 ± 2.34	0.051
2nd 50 m	33.67 ± 2.93	33.40 ± 2.78	0.058

Other swimming studies have focused on the start, as this skill requires a high-power production to be successful (Section 2.3.2). Considering this, Kilduff et al. (2011) investigated the influence of PAP on start time in a group of international sprint swimmers compared to a traditional swimming WU. Swimmers were required to perform two dive starts having completed their regular race WU or a back squat PAP conditioning activity (three repetitions at 87% 1RM) beforehand. Although results showed that PAP significantly increased peak horizontal and vertical force on the block, no significant differences were found for start time. Nonetheless, as previous swimming races have been won by 0.01 s, even small, non-significant improvements can influence overall performance and medal likelihood. The results of Kilduff et al. (2011) were also supported by Cuenca-Fernández et al. (2015) who studied the influence of a yoyo squat conditioning activity (four repetitions at maximum effort), a lunge conditioning activity (three repetitions at 85% 1RM) and a standardised swim WU (control) on the start performance of 14 national level swimmers. Participants completed all three conditions, and a dive start after an 8 min recovery. The yoyo squat significantly improved start time compared to the control by 2%. The lunge conditioning activity also positively affected start time by 2%, but this was not significant. Although the comparisons between both studies are limited because of slight differences in intensity and conditioning activity type, both have supported PAP to improve start performance in swimming.

More recently, Cuenca-Fernández et al. (2019) measured changes in start variables, including peak force and resultant power output, in 13 national level swimmers following an isotonic conditioning activity or a traditional swim WU, a similar protocol to Cuenca-Fernández et al. (2015). PAP had significant positive effects on vertical force, impulse, velocity and acceleration, yet this did not apply to the horizontal components, which were higher in the standard WU condition. Unfortunately, start time was not measured, limiting the ability to confirm this conditioning activity’s impact on overall start performance.

Although studies on PAP and start performance in swimming are sparse, multiple studies have aimed to assess the changes in CMJ performance after a PAP conditioning activity. Young et al. (1998) measured changes in CMJ height in ten male participants before and after a set of five half-squats at 5RM. They found a significant time effect between the jumps, with a 3% increase in jump height 4 min after the conditioning activity. A significant group effect was also identified, indicating that those who had a greater 5RM experienced the biggest potentiation effect. These results were later supported by Gołaś et al. (2016), who investigated changes in the rate of power development during a CMJ in 13 basketball players before and after four sets of four Keiser squats at 1RM. A significant change in the rate of power development was found, and increased by 18% on average; however, the recovery time between completing the conditioning activity and the final CMJ was not stated, which could have impacted the overall results and effectiveness of the conditioning activity.

More relevant to swimming, Kilduff et al. (2011) assessed differences in CMJ height and power output in nine international sprint swimmers following a set of three back squats at 87% 1RM. Although they found a significant decrease in CMJ height and power output 15 s after the PAP conditioning activity, both metrics were significantly higher after an 8 min recovery time. These results demonstrated the impact of PAP on CMJ performance and the importance of recovery time between the conditioning activity and subsequent performance, an area discussed later within this review (Section 2.4.4).

Positive findings suggest that PAP can be a beneficial pre-race intervention to ensure start performance is enhanced. Regardless, only a limited amount of research has been conducted assessing changes in start performance following a PAP conditioning activity, meaning no conclusions can be made confirming which PAP mode is best at enhancing start performance, with additional research necessary to support these previous findings.

2.4.2 Mechanisms and physiological responses to postactivation potentiation

Despite previous literature demonstrating the influence PAP can have on strength and power-driven movements, the underlying mechanisms and understanding behind this physiological phenomenon remain unresolved. Several theories have been developed, aiming to explain the biochemical and neurological changes within the muscles that contribute to the success of PAP as a pre-race intervention.

One strongly supported theory surrounding PAP is the phosphorylation of myosin regulatory light-chains. During a muscular contraction, calcium is released from the sarcoplasmic reticulum due to an action potential travelling along the T tubule. In short, this release of calcium exposes the actin-myosin binding sites previously blocked by the tropomyosin molecule, permitting actin-myosin cross-bridge formation (Noakes, 2001). It is theorised that the PAP conditioning activity activates the enzyme myosin light chain kinase, which elicits a phosphorylation of the myosin regulatory light chain, causing a structural change within the myosin head, increasing the sensitivity of actin and myosin to calcium. A heightened calcium sensitivity exposes more actin-myosin binding sites, increasing the likelihood of cross-bridge formation and the rate at which these cross-bridges can produce force (Blazevich & Babault, 2019; Hodgson et al., 2005; Lorenz, 2011).

In support of this theory, Manning & Stull (1982) investigated myosin light chain subunit (LC2) changes in rats following a tetanic stimulation within the extensor digitorum longus muscle. They found a 0.30 mol phosphate/mol LC2 increase. The soleus muscle was also studied using the same method. However, only minimal changes were found, with the conclusion that differences in LC2 concentration between the two muscles resulted from muscle fibre type differences. Despite Manning & Stull (1982) supporting this theory in rats, discrepancies between human participants have been found. Smith & Fry (2007) investigated regulatory light chain phosphorylation within 11 recreationally active men following a 10 s MVC of a single knee extension. Comparing muscle biopsies before and after the MVC, only seven participants had a positive response to the contraction. Regulatory light chain phosphorylation increased by 23% on average; the other four participants experienced a 15% decrease, and no changes in power output were recorded. However, variations in strength level and training history may have influenced the phosphorylation levels between participants, variables later discussed within this review (Section 2.4.5) and require consideration when developing a PAP conditioning activity.

Another hypothesis underpinning PAP is an increased recruitment of higher-order motor units based on the muscle's contractile history. As outlined in Section 2.3.5, the ability to recruit motor units is determined by the size principle whereby motor units are recruited in size order from smallest to largest. Larger motor units are recruited during high force movements alongside the smaller motor units, recruited during low force movements (Henneman, 1985). Therefore, larger motor units need recruiting to increase force production within the muscle and speed/strength performance. Using MVCs within a PAP conditioning activity is considered to recruit these large motor units and increase the excitation of motor neurons for a short duration after, aiding in subsequent performances of power-based movements (Gullich & Sehmidtbleicher, 1996).

As motor neurons are recruited through the central nervous system, the excitability of motor neurons can be monitored through the Hoffmann (H) reflex, a reflectory reaction of the muscle elicited by electrical stimulation (Anthi et al., 2014; Palmieri et al., 2004). To examine the impact of PAP on the H-reflex, Gullich & Sehmidtbleicher (1996) monitored H-amplitude within the lateral gastrocnemius and soleus muscles. They found a significant increase in the H-amplitude of the lateral gastrocnemius muscle between 4 and 11 min following a set of five MVC's. Before this increase, an initial decrease in H-amplitude was identified, likely due to the coexistence of fatigue and PAP within the muscle. A similar pattern was observed in the soleus muscle, however, H-amplitude did not reach the same peak as the lateral gastrocnemius muscle, likely because of muscle fibre differences. Nonetheless, this increase across both muscles following a PAP conditioning activity supports the theory of increased motor unit recruitment contributing to the mechanisms underpinning PAP.

Increased T_m has also been attributed to enhanced muscle function following a PAP conditioning activity. In a review by Blazevich & Babault (2019), changes in T_m were considered to result from increased muscle metabolism from a PAP conditioning activity. Myosin ATPase activity is linked to T_m and determines the rate of adenosine triphosphate (ATP) breakdown and thus the formation of myosin-actin cross-bridges (Noakes, 2001). If heightened enzyme activity is promoted from T_m, this, therefore, promotes an increased cross-bridge formation rate and power production. T_m and its relevance to performance is detailed throughout Section 2.5.

2.4.3 Fatigue mechanisms

Fatigue is an inevitable consequence of exercise and is associated with reduced voluntary force output and performance (Enoka & Duchateau, 2008). Upon completion of a conditioning activity, fatigue and PAP coexist within the muscle (Rassier & MacIntosh, 2000), however, the cause of fatigue is not considered specific to a single-factor but many physiological and psychological factors that contribute to decreased force output and performance (Enoka & Stuart, 1992). Fatigue's biochemical and neurological aspects have been split into two components: (i) Central fatigue, which relates to motor unit recruitment and the neural mechanisms contributing to muscle contractions. (ii) Peripheral fatigue, a change in the biochemical and contractile process within the muscle, often associated with increased lactate accumulation (Carroll et al., 2017).

A limited amount of research has been conducted considering central fatigue theories within maximal intensity exercise, likely because of the difficultly of measuring voluntary activation. Nonetheless, Ross et al. (2001) found that stride rate began to decrease during 100 m sprint performance, which was explained through a change in recruitment pattern and firing rate. Before this, Grimby et al. (1981) found a distinction between central fatigue and muscle fibre types. They concluded that fast-twitch muscle fibres experience central fatigue during MVC's because of a protection mechanism that prevents extreme exhaustion; slow-twitch fibres did not demonstrate signs of central fatigue.

One theory surrounding peripheral fatigue is a depletion of phosphocreatine (PCr) stores and a decreased energy supply to the muscles. ATP is supplied to the muscles during maximal intensity exercise through PCr and adenosine diphosphate (ADP) phosphorylation; however, PCr stores are quickly depleted, limiting maximal contractions (Marieb, 1995; Noakes, 2001). Once PCr is no longer readily available to the muscles, fatigue is induced, and maximal intensity cannot be sustained. PCr and ATP depletion within the muscles has been supported by previous studies that assessed the muscle's metabolites following maximal intensity contractions. For example, Cain & Davies (1962) compared ATP and ADP concentrations within the rectus abdominus muscles of frogs after a supramaximal stimulation or rested condition. ATP concentrations were reduced, suggesting that PCr stores were also depleted and unable to produce ATP. Assessing both ATP and PCr stores following a 30 s maximum effort sprint, Bogdanis et al. (1996) also found significantly decreased ATP and PCr stores. By-product (creatine and inorganic phosphate) and blood lactate concentrations were also analysed and significantly increased following the maximum effort sprint, again supporting the depletion of PCr stores inhibiting the production of ATP.

As PCr and ATP stores within the muscle are depleted, causing the onset of fatigue, it is necessary to ensure an appropriate recovery time is provided for these stores to regenerate before subsequent contractions.

2.4.4 Recovery time

Depending on the recovery time between the PAP conditioning activity and subsequent performance, power output can be enhanced, depressed or remain unchanged (Rassier & MacIntosh, 2000). Accordingly, an understanding of recovery duration is necessary to maximise PAP as an effective pre-race intervention.

Multiple studies investigating the effects of PAP on subsequent performance across different recovery durations have observed an initial decrease or stabilised performance compared to pre-PAP baselines. Immediately following a PAP conditioning activity, Gullich & Sehmidtbleicher (1996) found a decrease in the explosive force during voluntary plantar flexions. The explosive force returned to the baseline value at 2 and 3 min and then significantly increased between 4 and 13 min. On average, peak explosive force was produced at 9 min. H amplitude was also measured and significantly increased by 32% between 8 and 9 min, demonstrating that more higher-order motor units had been recruited following recovery from fatigue, a PAP mechanism outlined in Sections 2.3.5 and 2.4.2. However, a large SD (± 3.5 min) suggests a high variation between individuals regarding the required recovery duration after PAP, as differences in participant factors can impact the ability to harness PAP (Section 2.4.5), therefore knowledge of a participant's strength level and training history could indicate whether a PAP conditioning activity would aid an individual's subsequent performance. A similar pattern was observed by Kilduff et al. (2007) for PPO for the upper and lower body during a ballistic bench press throw and CMJ. Approximately 15 s after the PAP conditioning activity (3RM squat or bench press), PPO significantly decreased for both the CMJ and ballistic bench press throw. Upper-body PPO was significantly greater than the baseline at 8, 12 and 16 min by 3%, 5% and 1% respectively. Lower body PPO was also significantly greater than the baseline at 8 and 12 min by 7% and 8%, respectively, although it had returned to a similar value as the baseline by 16 min.

Kilduff et al. (2011) investigated the recovery duration required for PPO and peak jump height during a CMJ. Using a group of 13 international level swimmers, results showed that PPO and jump height were achieved 8 min after the PAP conditioning activity. They monitored these two variables across four other time points between 15 s and 16 min after the conditioning activity. Initially, they observed a significant decrease in CMJ performance, most likely due to fatigue being present within the muscles. At 4, 12 and 16 min, power output and jump height had returned to similar values as the baseline. This 8 min recovery duration was further supported by Seitz et al. (2017), who observed similar findings on 20 m sprint performance in 20 rugby league players following a 15 m loaded sled push (75% body mass) or a 9 m loaded sled push (125% body mass). Similar to Kilduff et al. (2011), diminished sprint performance was observed 15 s after both PAP conditioning activities. Sprint performance after the 15 m sled push began to improve at 4 min, and significant improvements were observed 8 and 12 min after the conditioning activity, with a 2% change in performance at 8 min. The 9 m sled push had significantly worse 20 m sprint performance than the baseline at each time point, with very likely harmful effects found at 15 s and 4 min after the conditioning activity. These results demonstrate the importance of recovery time after PAP to ensure performance is improved. They also suggest how differences in the conditioning intensity can determine the success of PAP on subsequent performance, an area considered within Section 2.4.6. A meta-analysis by Gouvêa et al. (2013) further established the pattern of PAP response and decay. They found that a 4 – 7 min recovery interval delivered similar results to baseline performance, whereas significant improvements were observed in multiple studies between 8 and 12 min. They concluded this was because fatigue and PAP were balanced within the muscle during 4 – 7 min, whereas PAP was heightened after 8 min because fatigue had diminished. They further established that performance returned to baseline values by 16 min.

Although there appears to be a generalised consensus that 8 min is an optimal recovery time following PAP, it is apparent within the results that interindividual variability impacts the relative effectiveness of PAP on subsequent performance. As previously discussed throughout this review, fibre type, training level and strength level are all participant variables that contribute to the success of PAP and the necessary recovery time required to enhance performance.

2.4.5 Participant factors that influence postactivation potentiation

Muscle fibre type

Section 2.4.2 gave brief examples of how muscle fibre type can influence the phosphorylation of myosin regulatory light chains. It was outlined that Manning & Stull (1982) and Moore & Stull (1984) found differences in LC2 content between the soleus and the extensor digitorum/gastrocnemius muscles in rats. Because the soleus muscle is primarily composed of type I muscle fibres, these results signified the importance of understanding muscle morphology when considering PAP effectiveness. As the phosphorylation of myosin regulatory light chains is theorised to be an underlying mechanism of PAP, if this process within the muscle is unable to be enhanced, the PAP response will be reduced. Therefore, it can be considered that muscles and individuals with higher type II muscle fibres will benefit the most from PAP.

Previous studies assessing the relationship between PAP response and muscle fibre type have been completed. Houston et al. (1987) analysed muscle biopsies from the different fibre types within the vastus lateralis of 15 participants after completing a 10 s isometric MVC or a 60 min cycle at moderate intensity on a stationary ergometer. Although LC2 content increased significantly after the MVC, differences between fibre types were minimal. These results support the theory of myosin regulatory light chain phosphorylation as a mechanism of PAP. Alternatively, Hamada et al. (2000) assessed the PAP response in 20 recreationally active men after a 10 s MVC. They found that participants who experienced the greatest PAP effect had significantly more type II fibres than those with the lowest PAP effect. Obtaining biopsies from the four highest and lowest PAP responders, fibre area was significantly larger for the high responders for both type IIa and IIb by 32% and 40%, respectively. While these results support the assumption that those with more type II muscle fibres benefit most from PAP, the maximum recovery time between the MVC and subsequent performance was only 5 min and, therefore, possibly an inadequate recovery time for all participants to recover from fatigue and maximise the PAP response.

Some researchers discuss how muscle fibre type is a determinant in understanding the mechanisms of PAP and, therefore, the protocols required for performance enhancement. However, only a limited sample of studies have taken direct muscle biopsies and measured the volume of each fibre type, with many making assumptions of fibre type based on the muscle's primary purpose (O'Leary et al., 1997; Vandervoot & McComas, 1983). If muscle fibre type remained constant within the muscle, these assumptions could be valid, yet, although predominantly genetic, muscle fibre type can adapt depending on training mode (Russell et al., 2003). With this in mind, the next section will explore the implications individual training level has on the PAP response.

Training level

Changes in motor unit recruitment is an adaptation associated with strength training that refers back to a proposed mechanism of PAP (Sections 2.3.5 and 2.4.2). If larger motor units can be harnessed more effectively within the muscle, the PAP response is likely to increase, as higher-order motor unit recruitment has been associated with acute increases in strength and power output (Gullich & Sehmidtbleicher, 1996; Henneman, 1985). With this in mind, research analysing the PAP response amongst different participant training levels has been conducted. Hamada et al. (2000) investigated the PAP response of the triceps brachii and triceps surae in triathletes, distance runners, recreationally active and sedentary men. After a 10 s MVC, twitch responses were elicited for each muscle, 5 s, 1, 3 and 5 min after the MVC to measure peak torque and time to reach peak torque. Triathletes and distance runners had significantly higher peak torque values in the triceps surae than the sedentary group by 30% and 24%, respectively. Time to peak torque was also significantly higher than both the recreationally active and sedentary groups. Triathletes had significantly higher peak torque values than the sedentary group for the triceps brachii, but this was the only significant result within this muscle. The other three groups had similar values. These results show that trained muscles do have a stronger PAP response compared to untrained. As distance runners did not experience a greater PAP response within the triceps brachii compared to the recreationally active and untrained groups, this signifies the importance of completing a PAP conditioning activity within muscles that are regularly trained and how a PAP response is not guaranteed for all muscles.

Chiu et al. (2003) also examined PAP response differences in the training level of seven athletic and 17 recreationally active participants who completed a control WU or a heavy resistance WU. Three squat jumps were then performed at 30%, 50% and 70% 1RM, 5, 10 and 18.5 min after the WU. Average power output was higher across all jumps for the athletic group, although this was only significant for the 30% 1RM jump. Peak power was also higher for the athletic group, with significant differences observed for the 30% and 50% 1RM jumps. The athletic group was composed of a football player, a triathlete, and five weightlifters, suggesting how an abundance of lower body training can influence the PAP response and the necessity of utilising PAP on previously trained muscles. Requena et al. (2011) found similar effects between endurance and strength athletes for a squat jump, CMJ and a 15 m sprint compared to untrained individuals after completing a 10 s isometric MVC knee extension in a seated position.

The literature suggests the PAP response is heightened in those with significant training experience, providing the conditioning activity utilises muscles that are predominantly used throughout this training. This is likely because of chronic adaptations within the muscle from various training types and intensities, such as increased hormone concentration and muscle hypertrophy, as outlined in Section 2.3.5, therefore untrained muscles might not experience as great a PAP response as those regularly trained.

Strength level

Participant strength level is another determinant that has been suggested to impact the magnitude of the PAP response and the necessary recovery time for fatigue to diminish (Seitz et al., 2014). Adaptations from strength training include increased power output, increased fatigue resistance and the ability to complete tasks at a lower effort than before the adaptation; an increased ability to recruit higher-order motor units is also associated with strength training (Hughes et al., 2018), a PAP mechanism previously mentioned in Section 2.4.2.

In support of this, Gourgoulis et al. (2003) investigated vertical jump performance in 20 men following a progressive half-squat conditioning activity. Participants were split into two groups: 1RM above 160 kg or 1RM below 160 kg. The stronger group had a 4% larger jump height compared to the group with a 1RM below 160 kg, however, this was not significant. Seitz et al. (2014) also observed changes in squat jump performance following a conditioning activity and found a heightened PAP response in stronger individuals. Jump performance was measured at 15 s, 3, 6, 9 and 12 min after completing three back squats at 90% 1RM. Although both groups followed a similar PAP response pattern, stronger participants reached significantly higher power outputs at 3 min than the weaker group, which were significantly higher than their baseline at 6 min; the same pattern was observed for jump height. These results suggest that stronger individuals can obtain a bigger PAP response and achieve this earlier following the conditioning activity, explained through the fatigue resistance adaptation achieved through strength training (Chiu et al., 2003). If fatigue is not as prominent within the muscles, then recovery should arise faster, permitting PAP to enhance subsequent performance earlier after the conditioning activity. This conclusion was further supported by Jo et al. (2010), who studied differences in Wingate test performance following five back squats at 85% 1RM. Correlation analysis showed that those with a greater 1RM tended to reach their maximum PAP response earlier than weaker participants ($r= 0.771$, $p < 0.05$), thus a knowledge of strength level is vital to determine the participant's potential ability to harness a PAP response, and whether a performance enhancement could be achieved through this pre-race intervention.

2.4.6 Conditioning activity factors

Conditioning intensity and type

As outlined above, fatigue and PAP coexist within the muscle, therefore intensity is another variable that must be considered to ensure recovery from fatigue occurs before the PAP response is also diminished.

An early study by Vandervoort et al. (1983) suggested that conditioning contractions needed to be at 75% 1RM or above to elicit a PAP response; contractions below this intensity produced little to no PAP response. Following this, McBride et al. (2005) investigated the differences between a 30% and 90% PAP conditioning activity. They found those who had completed the 90% intensity condition had significantly faster 40 m sprint times than the control. The 30% condition also had faster sprint times, but these were not significant. West et al. (2013) also found that greater conditioning intensities produced larger PPO values during subsequent performances.

Intensity is an essential component during a PAP conditioning activity to ensure higher-order motor units are recruited, to increase power output during subsequent performance. Although some evidence supports lower intensity conditioning activities (Sotiropoulos et al., 2010), based on PAP mechanisms and previous findings, it can be concluded that high or maximal intensity conditioning activities improve subsequent performance more substantially.

Many studies have used concentric and eccentric conditioning activities with intensities at 75% 1RM or higher, as outlined above. However, these contractions often require significant weight-lifting equipment to obtain a PAP response, but this may not be plausible within the competition venue. Athletes are also required to be present in a call room environment, sometimes 20 min before the race, restricting access to the required equipment for heavy loaded conditioning activities. Therefore, an alternative conditioning type which effectively elicits a PAP response and can be completed at high intensities, is easily transported and requires limited equipment is necessary.

Ballistic exercises are dynamic movements, using maximum velocities with the participant's mass as the only form of resistance; ballistic exercise has also been shown to quickly recruit higher-order motor units, therefore supporting its use as a PAP conditioning activity (Desmedt & Godaux, 1977). A literature review by Maloney et al. (2014) outlined the principles behind ballistic exercises to elicit the PAP mechanisms. In the review it was stated that ballistic exercises are able to recruit all motor units in a short timeframe, compared to alternative contraction types which rely on the size principle for motor unit recruitment. Therefore, ballistic exercises may require less time to elicit a PAP response. Additionally, this contraction type removes some of the limitations around equipment, and providing athletes are well-practised with the ballistic conditioning activity, can be performed within the call room at the ideal time before racing, without additional support staff. As a result, ballistic PAP conditioning activities have been studied to assess their effectiveness at enhancing subsequent performance. Wilcox et al. (2006) investigated changes in 1RM bench press performances following two medicine-ball chest passes or two plyometric push-ups. Bench press strength significantly improved by approximately 3 kg after both conditioning activities compared to the control. These improvements were also significantly better than the baseline value. West et al. (2013) supported the effects of ballistic PAP on the upper-body. After participants completed three sets of three ballistic bench presses at 30% 1RM, a significant increase in PPO was found. However, although not significant, when these results were compared to a heavy resistance training conditioning activity (three sets of three heavy bench press at 87% 1RM), ballistic PAP power output was lower. Despite supporting the use of ballistic PAP as a pre-race intervention, these results suggest that heavy loading conditioning types can provide greater increases in power output. These results are likely due to differences in conditioning activity intensity and support the need for maximal effort intensities when completing PAP conditioning activities.

In contrast, Hester et al. (2017) investigated differences between ballistic and heavy resistance conditioning activities on CMJ performance. Following ten rapid jumps or five heavy back squats, jump height was similar across both conditions. Back squats showed an initial decrease in jump height from the baseline 1 and 3 min after the conditioning activity, demonstrating a similar recovery time pattern, as mentioned in Section 2.4.4. Interestingly, jump height was greater immediately following the ballistic conditioning activity and did not return to baseline values until 10 min after; the same pattern was observed for PPO. Peak velocity and power were suppressed below baseline for the duration of the 10 min following the heavy resistance conditioning activity. Although none of these differences were significant, these marginal gains can determine medal likelihood in elite sport.

One of the consequences of repeated eccentric movements is EIMD, which has been shown to negatively affect performance (Clarkson et al., 1986; Clarkson & Newham, 1995). Symptoms of EIMD include impaired muscle function, muscle soreness and muscle stiffness, theorised to result from changes in neurological function and myosin-actin cross-bridge formation (Clarkson & Sayers, 1999). Isometric contractions are considered to result in limited EIMD. Therefore, they may be a more appropriate conditioning type for athletes who compete over multiple days and utilise PAP to enhance performance. Reduced EIMD will ensure muscle function can be maximised for each race, as the mechanisms underpinning PAP will be able to function effectively.

As a result of the reduction in EIMD, comparisons of PAP conditioning types have been explored to determine whether isometric PAP can also enhance subsequent performance. Esformes et al. (2011) studied isometric, eccentric, concentric and dynamic upper-body PAP conditioning activities and their effects on a ballistic bench press throw. PPO was significantly greater following isometric PAP, although throw distance was unchanged. Despite no significant differences between conditioning type, isometric PAP did provide the greatest force output and rate of force development (RFD). Concentric PAP experienced a decreased RFD and throw distance, suggesting that it is an ineffective contraction type. The results of Esformes et al. (2011) were further supported by Bogdanis et al. (2014), who also found a significant increase in baseline CMJ performance following an isometric conditioning activity compared to eccentric and concentric conditioning types.

Baudry & Duchateau (2004) assessed differences in conditioning type and their effect on the PAP response. They found similar PAP responses and time decays following eccentric, concentric and isometric conditioning activities, suggesting that conditioning type does not impact the PAP response. These conflicting results may be explained through the differences in participant training level. As previously discussed, training level can impact the success of PAP and the response achieved. Because Esformes et al. (2011) and Bogdanis et al. (2014) both used competitive athletes, a PAP response was expected, compared to the nine participants studied by Baudry & Duchateau (2004) who did not state training level. Therefore, all variables need consideration when designing and implementing a PAP conditioning activity.

Ballistic and isometric PAP conditioning activities are both performed at maximal intensities, ensuring higher-order motor units are recruited before subsequent performance. Considering motor unit recruitment and previous findings, it can be concluded that ballistic and isometric PAP conditioning activities can enhance speed and power-based movements. They also require limited equipment and can therefore be easily completed within the applied sporting environment.

Conditioning volume

Duration and number of sets/repetitions also needs consideration when manipulating PAP. The conditioning activity needs to ensure higher-order motor units are recruited and myosin regulatory light chains are phosphorylated to create a window of opportunity where fatigue is diminished and PAP is heightened within the muscle. However, only a limited amount of research has been conducted investigating conditioning activity volume on subsequent performance.

Xenofondos et al. (2017) investigated the effect MVC duration had on twitch torque. Six sets of isometric plantar flexion MVC’s were completed for either 3 s or 6 s. The 3 s MVC's had significantly higher peak torque values during all sets apart from the first. The 6 s MVC's showed reductions throughout the sets, suggesting this conditioning activity induced fatigue and the recovery duration was not substantial for PCr regeneration and therefore a window of opportunity could not be created.

Behm et al. (2004) studied the PAP response following one, three and five MVC repetitions. Force output was measured during a subsequent MVC leg extension at various time points to assess the PAP decay of each conditioning activity. The one repetition conditioning activity reported the highest force output during subsequent performance, and force output remained elevated for 15 min following the conditioning activity. The three repetition conditioning activity had a significantly diminished force output at 10 and 15 min. Interestingly, the five repetition conditioning activity followed the same pattern as outlined for recovery time in Section 2.4.4; there was an initial decrease in force output following the conditioning activity, before a rise in force output at 5 min, however, this did not reach the same values as the one repetition condition. This would suggest that a shorter conditioning activity is more effective at eliciting a PAP response. However, de Keijzer et al. (2020) only found a small increase in CMJ and long jump performance following one set of six half-squats, compared to two and three sets of the same exercise where a moderate change was identified. These results suggest a higher conditioning activity volume can recruit a greater number of higher-order motor units to better enhance subsequent performance. However, CMJ and long jump performances were only completed at 3 min and 6 min after the conditioning activity, which, as outlined in Section 2.4.4, may not be sufficient time to overcome fatigue.

Unfortunately, conclusions concerning conditioning activity volume are difficult to justify because of the limited research conducted directly investigating the effects of conditioning activity volume on subsequent performance. Although there is a wealth of literature surrounding PAP as a pre-race intervention, there is a considerable variation between study methods, therefore even comparisons are unable to support or contradict previous findings. Nonetheless, most studies have minimised the conditioning activity volume to ensure that a window of opportunity can be achieved, with diminished fatigue but a heightened PAP response.

2.4.7 Summary

Previous literature has given insight into the physiological phenomenon of PAP, intending to understand the mechanisms underlying the process and the necessary considerations to ensure PAP enhances subsequent performance. Research has shown that PAP recovery time is approximately 8 min, although there is a need to acknowledge the individual variation when designing a conditioning activity. A range of findings support different conditioning types, volumes, and intensities, with PAP responses being evident in eccentric, concentric, isometric and ballistic conditioning activities at high intensities. Further research within the applied setting could help determine which PAP conditioning activities can enhance start performance within trained participants who already utilise PAP as a pre-race intervention, thus limiting the variation training level has on PAP response.

2.5 Muscle temperature generation and maintenance

During training and competition, athletes regularly complete WUs to physiologically and psychologically prepare themselves with the aim of enhancing subsequent performance (Hedrick, 1992). A meta-analysis by Fradkin et al. (2010) assessed WUs across multiple activities, including swimming. Of the 32 studies included, 79% found subsequent performance improved by up to 20% from baseline values following a WU compared to no preparatory exercise. No change was reported for 3% of the studies. The remaining 17% reported a negative impact on performance by approximately 5%, although one study reported an 11% impairment during an activity listed as “other”. The suitability of the WU during these studies was discussed. It was outlined that WUs that did not improve performance were not specific to the proceeding task, or the duration was insufficient to attain WU benefits required to enhance subsequent performance, therefore signifying the importance of ensuring the body is appropriately warmed-up, and sport-specific exercises are included. Nonetheless, Fradkin et al. (2010) supported the use of WUs within swimming, as results from the meta-analysis found swim performance was either enhanced or remained unchanged. The physiological effects of a WU have been studied in length and include increased blood flow and nerve impulses to the contracting muscles (Hedrick, 1992; Safran et al., 1989). However, increased T_m has been identified as an essential mechanism for improved subsequent performance, especially in power-based movements, such as the swimming start (Altavilla et al., 2018; Hedrick, 1992; McGowan et al., 2015).

2.5.1 Physiological adaptations to increased muscle and core temperature

Throughout exercise, heat is produced as a by-product during metabolic reactions within the contracting muscles and can be used during subsequent contractions or emitted through the skin; any excess heat is dissipated into the bloodstream, initiating a rise in muscle and core temperature (Gleeson, 1998). Typically, the initial rise of muscle and core temperature is rapid across the first 3 – 5 min. Providing intensity is maintained, and environmental conditions do not considerably change, this temperature rise ceases after approximately 15 min when an equilibrium is reached, preventing any heat-related impairment to the body (McGowan et al., 2015).

Changes in T_m can stimulate an increase in the rate of metabolic reactions within the muscles and determine ATP usage. Ranatunga (1984) investigated this change in metabolic activity rate within the muscles across varying temperatures and observed a slower shortening velocity at 15°C within the extensor digitorum longus and soleus muscles of rats compared to 35°C. Using the cross-bridge formation theory outlined in Section 2.4.2, Ranatunga (1984) discussed how cross-bridge attachment, which determines muscle shortening velocity (Figure 2.3), is more temperature-sensitive than cross-bridge detachment. Therefore, if fewer cross-bridges are formed within the muscle, velocity will be slower, as available power output from the muscles will be reduced. In support of this, Gray et al. (2008), found rectal temperature and T_m were significantly higher by 9% and 0.3%, respectively, when hot water immersion was used to elevate T_m. ATP stores were more depleted for type IIa muscle fibres by 13% than the control condition; PCr stores were more depleted in the control group for type IIa fibres. This depletion in ATP stores corresponds to the significantly larger power output and pedal rate when muscles were passively heated and indicates a higher metabolic reaction rate is necessary to produce greater power outputs (Figure 2.5).

Increased T_m has also been associated with decreased viscosity resistance within the muscles and joints. Viscosity can be defined as "the resistance that a gaseous or liquid system offers to flow when it is subjected to a shear stress" (Zatsiorsky, 1997, p. 299); viscosity within the muscles and joints decreases as velocity increases. Hill (1922) detailed how the heat released alongside mechanical energy elicits a response within the visco-elastic properties of the muscle, causing a structural change which reduces the resistance. By investigating contraction duration within frogs, Hill (1922) reported slower twitch contractions by 16% when the sartorius muscle was at 5°C, compared to 15°C. It was concluded that this resulted from increased muscle viscosity with lower temperatures, emphasising how additional resistance within the muscle slows RFD and can impair performance. Further research by de Ruiter & de Haan (2000) supported this. They investigated the impact of passive heat on RFD and maximal isometric force output in the adductor pollicis muscle. Maximal isometric force output decreased by 79% when T_m fell from 37.1°C to 22.2°C, and RFD was significantly lower by 36%. Alongside decreased muscle viscosity, an increased release of calcium and increased motor unit recruitment have also been concluded to influence RFD during temperature changes (McGowan et al., 2015). However, additional research beyond the scope of this thesis investigating biochemical changes within the muscle under varying temperatures is required to confirm these physiological changes as temperature related mechanisms.

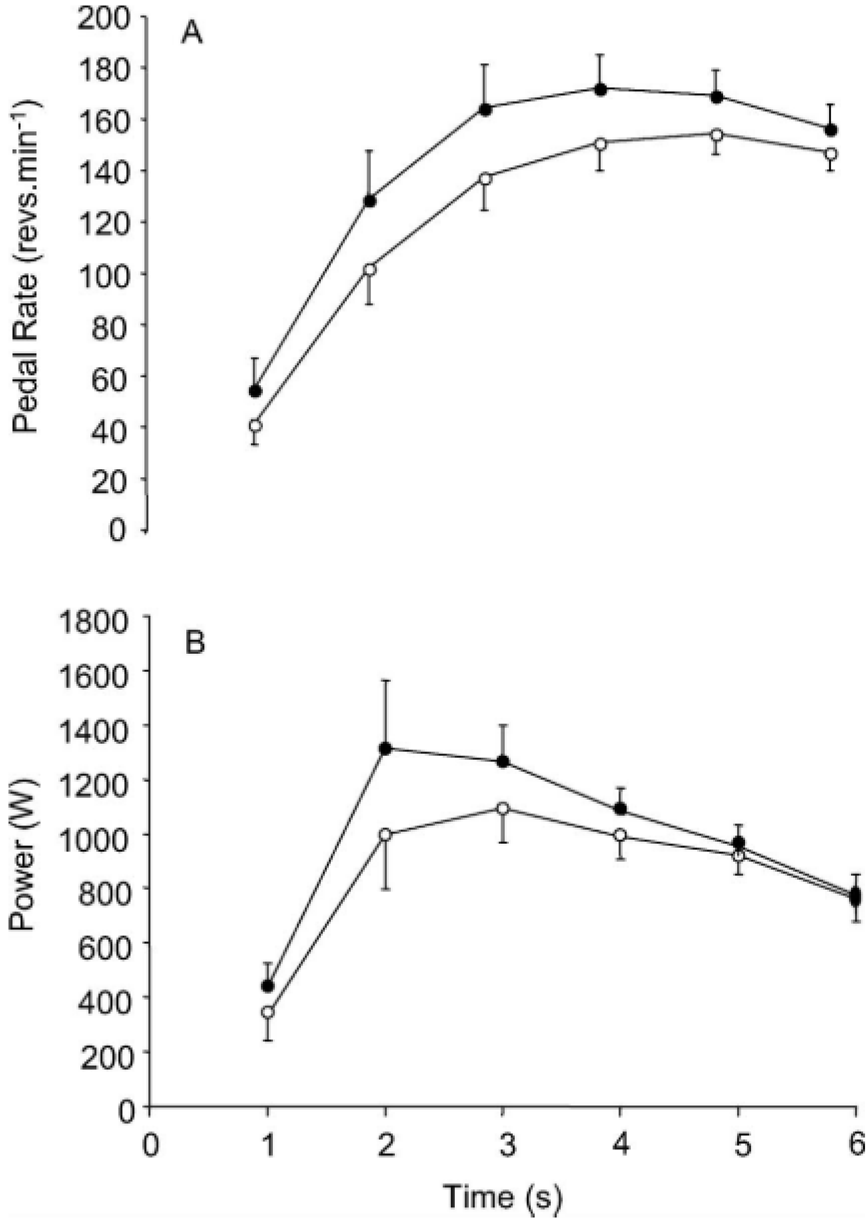

Figure 2.5 Pedal rate (A) and power output (B) during 6 s maximal sprint exercise under normal (mean ± standard deviation; open circles) and elevated (mean ± standard deviation; solid circles) muscle temperature conditions (extracted from Gray et al., 2008).

Based on past findings, increasing T_m either actively or passively can enhance external power output and subsequent performance. From the findings discussed within this review section, higher T_m is desirable because of the observed increased rate of metabolic reactions, improved muscle fibre performance and decreased muscle/joint viscosity. Therefore, to enhance performance, swimmers should maintain the T_m achieved during the WU or seek additional methods to warm muscles within the call room environment.

2.5.2 Muscle temperature and performance

Early research aimed to quantify the effects T_m has on external power output and sporting performance. For example, Asmussen & Bøje (1945) found the time taken to complete 35 revolutions when sprint cycling improved on average by 6% when participants had completed an active or passive WU, and 4% for longer distances (450 revolutions). Although this 3 – 8% temperature increase after the active WU only provided a limited enhancement for longer cycling distances, their findings confirmed previous hypotheses that a WU can improve power-based movements (Table 2.7). As a result, research into temperature related mechanisms has aimed to understand how the body reacts to preliminary exercise and its effect on subsequent performance. Additionally, the effects of passive heating were also measured by Asmussen & Bøje (1945). Two participants had a 10 min hot shower before completing the 35 revolution sprint cycle. As well as higher rectal temperatures, performances improved for both participants after the hot shower by 7% and 5%. Sargeant (1987) found similar results when investigating different leg T_m on external power output during sprint cycling. Participants were either immersed in water set at 45, 18 and 12°C for 45 min or sat in a control room set at approximately 21°C for 30 min followed by a 20 s sprint cycle. PPO increased by 11% following immersion at 45°C, whereas power output decreased during the 18 and 12°C conditions by 12% and 22%, respectively, all of which were significant changes compared to the control. Following immersion at 45°C, peak force output was maintained for longer and was greater across the 20 s sprint cycle compared to the other conditions. These results reinforce the importance of ensuring T_m is heightened before competing to enhance the performance of power-based movements and how this can be done through a passive method as well as a WU.

The effect of T_m on jump performance was studied by Bergh & Ekblom (1979), who found a 4% decrease in vertical jump height per 1°C decrease, as well as close associations between T_m and sprint cycling performance. These results were further supported by Ferretti et al. (1992), who measured high jump PPO in six sedentary male participants. Participants completed five jumps before completing a passive heat condition by immersing their lower body in 20°C water for 90 min, followed by an additional five jumps. PPO decreased by 27% on average for all participants, and T_m decreased by approximately 24% for the group. This decrease in performance and T_m supports the mechanisms outlined in Section 2.5.1, as PPO was impaired when muscles were cooled.

Galbraith & Willmott (2018) examined the use of passive heat garments on swimming 100 m time trial performance. Although PPO was not measured during the skills section of the trial (i.e. starts and turns), time trial performance was significantly improved by 0.6%, and reaction time and split times were also significantly faster when passive heat was used. Rate of perceived exertion (RPE) was also measured, and although no significant differences were found, scores were lower by 2% on average, suggesting that performance required less effort when T_m decay was minimised.

Alongside the temperature related mechanisms outlined in Section 2.5.1, there is a range of research supporting the use of heat to enhance power-based movements, through a WU or passive heat method. As swimming start performance has been strongly associated with PPO (Section 2.3.2) the above evidence suggests that increasing and maintaining T_m before a performance will benefit swimming start performance. Unfortunately, most swimming studies have placed limited focus on start time; therefore, the direct effects of increased temperature on start time are likely masked by other performance variables, such as stroke rate and technique. Therefore, additional research is required to directly understand the influence of heat generation and maintenance on start performance.

Table 2.7 Temperature and performance measures following 30 min of preliminary work. Shows the temperature and time take to complete 35 and 450 revolutions after a 30 min warm-up ("warm") compared to a 30 min rest period ("cold") as mean ± standard deviation (extracted from Asmussen & Bøje, 1945).

35 Revolutions				**450 Revolutions**			
"Cold"		**"Warm"**		**"Cold"**		**"Warm"**	
Rectal temperature (°C)	Cycle time (s)	Rectal temperature (°C)	Cycle time (s)	Rectal temperature (°C)	Cycle time (m:s.ms)	Rectal temperature (°C)	Cycle time (m:s.ms)
37.08 ± 0.15	14.15 ± 0.29	37.86 ± 0.08	13.32 ± 0.47	37.08 ± 0.15	5:06.58 ± 23.78	37.89 ± 0.10	4:54.48 ± 26.23

2.5.3 Heat loss window

Immediately after the cessation of exercise, T_m decreases rapidly and returns to near-baseline values by approximately 15 min, although this is dependent on environmental and participant characteristics (Kilduff et al., 2013; West et al., 2013). Therefore, the duration between WU and racing, commonly referred to as the transition period, can substantially impact subsequent performance depending on the measures taken by the athlete to ensure T_m remains elevated. Understanding the ideal transition period duration and heat loss window is essential to ensure subsequent performance is enhanced, particularly during extended transition periods after a WU due to call room regulations.

Multiple studies have investigated the transition period duration within swimming, to understand its effect on T_m and performance. For example, Zochowski et al. (2007) studied a range of transition period durations and their effect on 200 m time trial performance in 10 national level swimmers through a repeated-measures design. Following a 1500 m WU, participants rested for either 10 or 45 min before completing a 200 m time trial swim. Performances were significantly faster by 1% following the 10 min transition than the 45 min, and lactate values were lower for the 10 min condition. These results identified the performance benefits of a shorter transition period, although additional time conditions would have given more understanding into the ideal transition period time. Ideally, T_m differences between conditions would be collected to establish these changes between conditions. Nonetheless, these results were later supported by Neiva et al. (2017), who measured changes in 100 m freestyle performance after a 10 and 20 min transition period. They found the shorter transition period had significantly faster 100 m times, and start times were also faster by 2%. Only small differences in core temperature were measured following the transition period, with the 10 min condition having a 0.1% higher core temperature than the 20 min condition. Although only a small temperature difference was identified before the time trial, these results support the findings by Sargeant, (1987) who found a 4% increase in power output per 1°C increase in T_m and suggest that even 10 min differences in the transition period can significantly influence performance.

As previously discussed, swimmers are often required to attend a call room environment 15 - 20 min before racing and change into their racing suit, suggesting a shorter transition period is highly unrealistic. Therefore, for subsequent performance to be enhanced additional strategies are necessary to maintain T_m following the WU.

2.5.4 Methods of measuring temperature

As outlined above, when exercise is initiated, heat is produced as a by-product during the metabolic process of muscular contractions, which dissipates into the bloodstream, eliciting a rise in T_m. The ability to measure this change in T_m can offer insight into the effectiveness of WU and pre-race interventions to enhance PPO during subsequent performance because of the mechanisms outlined in Section 2.5.1. Several non-invasive methods are available to monitor temperature changes, varying in financial cost, ease of use and processing time. Skin thermistors are placed on the skin surface and are heated through thermal conduction to match skin temperature, with a response rate of approximately 5 s (Shaffer et al., 2016). Although a short adjustment period and good agreement between wireless and hardwired skin thermistors has been found (James et al., 2014) , limitations include sensor misalignment during exercise or losing the sensor altogether if not appropriately secured, and wires can potentially restrict movement or become entangled during use (Bach et al., 2015). Thermal imaging cameras also offer insight into skin temperature by producing a thermogram of the heat distribution across the body based on the thermal energy emitted. (Ring & Ammer, 2012; Sousa et al., 2017). Despite being a non-invasive and cost-effective measure, as outlined by James et al. (2014), thermal imaging cameras are unable to capture accurate skin temperature or determine T_m. Therefore, other temperature methods should be utilised, if available, to ensure accurate conclusions are made regarding changes in temperature, particularly when assessing pre-race interventions when minimal changes in temperature could significantly impact power output.

iButtons are small, wireless sensors placed directly onto the skin to record temperature using an internal thermometer and data logger (Lovegrove, 2009). Van Marken Lichtenbelt et al. (2006) aimed to validate iButtons and determine their response time to measuring skin temperature. 30 iButtons were placed into a water bath for 15 min along with a calibrated thermometer. Significantly high correlations were found between the iButtons and the thermometer, as well as a mean bias of -0.09 ± 0.22°C, although a correction equation reduced the bias to 0.05 ± 0.06°C. iButton response time was also measured by placing eight iButtons in a water bath at 18.7°C for 1 min before being placed into a water bath at 41.3°C. All iButtons responded to the new environment within the first min of the temperature change, and an equilibrium that matched 41.3°C was reached approximately 2 min later (Figure 2.6). However, the sampling rate was every min, so this is an estimation and could have been more accurately defined if a higher sampling rate was used. These results support the use of iButtons as accurate temperature measures, with high accuracy and a short response time. The similarity between the eight iButtons regarding response time also suggested high reliability between the sensors.

iButtons were compared to skin thermistors when applied to the skin by Harper Smith et al. (2010). Eight recreationally active males sat for 40 min in an environmental chamber at 10, 20 and 30°C, with a low wind velocity, high wind velocity, or whilst cycling at 50% volume of oxygen (VO_2) peak. iButtons and skin thermistors were applied to the skin in 14 locations during seated trials and eight during the exercise trial. There was a significant variation between conditions for the iButtons and the skin thermistors, despite high positive correlations and low error between the methods, suggesting an adjustment is required to account for temperature offset between the two methods. Reliability results were high for both methods, with errors below 0.1°C. These results support the use of iButtons to monitor changes in skin temperature providing results are compared with other iButton measurements, rather than a different methodology.

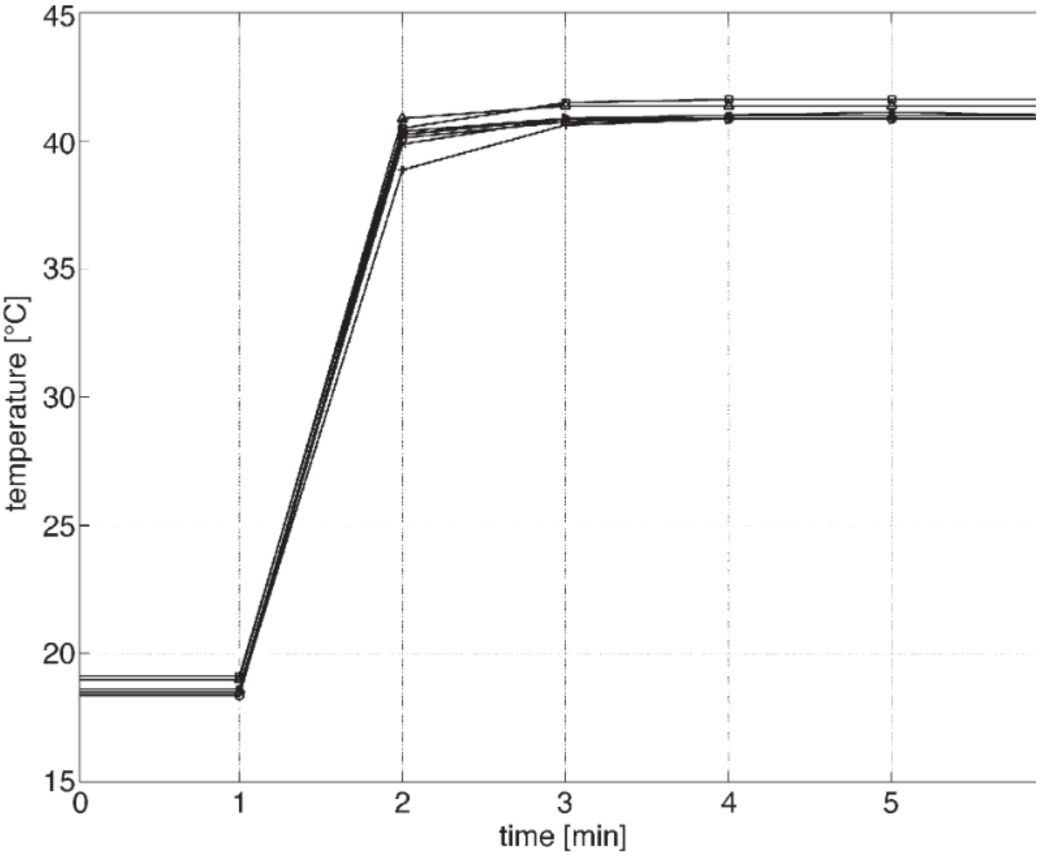

Figure 2.6 Temperature of eight iButtons in equilibrium with water at a temperature of 18.7°C and after a sudden shift to 41.3°C at t = 1 min (extracted from Van Lichtenbelt et al., 2006).

More recently, Flouris et al. (2015) aimed to validate the iButtons compared to an intramuscular temperature probe and assess whether, through regression analysis, an equation could be developed which utilises the iButton skin temperature measure to predict T_m for 36 healthy participants. Three iButtons were secured with surgical tape to the muscle belly of the vastus lateralis, triceps brachii and trapezius muscles. A neoprene disk covered each iButton to insulate the iButton and prevent heat loss from the skin to the external environment, eliciting a skin temperature similar to the muscle itself. An intramuscular probe was inserted into each location. Participants were requested to sit in an environmental chamber set to 24°C and 56% humidity, 30°C and 60% humidity or 40°C and 24% humidity. Following this passive rest period, participants were requested to cycle at 40% VO_2 max for 60 min (or 90 min in the 40°C environment) before completing a final passive rest period. The results from the intramuscular probes enabled T_m prediction equations to be developed for each muscle at rest, during exercise, and for recovery and no significant differences were found between the intramuscular probe T_m and the predicted T_m. These results support the use of iButtons to collect skin temperatures and predict T_m within a range of environmental conditions through regression equations. Although similar to the skin thermistors, no known research has investigated the use of skin temperature measurements recorded by skin thermistors to predict T_m. Providing the predictions are accurate across environments, iButtons could become invaluable within the elite sporting world to understand the internal environmental response to exercise, and pre-race interventions.

Several methods exist to measure temperature, but with varying levels of accuracy and reliability. iButtons have shown high levels of accuracy but seem most effective when temperatures are compared with other iButton measurements. Recent research has developed regression equations which use iButton skin temperatures to predict T_m, providing the iButtons are insulated with a neoprene disk, a method which has not been explored with the other measures outlined above. Therefore, to fully understand the impact of exercise on T_m, iButtons and their associated regression analysis should be used to avoid generalisations being made from skin temperature results.

2.5.5 Heat maintenance garments

As outlined in Section 2.5.2, achieving a heightened T_m through a WU or through passive heating can substantially affect power output and performance. To prevent T_m decreasing, athletes utilise garments to prevent or slow heat loss, ensuring that subsequent performance is enhanced and power output increases. One consideration is the type of heated garment worn, i.e. whether passive or active (generates heat).

Passive garments have been the focus of a large amount of research, with benefits found across various sports. Within swimming, Galbraith & Willmott (2018) measured different clothing strategies on 100 m time trial performance. Nine swimmers completed their individual race swim WU, followed by a 30 min passive rest period where they wore a set of warm clothing, including a hooded top and gloves or a t-shirt. Core and skin temperature measures were taken throughout the testing sessions. Those who wore warm clothing had significantly faster 100 m swim times by 0.6% than those who had only worn a t-shirt during the transition phase. Skin and core temperature were significantly higher by 5% and 0.8%, respectively, following the transition phase and remained elevated until after the time trial when warm clothing was worn; thermal comfort (TC) was also significantly greater after this phase. In rugby league, Kilduff et al. (2013) found significantly higher core temperatures before and after a repeated sprint assessment when athletes wore a blizzard survival jacket during a 15 min transition period than those who wore standard training gear. The first four sprints were significantly faster and elicited a larger power output for the passive heat group. Sprints five and six were similar for both conditions, despite core temperature remaining significantly elevated following passive heat; however, this likely resulted from fatigue mechanisms, as outlined in Section 2.4.3.

Fairbank et al. (2019) assessed the differences in temperature, speed, and time at high metabolic power throughout a simulated first half of a rugby league match following a passive heat intervention. Although core temperature only increased by 0.8% when participants wore an additional quilted jacket during the 15 min transition period, peak speed was likely higher during the first (effect size = 0.46 ± 0.57), third (0.47 ± 0.32) and fourth (0.56 ± 0.47) quarters when the quilted jacket was used, and time at high metabolic power was also likely longer during the first quarter (ES = 0.50 ± 0.55). As outlined previously, Sargeant (1987) demonstrated how small temperature changes can influence performance; therefore, although Fairbank et al. (2019) only found marginal differences in core temperature, the impact on power output and speed were beneficial.

West et al. (2016) also monitored the use of passive heat garments on sprint and CMJ performance within 16 professional rugby union players. Following a WU, participants rested for 20 min whilst wearing an insulative heat garment or their standard training attire; a PAP intervention and combined protocol were also studied. A CMJ and a six 40 m sprint test was completed. Throughout the 20 min transition period, core temperature decreased by 29% from the WU when the insulative heat garment was worn, whereas in the control and PAP conditions it decreased by 85% and 88%, respectively. CMJ PPO decreased for all conditions, although the combined and passive heat conditions experienced the smallest decrease in PPO. Participants also had significantly faster sprint times when passive heat was implemented independently by 0.6% compared to the control and when combined with the PAP conditioning activity, which was 0.9% faster than the control.

More recently, heated garments have been designed with integrated heating elements to actively warm the muscles or maintain the heat generated following the WU more effectively. As a result, studies have aimed to assess the performance enhancements resulting from active heat garments. For example, McGowan et al. (2016) studied the impacts of using a jacket with heat elements on the chest and lower back alongside a t-shirt and tracksuit bottoms on 100 m freestyle performance for 16 junior, competitive swimmers. A standardised WU was initially completed, followed by a 30 min transition period where the garments with integrated heating elements or a t-shirt and tracksuit top and bottoms were worn. Before the time trial, skin temperature was significantly higher when the heated garments were worn, and swim times were 0.5% faster, similar to Galbraith & Willmott (2018). Start time was also measured and was 0.2% faster than the control, and peak blood lactate values were significantly higher after the time trial. As mentioned throughout this review, although these changes are minor, marginal gains can impact medal likelihood and overall performance (Table 2.2).

One study that has compared passive and active heat garments was conducted by Wilkins & Havenith (2017). They assessed an upper-body electrically heated garment on sprint swimming and plyometric press-up performance within 12 elite-level swimmers, who were regular national or international competitors, compared to a standardised jacket. Following a 30 min standardised swim WU, participants completed a passive rest period where they sat wearing the active or passive heat garment, alongside a pair of tracksuit bottoms and a long-sleeve top for 30 min. Four maximum effort plyometric press-ups were then completed on a force platform before the 50 m freestyle time trial was completed, approximately 2 min after the press-ups. Swim times were faster by 0.8% after swimmers wore the active heat garments, although this was only significant for male swimmers, likely because of the small sample size for female swimmers (n = 4). Nonetheless, stroke rates and counts were significantly greater for both sexes. Participants also had greater starting strength and peak force values during the plyometric press-ups when the active heat garments were used by 10% and 11%, respectively. These results, therefore, support the use of heated elements within garments to improve subsequent performance and support the temperature related mechanisms outlined in Section 2.5.1.

There is still a limited amount of research available comparing active and passive heat garments, regardless of the performance benefits previously identified. Although the swimming start is as a lower-body power-based movement, only a few studies have measured differences between lower-body heated garments and start time, with many studies investigating the differences in upper-body PPO, despite the importance of lower-body PPO during the start. To ensure start performance is enhanced, understanding the methods and awareness for which garment provides the larger increase in lower-body PPO is necessary to obtain marginal gains that contribute to medal likelihood.

2.5.6 Summary

There is substantial evidence to support heat generation and maintenance within power-based sporting performances. With core temperatures and T_m significantly dropping approximately 15 min after WU completion, heated garments are beneficial to ensure heat decay is delayed across the transition period, especially when call room restrictions are enforced. Additional support for active heat garments suggests that T_m

can be sustained and even increased following a WU; however, comparisons between passive and active heated garments is limited. Despite the swimming start being a power-based movement, research assessing differences in T_m on start time is sparse. Many studies have focused on time trial and sprint performance; therefore, further research is necessary to ensure accurate conclusions can be made about the impact temperature has on start performance and the interventions that will improve start time.

2.6 Chapter summary

This review of literature aimed to review the relevant literature relating to the specific research objectives outlined in Chapter 1. Section 2.2 outlined the importance of the swimming start to overall race performance, but also detailed some of the equipment changes which may have seen this contribution change due to improvements in start performance. Some of the methods available to measure start time were discussed, with single panning cameras determined as the more realistic option within the applied setting. Section 2.3 reviewed the determinants of the start, with a particular focus on power output and the relationship between power, force and horizontal velocity and a substantial amount of research has supported increased motor unit recruitment to enhance power output. A relationship has been established between the start and CMJ, and therefore increases in CMJ PPO are likely to be transferred to the start, which can enhance performance providing the flight and underwater phases are performed efficiently. Section 2.4 reviewed "PAP", the first pre-race intervention investigated within this thesis. Although no firm conclusions have been made concerning PAP conditioning activity volume, intensity is required to be 75% of above 1RM for the PAP mechanisms to be elicited. Ballistic PAP is more realistic within the applied setting as it requires limited equipment, however isometric PAP is considered to reduce EIMD accumulation across the competition period. Finally, Section 2.4 discussed how increased T_m can enhance the performance of power-based movements and detailed some of the available, non-invasive methods for measuring T_m. Heat maintenance garments have been implemented to maintain or generate increases in T_m following a WU, however further research is necessary to assess their influence on CMJ and start performance.

Chapter 3. Accuracy and reliability of a single panning camera set-up to measure start time and the quantification of start time to overall race time

3.1 Introduction

Over 70% of swimming world records have been achieved since 2010, with 88% occurring between 2014 and 2019 (FINA, 2022b). The variation between finishing times has also decreased over recent Olympic cycles, for example, the time difference between 1st and 8th place in the men's 100 m and 200 m freestyle finals dropped by 0.29 s and 3.54 s respectively from the 2008 Beijing Olympics to the 2016 Rio Olympics. With some races won by small time differences, such as the men's 50 m freestyle final at the 2016 Rio Olympics which was won by 0.01 s, this highlights how even small changes in performance can impact medal likelihood and podium position.

One area of consideration, particularly for shorter, sprint events which Currie et al. (2018) identified as 200 m or less, is the start, defined by Cossor & Mason (2001) as the time from the first instant of the starting signal to when the centre of the swimmer's head reaches 15 m. The start is typically split into three sub-phases – the block phase, the flight phase and the underwater phase – and in some instances, the underwater phase is further divided into the glide and free-swim (Ozeki et al., 2012). The block phase is often the focus within training and research due to its potential impact on the start and overall race performance since each start phase is directly impacted by the previous (Ruschel et al., 2007; Slawson et al., 2013). Previous research investigating the block phase and its impact on start performance has included leg placement on the block (Carradori et al., 2015), weight distribution during block set-up (Barlow et al., 2014) and the position of the back plate on the block (Takeda et al., 2012) with results demonstrating how minimal changes to block set-up can influence performance.

In 2005, Lyttle & Benjanuvatra (2005) showed the start can contribute up to 30% of total race distance for 50 m races and that this relative contribution decreases as race distance increases, with 1500 m events having the lowest start contribution of 0.8%. Slawson (2010) analysed 50 m freestyle times from the 2008 Beijing Olympics and found start time contributed 26% of total race time. This contribution also decreased for freestyle events as distance increased, though this data was not reported. While these results do not align entirely with Lyttle & Benjanuvatra (2005), who only quantified the start's contribution by distance, each study reported a large start contribution to the total race, it was concluded by both that the start impacts sprint events. Nevertheless, there have been multiple equipment changes within swimming since these studies were undertaken, such as the back plate on the start block, approved in 2009 and the backstroke wedge introduced in 2014 (Section 2.2.1). Given the adoption of the back plate, which Garcia-Hermoso et al. (2013) found improved block time by 0.06 s and overall time by 0.45 s for 50 m freestyle and 0.90 s for 100 m freestyle, the results of Slawson (2010) potentially have limited application to the current swimming population.

More current insight into the elite swimming world was conducted by Morais et al. (2018), who analysed races swum after these equipment changes. The start as a percentage contribution to total race time for 100 m races at the 2016 European Swimming Championships was categorised by sex and stroke to determine any variation across these variables. Males and females had similar percentage contributions across all strokes with 11.50% and 11.96%, respectively. However, this differed when classified by stroke, with freestyle having the highest percentage contribution for males (11.96%), and backstroke for females (12.31%). Butterfly showed the lowest percentage contribution for males (11.01%) and breaststroke was lowest for females (11.58%). Although Morais et al. (2018) offered insight into the start's percentage contribution, it is still unclear how equipment changes have impacted other sprint distances (50 m and 200 m) which also have a large start contribution, and whether differences between sex are present across all events, including those not previously analysed.

Both Morais et al. (2018) and Slawson (2010) obtained their data at competitions using race analysis software, a process utilised by international swim teams within competition and training (Veiga et al., 2013). Implementing a similar method to advance the knowledge of the start as a percentage contribution of total race time and an absolute time would provide an understanding into how the start has been impacted as a result of new equipment across each event and whether this is different for males and females. Using multiple cameras is often unrealistic within the competition environment due to access restrictions and therefore, an adaptable, yet accurate analysis method is required.

One method to resolve this problem is by using a single panning camera, placed perpendicularly to the centre of the pool (25 m for long course competitions). This system is adaptable and has a fast processing time, ensuring feedback is provided quickly to coaches and athletes, another potential limitation of the gold standard set-up.

In unpublished results, Kelley (2014) assessed the validity of a single panning camera to measure times to reach predetermined distances considering the potential parallax error which can result when using a single camera rather than multiple perpendicular cameras. Using a perpendicular camera and a single panning camera, start times were analysed. The mean error between the two methods ranged from -0.3 s to 0.2 s for start time with a mean error (± SD) of -0.047 s (± 0.076 s). Although these results give insight into the mean error for start times when measured using a single panning camera, awareness of the SWC for start time is required to further interpret these results and their application to the start. Kelley (2014) outlined that 0.2 s was considered a worthwhile change, however this was anecdotal and applicable for turns only; a worthwhile change for start time was not identified. Consequently, the accuracy of start times measured using the single panning camera and the context for these within the elite swimming environment remains unclear, making conclusions about changes in start time recorded by a single panning camera difficult to justify.

Currently, no research has analysed the start across all strokes, distances and between sexes. Since most results were collected before equipment changes that will have impacted start performance (Section 2.2.1), the application of these studies to the current swimming population is limited. An update, providing insight across all of the above variables, would resolve this and establish relevant data based on races swum since the introduction of the new start block and backstroke wedge. Understanding the relevance of the start within each event would provide informed coaching decisions of whether an improvement in start time would elicit a worthwhile change and therefore offer a technical focus within training.

A validation of start times measured using a single panning camera, within the context of a predetermined SWC, based on a higher number of races across several meets and events is required to ensure this method is an accurate tool for measuring start time and outlining the start as a percentage contribution to total race time. Therefore, the overall aim of the current study was to determine how accurately and reliably start time can be measured using a single panning camera analysis system and, if this analysis method yields an acceptable level of accuracy based on the predetermined SWC, determine the contribution of the start to total race time for every event and between sexes.

As the current study contains two separate aims, the methods have been written in two parts. The first part addresses the accuracy of the single panning camera analysis system, and this also incorporates reliability trials. The second section focuses on the start as a percentage contribution to total race time, as the methods and results for this were dependent on the first aim, assuming start times measured by the single panning camera were accurate within the SWC context. The results and discussion are also presented sequentially in this format.

3.2 Accuracy and reliability of the single panning camera analysis system methods

3.2.1 Participants

Swimmers who competed at the 2019 British Swimming Championships, Glasgow, British Summer Championships, Glasgow, Welsh Winter Championships, Swansea and the Euro Meet 2020, Luxembourg participated in the current study. Participants (22 females, 30 males) were all able-bodied swimmers and predominantly Welsh, although other nationalities were included during 50 m races to increase the sample size. All swimmers were at least national level or above. No anthropometric variables were measured because of access restrictions, and as all participants had agreed to the recording for media and research purposes, neither informed consent nor ethical approval was required.

570 sprint races were recorded across the four competitions, although 50 m races were only collected at the Welsh Winter Championships and Euro Meet due to access restrictions. Races of 400 m or above were excluded to align with previous conclusions

by Slawson (2010) of the start only impacting sprint events. Ten races were further excluded because the timing light was not visible within the two camera views, resulting in 560 races for data analysis (Table 3.1).

3.2.2 Data collection

Pool calibration was completed before each competition to identify the exact 15 m landmark. Two tape measures were placed on both sides of the pool, and 15 m was marked from the start end. Buoys on every lane rope were tightly pushed together and clamped in place for the remainder of the competition to prevent any displacement of the buoys or the 15 m landmark. A photo of the two markers was taken and used to identify the buoy that most closely corresponded to 15 m for each lane (Figure 3.1).

Start times with the single panning camera were collected using a video camera (Sony, PJ410 Handycam, Tokyo, Japan) attached to a tripod placed near the 25 m mark, with its optical axis looking down to the lane directions in the pool, and recorded at 50 Hz. A second camera (Sony FDR-AX53 4K Camcorder, Tokyo, Japan) secured to a tripod and recording at 100 Hz, in a high-speed setting, collected criterion measures of start time. This camera was placed perpendicular to the 15 m landmark as identified during pool calibration. A timing light either between the starting blocks of lanes 4 and 5, or next to lane 1 signified the start of each race and was visible to both camera views. The gold standard camera was set-up to ensure both the timing light and the 15 m mark could be viewed simultaneously across all lanes.

Table 3.1 The athlete distribution for all events, distances and strokes recorded across all four competitions used to determine the accuracy of start times measured using the single panning camera.

	Backstroke	**Breaststroke**	**Butterfly**	**Freestyle**	**Total**
50 m	137	95	58	92	382
100 m	19	17	36	30	102
200 m	9	13	35	19	76
Total	165	125	129	141	560

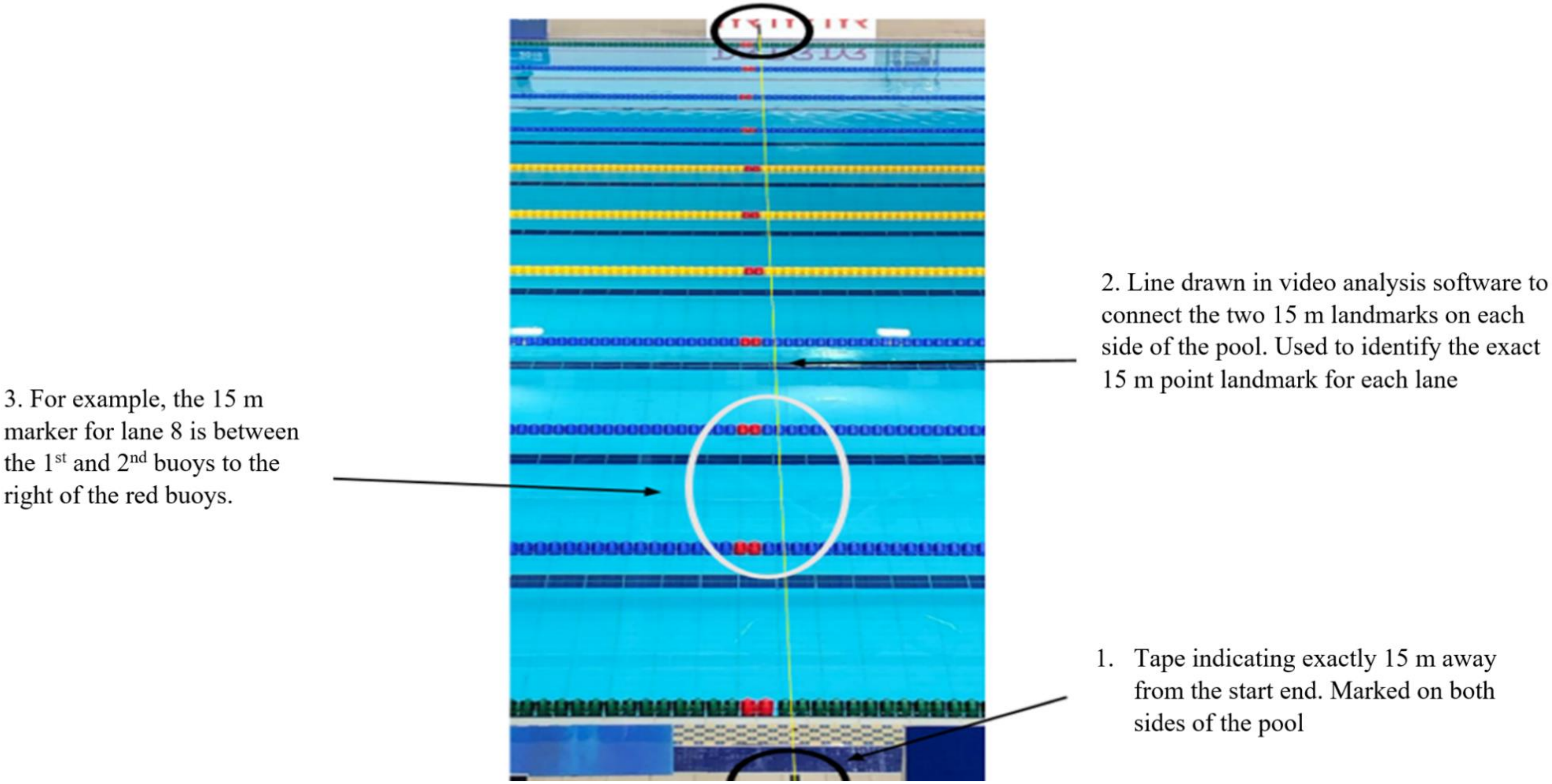

Figure 3.1 The 15 m buoys identified for each lane at the British Swimming Championships. The line drawn through the middle aids in determining a precise 15 m landmark by connecting this with the two tape markers at 15 m on either side of the pool.

The start definition previously used within literature (Cossor & Mason, 2001) was implemented within the current study when determining start time for both camera methods. The time elapsing from the first frame when the timing light was visible to when the centre of the swimmer's head crossed the 15 m marker, as identified from the buoy determined during pool calibration, therefore defined start time. Start times collected using the single panning camera were processed using bespoke analysis software (Nemo V 2.0.12), while Dartfish (Dartfish 10, Fribourg, Switzerland) was used to determine criterion start times from the 100 Hz video camera. All trials were processed by an analyst who had approximately two prior years of experience with the single panning camera set-up and had used the bespoke analysis system within competitions and training environments throughout this time.

3.2.3 Determination of a SWC value

A SWC was calculated by collecting start time differences from the results of eight studies that used national level swimmers or better throughout a variety of technical and physiological interventions (Table 3.2). The average difference in start time between the control/baseline and intervention was calculated for each study and averaged across the eight studies, resulting in a SWC value of 0.187 s. All studies included were from 2010 onwards to ensure new equipment had been implemented by the time of study completion, ensuring the SWC value was relevant to the current elite swimming population. Therefore, for start times measured using the single panning camera to be concluded as accurate, differences between the two camera set-up methods were required to be less than 0.187 s for all trials to ensure that worthwhile changes for start time could be confidently identified using the single panning camera analysis system.

3.2.4 Data and statistical analysis

Differences in start times between the two analysis systems were calculated for each trial (single panning camera start time minus criterion start time) and averaged by stroke, distance and event (e.g. 50 m backstroke) representing the systematic error.

The SD of these differences were calculated and were used to determine 95% limits of agreement, representing the random error associated with the single panning camera start times (Bland & Altman, 1986). Bland-Altman plots were developed to visualise the error between the two analysis systems and 95% limits of agreement quantified the accuracy of the single panning camera to measure start times across all events in the context of the 0.187 s SWC. Therefore, as mentioned in Section 3.2.3, for the single panning camera analysis system to be deemed an accurate method for measuring start time, all random errors needed to be less than 0.187 s.

Linear mixed models were developed using SPSS 26.0 (SPSS Inc., Chicago, IL, USA) to assess the systematic error for start times, considering interactions from additional variables. Stroke, distance and session type (heat/final) were included as fixed effects, and heat number, lane number and athlete ID were included as random effects. Variables were considered fixed effects if all conditions were incorporated within the sample; for example, all possible stroke variations were measured within the current study, therefore stroke was a fixed effect. Variables that did not include all possible variations were random effects (Field, 2009). Start time was the dependent variable, and analysis method (single panning camera; criterion) was the predictor across all models. Fixed and random effects were added individually to assess their interaction on start time in isolation of other variables. All model estimates used restricted maximum likelihood and a variance components covariance matrix. Significant interactions (i.e. $p \leq 0.050$) used estimates of fixed effects and the restricted log likelihood, alongside 95% confidence intervals, to examine these further and their impact on the systematic error between the two analysis systems.

Nine races from each event had start times recalculated to determine the reliability of both analysis systems. Using nine races ensured all races from the event with the lowest sample size (200 m backstroke) were included. The nine races for each event were randomly selected and reanalysed on ten separate occasions. The same processes were used to measure start time as outlined above for the initial single panning camera and criterion videos. Once remeasured, the agreement between the 11 start times (10 repeated trials and the original start time) was measured using a two-way mixed model intraclass correlation coefficient (ICC; Atkinson et al., 2005; Dingenen et al., 2018), with results interpreted as poor (< 0.500), moderate (0.500 – 0.750), good (0.750 –

0.900) or excellent (> 0.900) (Koo & Li, 2016). A paired samples t-test confirmed any significant differences between the initial start time and the repeats. Using the same method as above, 95% limits of agreement were calculated to quantify the reliability of the single panning camera within the context of the SWC.

Table 3.2 The studies used to determine the SWC value for start time. All used national level swimmers or better throughout various technical and physiological interventions to assess start time differences. Average of reported change in start time is 0.187 s.

Study	Type of intervention	Participants	Stroke (if specified)	Performance Level	Reported change in start time (s)
Vantorre et al. (2010)	Technical	7 M	Freestyle	Elite	0.05
Ozeki et al. (2012)	Technical	11 M	All strokes included	Elite collegiate	0.14
Barlow et al. (2014)	Technical	7 M, 3 F	Freestyle	Australian national underage or open qualifiers. 100 m FR PB = 56.7 ± 3.3 s	0.18
Carradori et al. (2015)	Technical	13 M, 2 F		767 FINA points	0.21 0.58
Cuenca-Fernández et al. (2015)	Physiological	10 M, 4 F		National level with five years + experience	0.18
Garcia-Ramos et al. (2015)	Physiological	5 M, 8 F	Freestyle	National	0.28 0.06
Tor et al. (2015)	Technical	11 M, 3 F		National level with five years + experience 787 ± 19 FINA points	0.14
Cicenia et al. (2019)	Technical	10 M, 5 F		National level or higher	0.047

M male, *F* female, *PB* personal best

3.3 The start as a component of total race time methods

3.3.1 Data collection

12950 races between 2010 and 2019 were extracted from the bespoke analysis system database used when completing analysis with the single panning camera (Nemo V 2.0.12) to determine average absolute start times and percentage contributions of the start to total race time across all events and between sexes (Table 3.3) for each year. The sample contained 1029 swimmers from 48 different nations. Aligning with the implementation of new equipment, races before 2010 were excluded to ensure results represented the current swimming regulations and races were sampled from competitions with qualification times equal to or greater than the 2010 British Swimming Championships to maintain a high level of swimmer across the sample. Para-swimming and relay events were also excluded to ensure a consistent start technique was performed across all races. Although the men's 800 m freestyle and women's 1500 m freestyle were originally extracted from the database, these were removed from further analysis because of the low sample size across the nine-year period (Table 3.3).

Alongside absolute start times providing insight into how the start has changed since 2010, and the possible impact the introduction of the back plate on the start block and backstroke wedge had on these times, a growth curve model was fitted to identify significant changes in start time. Start time was used as the dependent variable, with year as the predictor and athlete ID and event type as participant variables with start times nested within these. Maximum log likelihood and Chi-square distribution values were used to assess which level of polynomial best fitted the model when describing the rate of change over time; once concluded, this variable was then included within the model during further analysis. Fixed and random effects were determined using the same definition as previously mentioned (Section 3.2.4); fixed effects were competition, nationality, sex, pool length and time of day, with session type, lane number, block time, breakout time and breakout distance as covariates and random effects, using a diagonal covariance matrix. When a variable had no significant interaction with start time, it was removed from the model. The final model was used to determine which variables impacted start time since 2010, with post hoc analysis being conducted to assess this change between the cases within each variable.

The level of significance across all results was set at $p \leq 0.050$. Growth model analysis was completed using SPSS 26.0 (SPSS Inc., Chicago, IL, USA), and Post-hoc tests were performed in Jamovi 1.2.22 (The Jamovi Project, Sydney, Australia). Unless otherwise stated, data is presented as mean ± SD.

Table 3.3 The sample numbers for all events and strokes broken down by sex, used to determine the absolute times and percentage contributions for the start to total race time from 2010 to 2019.

	Backstroke		**Breaststroke**		**Butterfly**		**Freestyle**		**Individual Medley**	
	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female
50	313	368	323	294	288	365	557	599		
100	516	532	568	485	471	510	695	616		
200	345	338	465	388	325	351	593	474	429	437
400							289	295	241	281
800							22[+]	89		
1500							78	10[+]		
Total	1174	1238	1356	1167	1084	1226	2234	2083	670	718

[+] Indicates the low sample for men's 800 m freestyle and women's 1500 m freestyle which were excluded from further analysis.

3.4 Results

3.4.1 Single panning camera analysis system accuracy

Based on systematic errors, the single panning camera overestimated start time for all events except 200 m breaststroke (Figure 3.2). Mixed model analysis reported no significant interactions between start time and distance (F(1, 1116) = 0.230, $p = 0.631$) or stroke (F(1, 1112) = 0.390, $p = 0.532$). 95% limits of agreement across all events ranged between -0.080 s (200 m breaststroke) to 0.112 s (50 m breaststroke) and all trials had start time differences below the 0.187 s SWC value (Table 3.4).

Although lanes 0 and 9 had the highest systematic error across all lanes (0.037 s) with 95% limits of agreement between -0.037 s to 0.111 s, mixed model results did not report a significant interaction between lane number and start time (F(1, 798.998) = 0.349, $p = 0.555$). 95% limits of agreement for all lane numbers ranged from -0.057 s to 0.111 s. No significant interactions for heat number (F(1, 800) = 0.349, $p = 0.555$), round type (F(1, 1111) = 0.408, $p = 0.523$), or athlete (F(1, 797.986) = 0.356, $p = 0.551$) were observed for start time differences.

3.4.2 Reliability trials of the single panning camera

Excellent reliability was found for start times measured using the single panning camera (ICC = 1.000, $p < 0.001$) and there were no significant differences between trials ($p > 0.050$). Criterion start times also had an excellent correlation (ICC = 0.994, $p < 0.001$), and differences between trials were also not significant ($p > 0.050$). 95% limits of agreement across all events ranged between -0.024 s and 0.021 s for the reliability of the single panning camera, and -0.009 s and 0.007 s for the gold standard camera. All trials had start time differences below the 0.187 s SWC value.

3.4.3 The start as a component of total race time

Start times were calculated as absolute times and as percentage contributions to total race time and were averaged by event and the most recent results from 2019 are presented for females

(Table 3.5) and males (Table 3.6). Female 800 m freestyle results are shown for 2018 due to the low sample available for 2019 (n = 1). Female 50 m backstroke had the greatest percentage contribution from the start (26.07 ± 0.72%), and male 1500 m freestyle had the lowest percentage contribution (0.73 ± 0.01%).

The growth model analysed polynomials to identify which trend best represented the rate of change in start times since 2010. The initial linear trend was significant in representing the rate of growth over time within the growth curve model ($p < 0.001$), and the grand mean of the intercepts was 7.13 s, with a model fit (-2LL) of -133.753. The quadratic trend (start time^2) also significantly represented the rate of growth ($p < 0.001$), and since the model fit decreased to -314.446, this was a significant improvement based on Chi-square distribution values. The cubic trend (start time^3) was also significant, and the model fit was further improved (-2LL -320.935 $p = 0.011$); as this was a significant change under Chi-square distribution values ($p < 0.01$), the cubic trend was concluded to best represent the rate of growth over time (Figure 3.3).

Table 3.4 The systematic error and 95% limits of agreement between the single panning camera and criterion start times for all strokes and distances (s).

	50 m	100 m	200 m	All distances
Backstroke	0.027 (-0.048, 0.102)	0.035 (-0.019, 0.089)	0.025 (-0.051, 0.100)	0.028 (-0.045, 0.101)
Breaststroke	0.024 (-0.065, 0.112)	0.005 (-0.067, 0.078)	-0.003 (-0.080, 0.075)	0.018 (-0.069, 0.106)
Butterfly	0.035 (-0.029, 0.099)	0.039 (-0.024, 0.102)	0.031 (-0.046, 0.108)	0.035 (-0.033, 0.103)
Freestyle	0.021 (-0.044, 0.085)	0.026 (-0.031, 0.082)	0.016 (-0.042, 0.073)	0.021 (-0.041, 0.083)
All strokes	0.026 (-0.050, 0.101)	0.029 (-0.035, 0.093)	0.020 (-0.058, 0.098)	0.026 (-0.048, 0.100)

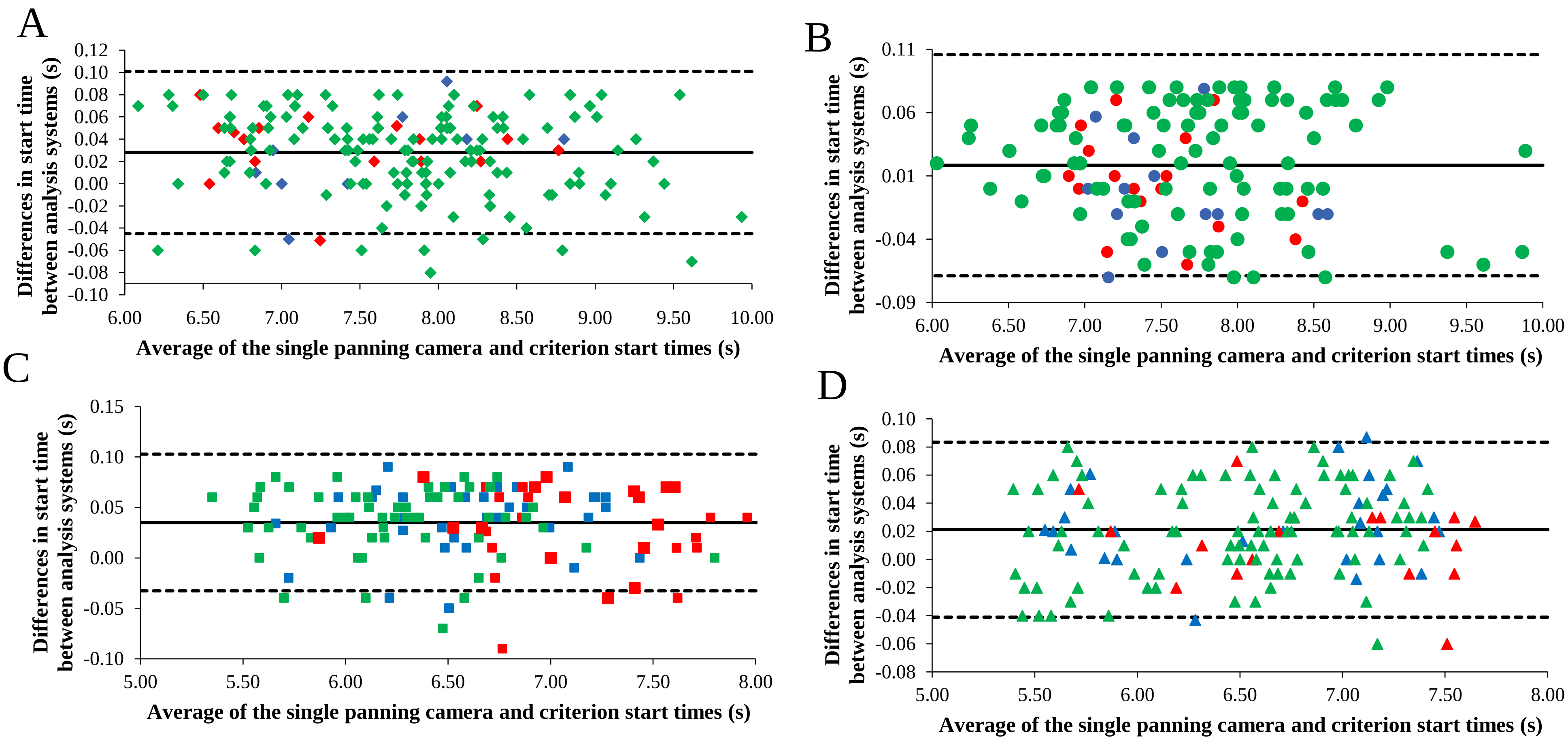

Figure 3.2 Systematic error (solid line) and 95% limits of agreement (dashed lines) between the single panning camera and gold standard start times for backstroke (A), breaststroke (B), butterfly (C) and freestyle (D). Green data points represent 50 m races, blue represent 100 m races and red are 200 m races. Positive values indicate an overestimate of start times measured using the single panning camera, whereas negative values are underestimates of start times measured using the single panning camera compared to the criterion videos.

Growth model analysis found a significant decrease in start time by 0.11 ± 0.01 s on average each year from 2010 to 2019 ($p < 0.001$) (Figure 3.3). Significant variation was reported for random intercepts (0.59 ± 0.17 s, $p < 0.001$) and random slopes ($\sigma^2 = 0.001$, $p < 0.001$), indicating different events, and the athletes nested within these, had different start times in 2010 and did not follow the same rate of change over time. Since 2010, absolute start times decreased for all events, with 50 m butterfly having the highest average decrease (0.75 s) for males and 200 m individual medley for females (0.68 s). Figure 3.4 demonstrates that the percentage contribution also decreased for all events except 1500 m freestyle, which increased by 0.76%; however, total race time for this event dropped by 18.60 s since 2010. The highest loss in percentage contribution was 50 m butterfly for both males (1.90%) and females (0.95%).

Across all events, males had significantly faster absolute start times than females by 0.95 s (t = 32.292, $p < 0.001$). Males also experienced less percentage contribution from the start than females (Tables 3.5 and 3.6). Competition significantly interacted with start time (t = -12.846, $p < 0.001$), and post-hoc results revealed the Commonwealth Games (n = 1015), Olympic Games (n = 416) and World Championships (n = 906) had an estimated 0.23 s faster start times than other competitions, such as the British Swimming Championships (n = 1548). World Championships start times were significantly faster than the Commonwealth Games ($p < 0.001$) and the Olympic Games ($p < 0.001$), however, the model did not consider total race time when analysing fixed or random effects and whether this was also significantly different across competitions. Time of day also showed significant interactions (t = -12.523, $p < 0.001$), with 0.05 s faster start times for evening races. Pool length significantly interacted with start time, with short course races displaying a 0.06 s faster start time than long course races (t = 6.313, $p < 0.001$).

The random variables that significantly explained the variance within the model were block time ($\sigma = 0.249$, z = 3.116, $p < 0.001$), breakout time ($\sigma = 0.002$, z = 4.542, $p < 0.001$) and breakout distance ($\sigma < 0.001$, z = 3.116, $p = 0.002$). Lane number ($\sigma < 0.001$, z = 0.124, $p = 0.902$) and session type ($\sigma < < 0.001$, z = 1.303, $p = 0.193$) were not significant and therefore, were removed from the model. Year was also included in post hoc tests, with 2010 reporting significantly slower start times than all years from 2014 onwards ($p > 0.050$). 2019 had significantly faster start times for all years included within the analysis ($p < 0.010$).

Originally, nationality was significant within the model (t = -3.382, $p = 0.001$), however, once all additional variables had been included, nationality was no longer significant (t = -1.739, *p*

= 0.082). Post-hoc results reported significantly slower start times for British swimmers compared to nine other nations including America ($p < 0.001$), Australia ($p < 0.001$), China ($p < 0.001$) and Japan ($p = 0.019$). As 60% of the sample were British swimmers (n = 7735), two additional models were developed to reassess model interactions; one only included British swimmers (British model) and the other excluded British swimmers (additional nationalities model). The British model had similar interactions to the original model, with the same significant variables and was also best represented by a cubic trend (-2LL = -1312.159, $p = 0.001$). A quadratic trend best represented the rate of growth for the additional nationalities model (-2LL = 1349.712, $p = 0.039$), and the only random factor to significantly interact with start time for the additional nationalities model was block time ($\sigma = 0.382$, z = 7.249, $p < 0.001$), compared to breakout time and breakout distance which had been significant interactions within the other two models. Nationality was not significant within the additional nationalities model (t = -0.937, $p = 0.349$).

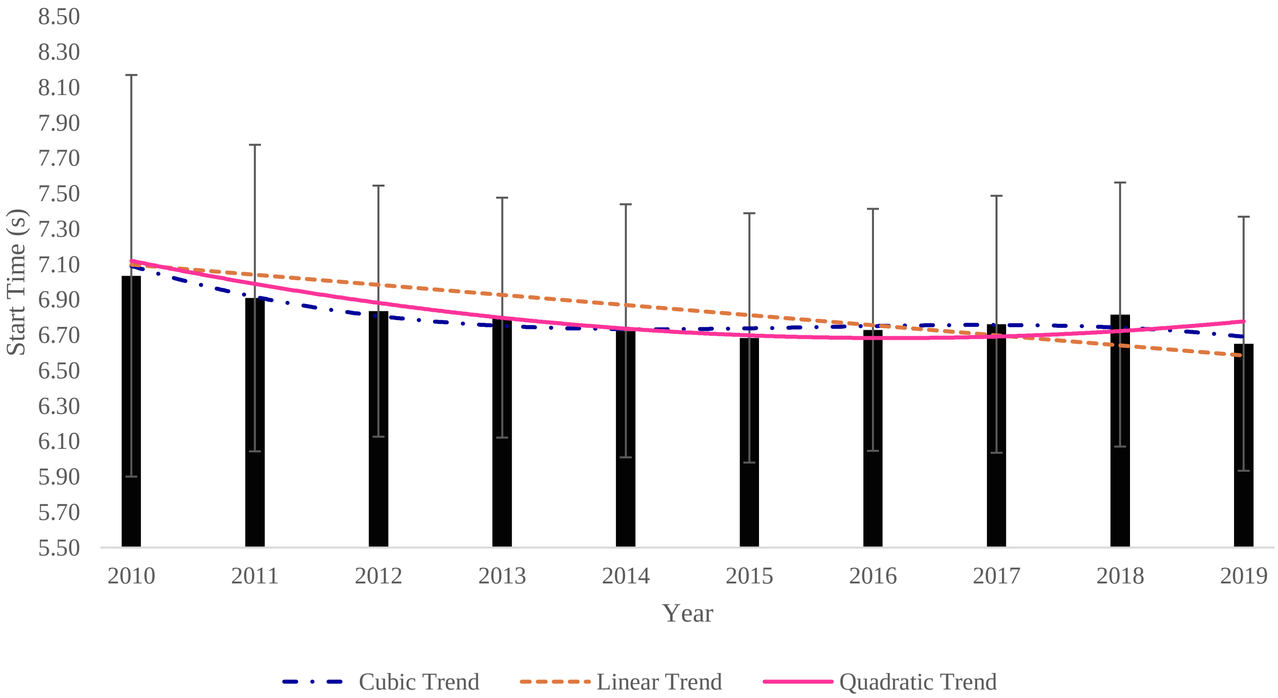

Figure 3.3 Average absolute start times (± SD) for each year between 2010 and 2019 for all events and sexes. All three trend lines are illustrated and identify the cubic trend as the best polynomial to describe the rate of growth over time compared to the linear and quadratic trends, alongside growth model results.

Table 3.5 Average absolute start times (mean ± SD) and percentage contributions for females across all events for 2019.

	Backstroke		**Breaststroke**		**Butterfly**		**Freestyle**		**Individual Medley**	
	Start time (s)	Start Contribution (%)	Start time (s)	Start Contribution (%)	Start time (s)	Start Contribution (%)	Start time (s)	Start Contribution (%)	Start time (s)	Start Contribution (%)
50 m	7.41 (± 0.35)	26.07	7.82 (± 0.30)	24.91	6.63 (± 0.32)	24.64	6.40 (± 0.27)	25.75		
100 m	7.46 (± 0.35)	12.23	7.88 (± 0.25)	11.52	6.79 (± 0.31)	11.46	6.55 (± 0.23)	11.97		
200 m	7.68 (± 0.36)	5.86	8.06 (± 0.30)	5.50	7.05 (± 0.23)	5.42	6.83 (± 0.17)	5.76	6.77 (± 0.33)	5.11
400 m							7.05 (± 0.17)	2.86	7.23 (± 0.29)	2.55
800 m							7.15^{+} (± 0.40)	1.47^{+}		

$^{+}$ Indicates times and percentage contribution taken from 2018

Table 3.6 Average absolute start times (mean ± SD) and percentage contributions for males across all events for 2019.

	Backstroke		Breaststroke		Butterfly		Freestyle		Individual Medley	
	Start time (s)	Start Contribution (%)	Start time (s)	Start Contribution (%)	Start time (s)	Start Contribution (%)	Start time (s)	Start Contribution (%)	Start time (s)	Start Contribution (%)
50 m	6.52 (± 0.44)	25.52	6.67 (± 0.28)	24.42	5.58 (± 0.36)	23.52	5.50 (± 0.26)	24.91		
100 m	6.68 (± 0.26)	11.32	6.68 (± 0.25)	11.32	5.77 (± 0.26)	10.96	5.75 (± 0.22)	11.69		
200 m	6.65 (± 0.29)	5.58	6.82 (± 0.31)	5.18	6.12 (± 0.27)	5.23	6.08 (± 0.25)	5.61	6.12 (± 0.30)	5.09
400 m							6.38 (± 0.23)	2.76	6.18 (± 0.22)	2.43
1500 m							6.58 (± 0.20)	0.73		

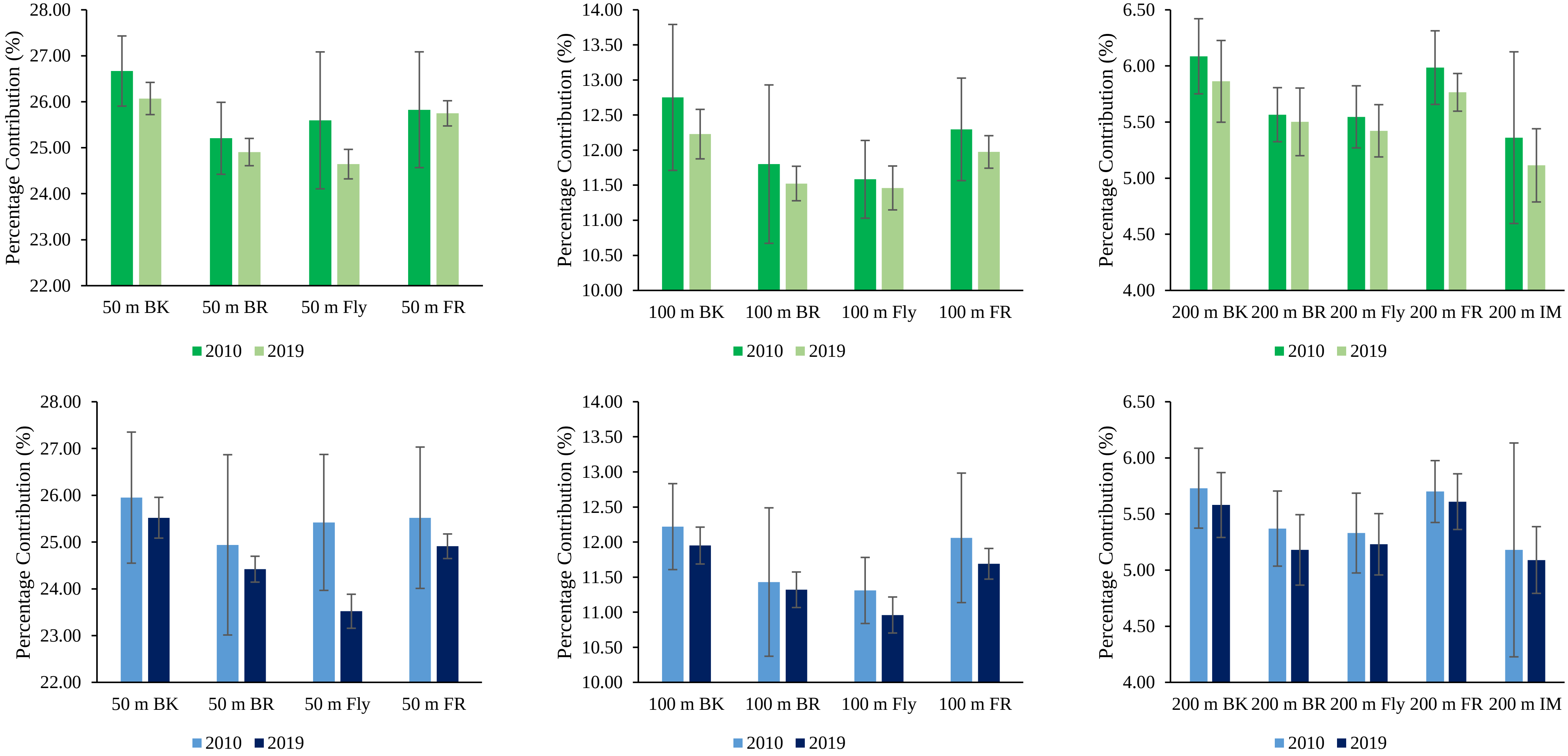

Figure 3.4 Mean (± SD) percentage contribution from the start for 2010 and 2019 across all sprint distances for females (green) and males (blue). All show that the start's percentage contribution has decreased for all events since 2010, and standard deviations between these times have also narrowed, suggesting there is less variation in start time between swimmers. *BK* Backstroke, *BR* Breaststroke, *Fly* Butterfly, *FR* Freestyle, *IM* Individual Medley.

3.5 Discussion

The current study aimed to assess the accuracy and reliability of start times measured using the single panning camera analysis system within the context of a predetermined SWC (0.187 s) compared to a gold standard method. Start times measured using the single panning camera were determined as accurate compared to criterion start times, with a 0.026 s systematic error and 95% limits of agreement between -0.048 s and 0.100 s across all trials. No significant interactions from additional variables, such as distance or stroke, were identified within the mixed model. Furthermore, excellent reliability was reported for an experienced analyst using the single panning camera analysis system to measure start times (intraclass correlation coefficient = 1.000, $p < 0.001$), and 95% limits of agreement ranged between -0.009 s and 0.007 s. The current study's second aim was to use a historical database to gather start times obtained by experienced analysts from the bespoke analysis software used by the single panning camera to calculate the percentage contribution of the start to total race time and the differences in absolute start time since 2010 for all events and between sexes. Absolute start times and percentage contributions decreased for all events (except 1500 m freestyle) and both sexes. Significant interactions within the growth model were reported for competition, time of day, sex, pool length, block time, breakout time and breakout distance. Faster start times were produced by male swimmers, during evening races, and swims within 25 m pools. World-class competitions also had faster start times across all competitions. British swimmers experienced a different rate of change in start times since 2010 compared to the other pooled nationalities (n = 47) included within the sample.

3.5.1 Accuracy and reliability of the single panning camera analysis system

Although the single panning camera analysis system overestimated start time for all events except 200 m breaststroke, with 95% limits of agreement ranging between -0.048 s to 0.100 s across all trials (Table 3.4), start times measured by the single panning camera were determined as sufficiently accurate for applied use within a high-performance setting based on the *a priori* context of a 0.187 s SWC value for start time. Results were reported by event (Table 3.4) to provide insight into stroke and distance impacts on start time differences between the two analysis systems. No significant interactions were found between start time differences and distance ($F(1, 1116) = 0.230$, $p = 0.631$) or stroke ($F(1, 1112) = 0.390$, $p = 0.532$). Heat number ($F(1, 800) = 0.349$, $p = 0.555$) and round type ($F(1, 1111) = 0.408$, $p = 0.523$) were included to assess their impact of start time differences for the two analysis methods, but these were also not significant. Despite initially considering lane number to impact start time differences, with lanes closer to the camera having a greater level of accuracy because the swimmers head would be more easily identifiable, no significant interaction was found for this variable ($p = 0.555$). In fact, lanes 0 and 9 experienced the highest systematic errors across all lanes (0.037 s), with the lowest systematic error in lanes more central to the camera view, potentially because of the increase in perspective error when objects are closer to the camera (Stephens et al., 2019) and the reduction in effective resolution when analysing swimmers in lanes further away from the camera. Nonetheless, 95% limits of agreement for lane number were lower than the 0.187 s SWC, and in major competitions such as the Olympic Games and Commonwealth Games, only lanes 1 – 8 are used. Round type was also not significant ($p = 0.523$) within the model, further supporting the ability of the single panning camera analysis system to maintain an accurate measure of start time with errors below the SWC, regardless of race conditions. There are several individual factors and technical differences which could impact the systematic error, however, as the current results for all start times measured within the current study were below 0.187 s (Table 3.4), and start times are often compared within individuals, the systematic error was concluded to not be a concern when assessing changes in start times.

The current results showed improvement from the original, unpublished findings by Kelley (2014), who concluded start times measured using the single panning camera had a mean error of -0.047 s and 95 % limits of agreement between -0.2 s to 0.1 s for start time. They also reported an error distribution range of -0.3 s to 0.2 s, and although these were not reported more accurately within the paper, these ranges are greater than the 0.187 s SWC. However, as it was unclear whether these 15 m times (n = 62) were only start times or included turns as well, this could explain the large error distribution. Therefore caution must be applied when making a comparison against the current results. Another possible explanation for the improvement in the current study is the data collection environment. The current study collected start times in three different locations, whereas Kelley (2014) completed all trials in one pool not included within the current study which may have impacted the results by differences in pool lighting, as images collected in low light environments often result in poor image quality overall and can impact the analyst's ability to determine accurate start times (Guo et al., 2017). Despite this, results from the current study suggest that the single panning camera analysis system is adaptable, not significantly impacted by the environment and reports accurate start times since 95% limits of agreement were smaller than 0.187 s. Nonetheless, analysing the accuracy of start times using the single panning camera analysis system within pools of varying light exposures would support this further.

Results found excellent reliability for both analysis methods, particularly start times measured using the single panning camera (r = 1.000), no significant differences were reported through the paired sample t-test (p > 0.050) and 95% limits of agreement were less than the 0.187 s SWC value. Despite start times measured using the single panning camera reporting better reliability than the criterion start times, this is likely because of the differences in frame rates of both analysis cameras. With criterion start times recorded at 100 Hz, the swimmer would still appear close to the 15 m mark within the two adjacent frames from where the 15 m point was measured. As the single panning camera recorded at 50 Hz, the swimmer travelled further between adjacent frames, therefore identifying when the swimmer reached 15 m was easier to repeat on a lower frame rate, because it is more apparent when the swimmer was at 15 m. Therefore, coaches and swimmers can have confidence that start times measured using the single panning camera are not only sufficiently accurate for measuring a swimmer’s response to training or interventions in start time, within the context of a 0.187 s SWC, but are also perfectly repeatable when determined by an experienced analyst.

White water was initially expected to be a potential source of error for both analysis methods, particularly 50 m events, where stroke rate is often increased (Navandar et al., 2016). When swimmers apply force to the water during free-swimming, an opposite force acts on the swimmer, developing wave drag, which presents itself in the form of white water around the swimmer's body. Therefore, an increase in the magnitude or frequency of the force applied to the water will increase the volume of white water surrounding the swimmer (Takagi & Sanders, 2000). However, neither distance nor stroke were significant within the model, suggesting that white water is not a substantial error source. The reliability of both methods also demonstrates the limited error from white water, as repeated trials reported minimal or no differences, start times could be measured repeatedly for a given trial, regardless of white water. As an experienced analyst with approximately two years of experience using the single panning camera analysis system completed the analysis for all trials, error sources may be reduced because of the experience that has been developed throughout this time. It is therefore recommended that novice analysts apply caution when completing analysis, particularly for swims with excessive white water, and where possible, assess their reliability and accuracy against an experienced analyst before reporting data from the single panning camera analysis system back to coaches and athletes, or using it for research purposes.

Start times measured using the single panning camera analysis system were determined as accurate and reliable within the context of a 0.187 s SWC, regardless of additional context and race variables. These results give confidence for using the single panning camera analysis system as a measure of start time during training and competition. The single panning camera analysis system enables coaches to quickly receive accurate race analysis to implement any necessary changes before future races and use retrospective data recorded by experienced analysts to identify key areas that will contribute more to their race and increase medal likelihood if improved.

3.5.2 The start as a component of total race time

The second aim of the current study was to determine the start's percentage contribution to total race time and observe how absolute start times had changed since 2010 when new equipment was introduced. Based on the raw data, absolute start times were faster in 2019 than 2010, as were total race times, yet percentage contributions decreased, with 50 m butterfly showing the largest decrease from 2010 to 2019 (Figure 3.4). Overall, start times were found to contribute between 0.73% and 26.07% to total race time. Growth model results indicated significant interactions with start time and sex, time of day, pool length, competition, block time, breakout time and breakout distance.

The current study also analysed the start across all events and between sexes, an expansion from Morais et al. (2018) who only considered 100 m events. Within the current study, backstroke had the highest percentage contribution for males and females across sprint distances. Whilst this does not align with Morais et al. (2018) who concluded that backstroke had the highest percentage contribution for females only, the increased sample size across multiple competitions and distances in the current study could explain this difference. Backstroke races are the only events where swimmers set-up in the water, therefore the technique exhibited during this phase is different from those diving off the new start blocks with an additional back plate. Although multiple studies have provided insight into the backstroke start technique (de Jesus et al., 2011; Takeda et al., 2014), and variations that could enhance backstroke start performance (de Jesus et al., 2013, 2016; Nguyen et al., 2014), the differences between the two starts are currently unknown in terms of power production and velocity comparisons, as well as the distances covered during the flight phase. Backstroke starts have a highly flexed leg position during set-up (Takeda et al., 2014), which would seemingly elicit a similar, or possibly greater level of force compared to those on the start blocks with an additional back plate. However, the differences in percentage contribution and absolute start time are still greater compared to butterfly and freestyle for both sexes. As backstroke begins in the water, it can be hypothesised that swimmers will cover less vertical distance and therefore have a shorter flight phase compared to those situated on the 65 cm high start blocks. Consequently, this leads to an earlier water entry and exposure of drag forces acting on the swimmer causing a deceleration in initial velocity, particularly when swimmers are closer to the surface of the water (Tor et al., 2015a). As a result of this earlier deceleration, backstroke swimmers have slower start times compared to freestyle and butterfly swimmers and therefore spend longer completing the start.

The breaststroke start technique also varies compared to other strokes; however, this occurs during the underwater phase and explains why the breaststroke start is the slowest. The underwater phase for breaststroke consists of a single underwater fly kick and a single arm stroke before transitioning into the free-swim segment of the race (Seifert et al., 2007). For all other strokes, swimmers perform continuous underwater fly kicks, aiming to maintain their velocity from the block and flight phases before breaking out and transitioning into free-swim (Lyttle et al., 2000). Without continuous underwater fly kicks for propulsion, breaststroke swimmers experience a deceleration during the start, where other strokes maintain their velocity (Yamakawa et al., 2017). With FINA permitting breaststroke starts to continue past the 15 m marker, swimmers aim to maximise their time underwater during this stroke, ahead of increasing their drag profile once free-swimming begins (Morais et al., 2018). The relevance of the current start definition is therefore unsuitable for breaststroke, and reconsideration is necessary to ensure the underwater phase has been completed when providing start time feedback to coaches and swimmers, with breakout time providing a more appropriate start endpoint. Since the current study used retrospective data to determine the start as a percentage contribution, the definition from previous literature was maintained across all strokes to ensure consistent comparisons, as reliability could be reduced when assessing breakout times, especially considering different breakout distances and the subjective variation between analysts when determining breakout time, compared to using a calibrated, know distance (15 m) as employed in the current study.

The current study also aimed to understand how absolute start times have changed since 2010 after the new start block and backstroke wedge were introduced. Assessing absolute start times gives insight into how much start times have changed, potentially due to new equipment; the percentage contribution only provides an understanding of how these changes have impacted the duration of the start as a proportion of the overall race compared to previous years. Absolute times also provide a practical application to coaches when assessing necessary targets for swimmers to improve performance and medal likelihood. The growth model and absolute start times showed an improvement in start time, alongside a reduction in total race time, also observable from the official FINA timings (FINA, 2022a).

Males had faster absolute start times that contributed less to total race time than their female counterparts. Previous sprint cycling and running results concluded that because males have a larger muscle mass, they can produce greater absolute peak power values and greater power production per unit mass than females (Perez-Gomez et al., 2008; Slawson et al., 2013). Applying these findings to swimming implies that males can generate greater relative power on the blocks, a finding previously confirmed by Slawson et al. (2013), enabling them to reach higher velocities before water entry. Height differences are also considered to contribute to males achieving faster start times. For example, Miller et al. (1984) included height as a covariate when assessing start time differences between sex and found taller athletes could travel greater distances on the block before take-off. This could enable a greater impulse during the block phase for taller swimmers, as they are able to travel a greater distance, whilst maintaining contact with the block to produce force. Additionally, Miller et al. (1984) found stronger swimmers could achieve greater horizontal velocities, which has been supported since by more recent findings (Perez-Gomez et al., 2008; Slawson et al., 2013). As well as height contributing to faster start times, Veiga et al. (2016) found that elite male swimmers typically have longer underwater phases compared to elite female swimmers. As previously mentioned, a longer underwater phase can reduce the drag profile of the swimmer, limiting the deceleration experienced. Once free-swimming begins, drag forces are more prevalent and horizontal velocity decreases, which is evident from the start and finish velocities within swimming. Considering this, males achieve faster start times by producing higher initial velocities and effectively utilise the underwater phase to reduce deceleration during the start (Cossor & Mason, 2001). This could suggest that females begin to decelerate earlier during the race, with males experiencing deceleration once free-swimming begins, explaining the lower percentage contribution from the start for males compared to females. This supports the investigation into pre-race interventions which facilitate increases in power output, and therefore horizontal velocity during the start, which could aid female swimmers in reducing the deceleration experienced during the start, and therefore enhance overall swim performance.

There was also a significant decrease in start time from morning to evening races. Typically during swimming competitions, heats are performed during morning sessions, with finals in the evening, where swimmers will aim to improve their qualifying swim time to increase medal likelihood. However, session type (heats; semi-finals; finals) did not significantly interact with start time within the growth model ($p = 0.193$), indicating that time of day influences start time more than session type. Several physiological factors have previously been linked to time of day and performance in support of these findings, for example, changes in circadian rhythms, such as body temperature, have been regularly associated with better contractile properties within the muscle, and larger power productions during evening races (Chtourou et al., 2010; Nicolas et al., 2005; Souissi et al., 2004). With this in mind, swimmers competing in morning finals (e.g. as done at the 2020 Tokyo Olympic Games), should aim to increase their T_m for an improved performance from heat to final (West et al., 2009), a concept explored in Chapter 5. If an increase in T_m cannot be achieved, other pre-race strategies should be explored to elicit a similar improvement in performance, e.g. PAP which is investigated in Chapter 4. Given the different physiological demands across swimming events, individual strategies might be a more appropriate option to enhance the impact a strategy has on performance.

A significant interaction was also exhibited for competition and start time, with post hoc tests showing that start times were faster during the Olympic Games, Commonwealth Games and World Championships than in other national competitions. With these three competitions being composed of world-class, elite athletes, it is no surprise that these are the competitions with the fastest absolute start times. This demonstrates that world-class swimmers at their intended peak are not only better during the free-swimming segments of the race than national level athletes, but also utilise their faster starts to enhance their performance and increase medal likelihood, thus demonstrating the importance of the start within sprint events.

One interesting observation from the two additional growth models was the interaction of year for British swimmers and other nationalities. A cubic trend best represented the rate of growth for the original model ($p = 0.011$) and the British swimmers' model ($p = 0.001$), yet this was not significant with the additional nationalities model ($p = 0.651$), indicating that start times for British swimmers have not followed the same rate of growth as other nationalities. Post-hoc results identified several nations that produced significantly faster start times than British swimmers, showing that this difference in the rate of change for start times has not necessarily benefitted British swimmers. Although this could be explained by British swimmers having faster start times in 2010, with other nations improving their start times to now match British swimmers, when the raw data was examined, this was not the case; in fact, the average start time for British swimmers was slower in 2010 than other nations by 0.01 s. Therefore, it is recommended that British coaches identify interventions that could acutely improve start performance and potentially obtain faster start times than their competitors. As the start is determined by power output off the block (Section 2.3.2), pre-race interventions such as PAP and heat maintenance could be beneficial, as previous research has supported their use to enhance the subsequent performance of power-based movements (Sections 2.4.1 and 2.5.2).

3.6 Conclusions and further recommendations

Although a single panning camera analysis system was previously validated (Kelley, 2014), this validation was predominantly for turn times, whereas the current study determined start times measured using the single panning camera as accurate across a much higher sample size, with more events and within several competition environments. These results support the use of the single panning camera analysis system when measuring start times and identifying worthwhile changes based on the 0.187 s SWC for start time. Further recommendations are to utilise both the single panning camera analysis system set-up and bespoke software, particularly within the competition environment where more complex analysis methods are often limited due to access restrictions, and also the fast processing time, which ensures coaches and swimmers receive their race analysis promptly and can make necessary changes ahead of future races. It is recommended that analysts are well trained, competent and complete an intra-rater reliability check as well as a validity check against an experienced analyst to ensure the integrity of the obtained data is maintained to a high standard, particularly within events that exhibit a considerable accumulation of white water.

Start times as percentage contributions confirmed past findings from before equipment changes were implemented (Lyttle & Benjanuvatra, 2005; Morais et al., 2018; Slawson, 2010) and further emphasised the importance of the start for sprint events within the current swimming environment. Additional variables that influence start time were also identified, offering coaches the ability to consider interventions to aid start performance. Differences in start percentage contributions between nationalities and morning/evening races suggest that additional pre-race interventions can benefit swimmers to enhance swim performance. However, these pre-race interventions need to minimise fatigue or EIMD which could accumulate across a multi-day competition, such as isometric PAP and heat maintenance.

Chapter 4. The effects of ballistic and isometric postactivation potentiation on the swimming start

4.1 Introduction

The swimming start, defined as the time from the first instance of the timing light to when the centre of the swimmer's head reaches 15 m (Cossor & Mason, 2001), can contribute up to 26% of total race time as outlined in Chapter 3. To enhance start performance, swimmers aim to maximise power off the starting block/backstroke wedge to increase flight velocity before entering the water and reduce any deceleration from drag forces (Cuenca-Fernández et al., 2019; Gonjo & Olstad, 2020; Vantorre et al., 2014). Consequently, a wealth of research has been conducted detailing the technical interventions a swimmer can utilise to maximise power output and their resultant velocity off the starting block. To enhance power output further, researchers have focused on physiological strategies implemented during race preparation to increase power output. One of these is PAP, a physiological phenomenon that creates a temporary window of opportunity for increased strength and power production within the muscle, providing the conditioning activity is biomechanically similar to the proceeding movement (Barbosa et al., 2016; Weber et al., 2008).

Although the mechanisms underpinning PAP remain unresolved, one strongly supported theory surrounds the phosphorylation of myosin light-chains, which provokes an increase in actin and myosin sensitivity to calcium (Sale, 2004). It has been theorised that this phosphorylation increases the mobility of myosin heads, enabling them to move closer to the actin binding sites, therefore increasing the likelihood of actin-myosin cross-bridge formation and production (Blazevich & Babault, 2019). This heightened sensitivity enhances subsequent contractions following the PAP conditioning activity, improving the performance of power and speed-based movements. One other PAP mechanism theory includes a surge in motor neuron activity from an increased excitation at the spinal cord, recruiting higher-order motor units (Blazevich & Babault, 2019; Tillin & Bishop, 2009).

Regardless of PAP mechanisms, multiple studies have supported its use within swimming to enhance the power production of subsequent performance. For example, Hancock et al. (2015) found a significant improvement in 100 m swim time by 0.85% for elite collegiate swimmers who completed a standardised swim WU proceeded by a dynamic, resistive 10 m sprint PAP conditioning activity. A gender interaction with PAP was also considered by Hancock et al. (2015), though no significant interactions were found, suggesting PAP is effective for both males and females. Cuenca-Fernández et al. (2015) also investigated a PAP response in trained swimmers following a lunge protocol and a YoYo squat protocol; this consisted of swimmers adopting a similar position to the swimming start on an inertial flywheel device. They analysed the effects of the two PAP conditioning activities on various swimming start metrics, including block time, flight time and start time, and found start times were significantly faster by 2.39% for those who had completed the YoYo squat PAP conditioning activity compared to a standardised swim WU, as well as greater flight distances and shorter block times following the YoYo squat. No significant differences were found for any of the swimming start metrics for the lunge protocol compared to the standardised swim WU and start time was slower than the YoYo squat protocol by 0.54%. These findings suggest that the YoYo squat set-up was more biomechanically similar to the swimming start than the lunge, an important consideration when aiming to elicit a PAP response.

Additional studies have outlined the optimal methods for maximising PAP effects, including the recovery duration between the PAP conditioning activity and performance. Kilduff et al. (2011) investigated recovery time in a group of elite sprint swimmers. They found peak CMJ height and PPO was achieved after an 8 min recovery from a PAP conditioning activity. Although start time did not significantly improve, horizontal and vertical force production on the start block were significantly higher by 5.71% and 3.83%, respectively, following PAP. Similar results were found by Bevan et al. (2009), who reported that PPO and peak throw height was achieved 8 min after a PAP conditioning activity for 26 rugby players performing bench press throws. Additional time points were measured and power output and throw height remained elevated from 8 min until 12 min after the conditioning activity, suggesting that whilst 8 min is the optimal recovery time, performance enhancements are still achievable if an 8 min recovery is not realistic within the sporting environment.

As previous research has reported, PAP can enhance power-based movements, such as the CMJ and the swimming start, providing the recovery time is sufficient to the individual. However, PAP has only been tested during controlled sessions instead of within the competition environment, where it is most commonly practised. Swimmers regularly race over multiple days, with the most recent Commonwealth Games concluding after six days. Throughout this period, swimmers often compete in more than one event and several rounds (i.e. heats, semi-finals, and finals); therefore, some swimmers may race every day throughout the competition alongside completing a PAP conditioning activity when necessary. Repetitive eccentric exercises have been linked to EIMD, resulting in muscle soreness and impaired power production; however, the severity of these effects is considered to be less following isometric contractions (Clarkson & Newham, 1995). Considering this, Lim & Kong (2013) investigated an isometric PAP conditioning activity and found no significant differences between an isometric knee extension, isometric squat, and a dynamic squat on sprint performance. However, faster mean sprint interval times were found for 20 m and 30 m for all three PAP conditioning activities compared to the control, although these were not significant. Although no significant differences were found between the control and the tested PAP conditioning activities, only a 4 min recovery time was permitted, which, as explained (Section 2.4.4), is potentially too small a recovery duration to overcome fatigue and utilise PAP. Esformes et al. (2011) have also supported the use of isometric PAP for the upper body. Using ten elite rugby players, they assessed the differences in isometric, concentric, eccentric and dynamic PAP conditioning activities and their effects on a ballistic bench press throw. The isometric PAP conditioning activity was the only condition where PPO significantly increased during the proceeding ballistic bench press throw and no significant differences were found between PAP conditions for the other performance variables. Despite these studies supporting the use of isometric PAP, there is still some contradiction surrounding its effectiveness to improve performance amongst other sporting movements.

Ideally, swimmers competing at regular intervals throughout competition would utilise an isometric PAP conditioning activity because of the reduction in EIMD compared with eccentric exercises and the window of opportunity for increased power production it elicits; however, the use of isometric PAP within swimming has not yet been considered. Therefore, the current study aimed to determine the effectiveness of an isometric squat PAP conditioning activity compared to a ballistic PAP conditioning activity on start time. A secondary aim was to assess the effectiveness of the two protocols on CMJ performance, as this movement can isolate and provide a direct measure of lower-body PPO (Cossor et al., 2011).

4.2 Methods

4.2.1 Participants

Upon receiving ethical approval from the Swansea University College of Engineering Research Ethics Committee, 14 participants (3 females, 11 males; Table 4.1) volunteered to complete the study after providing written informed consent (APPENDIX A). All participants were national-level swimmers (FINA points > 679) who completed approximately nine swim training sessions and three gym training sessions a week. Training backgrounds were predominantly sprint-based, although one distance swimmer also completed the study. Stroke background included five backstroke, two breaststroke, four butterfly and four freestyle swimmers; all participants performed the 20 m swim on their best stroke. The study was completed during the training cycle, and data collection took place during afternoon training sessions at the Wales National Pool, Swansea.

All participants were well practised with the ballistic PAP conditioning activity, having performed this at multiple competitions and within training. A familiarisation period was conducted for the isometric PAP conditioning activity five months prior to the study within training, although four swimmers had also performed the isometric PAP conditioning activity at recent competitions.

Table 4.1 Participant characteristics as mean ± standard deviation for the whole group, females and males.

	Group (n = 14)	**Female (n = 3)**	**Male (n = 11)**
Age (years)	19.9 ± 1.6	19.0 ± 0.8	20.1 ± 1.6
Height (cm)	177.2 ± 8.5	166.6 ± 7.7	179.9 ± 6.2
Mass (kg)	73.2 ± 9.2	63.2 ± 6.2	75.6 ± 8.2
FINA Points	777 ± 57	790 ± 61	774 ± 55

4.2.2 Pool calibration

As access restrictions were not a limitation within the pool used for this study, the gold standard camera set-up described in Chapter 3 was implemented during this study, removing any systematic error from perspective error, which could differ by lane. As a result, lane two was used for every testing session due to pool availability, and this was calibrated prior to participant arrival to identify a 15 m landmark from the starting end. Using the same protocol as Section 3.2.2, the buoys on both lane ropes were tightly pushed together and held in place with a clamp at each end of the pool; this ensured the buoys would remain stable and prevented any horizontal movement of the 15 m landmark. From the starting blocks, a tape measure identified 15 m along both sides of the pool, and tape was placed at these points. A video camera (Sony FDR-AX53 4K Camcorder, Tokyo, Japan) was attached to a tripod perpendicular to the 15 m landmark and was set to record at 100 Hz. All videos included the starting blocks and 15 m landmark within the camera view, so no additional panning was necessary during the trials.

4.2.3 Main trial procedures

Participants completed all three conditions on separate days, at least three days apart and trials were completed at the same time of day to control for circadian rhythms (Figure 4.1). Height was measured, and a resting blood lactate was collected from the participant's ear or index finger using a lactate analyser (LactatePlus, Nova Biomedical, Cheshire, UK). Three baseline maximum effort CMJs with arms akimbo and wearing trainers were carried out on a portable force platform (Type 9260AA6, Kistler, Winterthur, Switzerland). The CMJ was selected as it is an isolated movement which is not affected by additional variables, as is a potential limitation with the swimming start; therefore, any changes in PPO or force production are more easily identifiable during the CMJ. Prior to and throughout the current study, all participants regularly completed CMJs during gym sessions and strength testing procedures, therefore, to minimise the impact of the current study on the participant's CMJ technique during gym sessions, and to maximise the reliability of the obtained measures, no changes were made to alter the participant's technique, or control for jump depth. Each participant completed their individual race WU before post-WU measurements were collected. The 6 – 20 Borg scale (APPENDIX C; Borg, 1982) was used to score all RPE throughout the data collection sessions. During the 15 min changing period, participants also wore a standardised hooded top and pair of tracksuit bottoms.

For both PAP conditioning activities, participants were required to use maximum effort when performing the exercises. Ballistic PAP took approximately 3 min to complete, whereas isometric PAP took approximately 4 min. During the isometric squats, participants stood on a custom-made rig with a weightlifting belt around their waist, chained to the rig's centre (Figure 4.2). When instructed, participants positioned themselves into a squat position and performed each maximal effort isometric squat, pulling away from the rig for 3 s before relaxing.

An 8 min seated, passive rest period was then completed, during which, participants reported an RPE for the PAP intervention and completed the readiness to compete questionnaire, comprised of three Likert format scales (Figure 4.3; Krane, 1994). The standardised clothing was removed after 7 min to ensure the CMJ was performed at 8 min. The 20 m maximum effort swim took place 2 min after the CMJ and was performed on the participant's best stroke from a dive or backstroke start. Each swim was started using the timing light, preceded by a "take your marks" signal. Each 20 m swim was filmed using the high-speed camera, placed perpendicularly to 15 m. A final blood lactate and RPE score were recorded after the swim.

The vertical component of the ground reaction force data from each CMJ was collected using BioWare 5.4.3.0 (Kistler, Winterthur, Switzerland). Bespoke CMJ analysis software was used to calculate CMJ height and PPO using standard integration-based procedures (Table 2.5; Owen et al., 2014) for the CMJs taken at each time point (i.e. baseline, post-WU and post 8 min passive rest). PPO was selected as a performance variable alongside jump height because it gives a direct insight into a swimmer's capacity to produce force at high velocities, a crucial component of a successful start (Figure 2.2; Section 2.3.2). Although time to reach PPO may have given insight into the effectiveness of the PAP intervention, previous literature has found a strong relationship between CMJ PPO and start performance, with little regard to the time this point was reached as this is often highly consistent between individuals given that it occurs when force and velocity are both high, soon before take-off (West et al., 2011; Section 2.3.3). Additionally, as CMJ depth was not controlled for, PPO was considered to provide a more accurate comparison between conditions. CMJ height is also dependent on power output but can also be seen as a reflection of impulse, with a longer push-off phase eliciting a greater impulse because of the time spent on the force platform. Videos for the 20 m swims were analysed using Dartfish (Dartfish 10, Fribourg, Switzerland) to obtain block, flight and start times. Block time was defined as the time from the first instance of the timing light on the video to the last frame the swimmer's foot was on the starting block, or timing pad for backstroke. Flight time began at the end of block time and ended when the centre of the swimmer's head was submerged within the water. Finally, using the same definitions as Cossor & Mason (2001), start time was the time between the first instance of the timing light until the centre of the swimmer's head crossed the 15 m landmark, identified during pool calibration.

A value of 0.18 s was selected as the SWC for start time. This value was determined by obtaining start time differences from previous swimming start intervention studies (Table 3.2). Therefore, if swimmers had an improved start time following PAP of ≥0.18 s compared to the control, this was considered worthwhile.

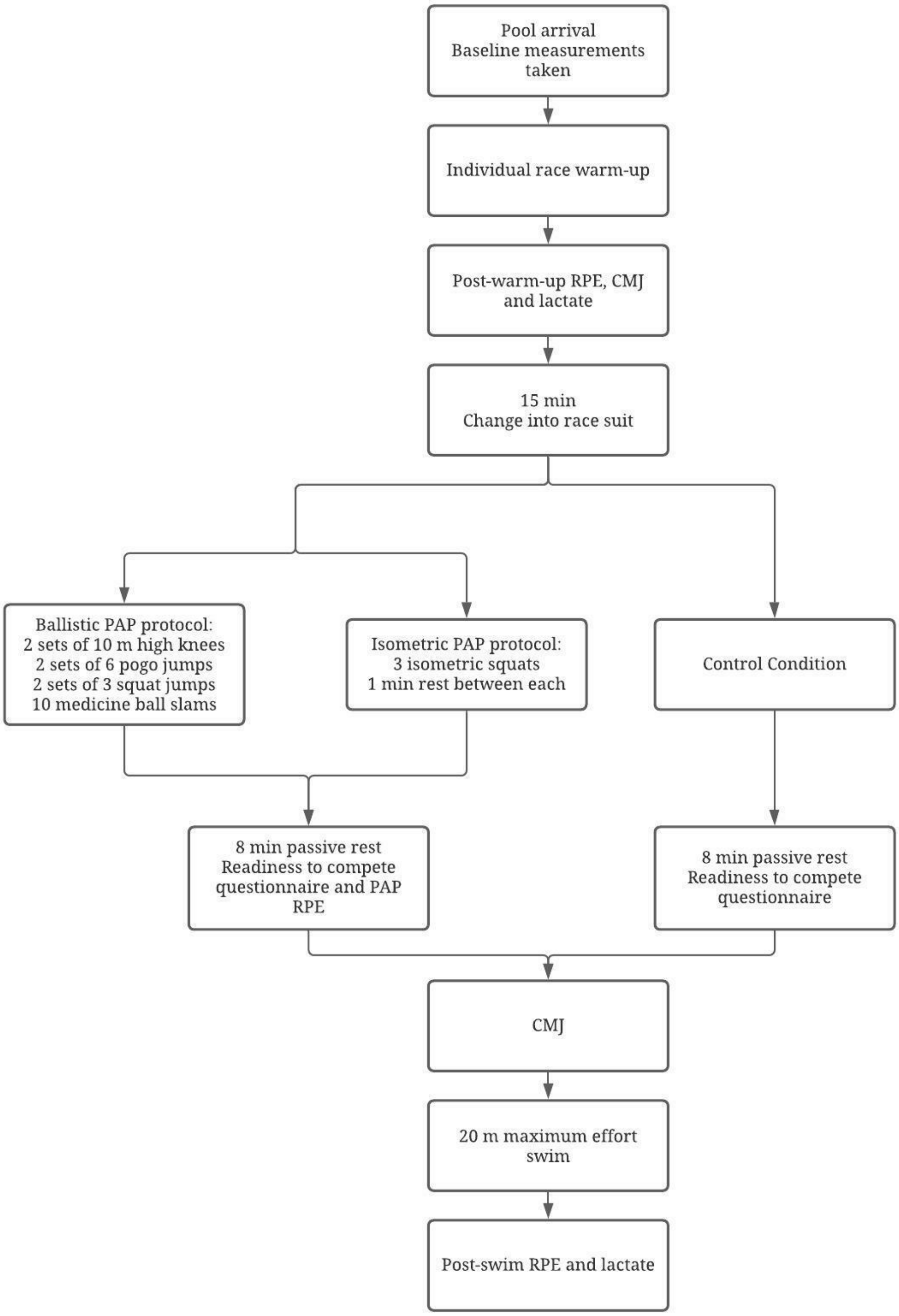

Figure 4.1 Flowchart of main trial procedures.

Figure 4.2 An isometric squat performed on the custom-made isometric pull rig during a data collection session.

My thoughts are:

1	2	3	4	5	6	7	8	9	10	11

CALM **WORRIED**

My body feels:

1	2	3	4	5	6	7	8	9	10	11

RELAXED **TENSE**

I am feeling:

1	2	3	4	5	6	7	8	9	10	11

CONFIDENT **SCARED**

Figure 4.3 The readiness to compete questionnaire in Likert format completed by participants after the 8 min passive rest period.

4.2.4 Statistical analysis

All data is presented as mean ± SD. Statistical analysis was completed using SPSS 28 (SPSS Inc., Chicago, IL, USA), and the significance value was set to $p \leq 0.050$. Once parametric data assumptions and sphericity were established, a repeated measures one-way analysis of variance (ANOVA) was used to identify any significant differences between conditions for single time point variables (i.e. block, flight and start times, readiness to compete questionnaire scores and the post 20 m swim RPE). The Bonferroni confidence interval adjustment method controlled type 1 errors during post hoc analysis when results were significant (Field, 2013).

A factorial repeated measures ANOVA established any significant differences between conditions for multiple time point variables (i.e. CMJ PPO, CMJ height and blood lactate), which gave a condition, time and time*condition interaction. When an interaction was significant, simple effects analysis was conducted to identify the level where this significant interaction occurred.

A one-tailed Pearson's product-moment correlation coefficient analysed relationships between baseline PPO and change in PPO following PAP. PPO change was calculated by subtracting baseline PPO away from the post 8 min rest PPO for ballistic and isometric PAP. This change was then correlated with baseline PPO for each condition to assess the relationship between baseline PPO and the ability to harness PAP.

Change in start time was calculated by subtracting control start time from ballistic and isometric start time, and this change was correlated with baseline PPO, to see whether those who had faster start times during the PAP conditions were more powerful.

Thresholds for the r-values obtained were defined as small (0.1), moderate (0.3), large (0.5), very large (0.7) and extremely large (0.9) for the correlation results (Malcata et al., 2014).

4.3 Results

4.3.1 Start performance

No significant main effects of condition were found on block time (F = 2.186, p = 0.154), flight time (F = 0.792, p = 0.463) or start time (F = 0.440, p = 0.649; Table 4.2).

4.3.2 Swimming rate of perceived exertion

After the 20 m maximum effort swim, RPE was not significantly different between conditions (F = 0.879, p = 0.427; Table 4.2).

4.3.3 Readiness to compete questionnaire

A significant main effect of condition was found on the calmness of the participants' thoughts (F = 3.500, p = 0.045; Table 4.2); however, pairwise comparisons did not reveal any significant differences (p = 0.155 – 0.568). No significant differences were found when participants were asked to rate how their body felt (F = 0.341, p = 0.613) or how they were feeling (F = 0.068, p = 0.935) during the 8 min passive rest period (Table 4.2).

4.3.4 Countermovement jump peak power output

A significant main effect of time was found on PPO (F = 22.201, $p < 0.001$), with increased PPO after the WU ($p < 0.001$) and the 8 min passive rest period (p = 0.002) compared to the baseline (Figure 4.4A). No significant main effect of condition was found on PPO (F = 3.014, p = 0.066). A significant time*condition interaction was found (F = 4.035, p = 0.006) and simple effects analysis found mean ballistic PAP PPO was greater by 4.0% than the control following the 8 min passive rest period (p = 0.004). There were no significant differences between isometric PAP PPO and the other two conditions following the 8 min passive rest period (p = 0.091 – 0.296). Following the 8 min passive rest period, mean isometric PAP PPO was greater than the baseline by 5.1% (p = 0.006).

4.3.5 Countermovement jump height

A significant main effect of time was found on CMJ height (F = 26.834, p < 0.001), with higher CMJs after the WU (p < 0.001) and the 8 min passive rest period (p < 0.001) compared to the baseline (Figure 4.4B). No significant main effect of condition was found on CMJ height (F = 1.012, p = 0.377). A significant time*condition interaction was found (F = 3.705, p = 0.010), and simple effects analysis found that mean ballistic PAP CMJ height was 6.6% higher following the 8 min passive rest period than the control (p = 0.045, Figure 4.4B). There were no significant differences between isometric PAP CMJ height and the other two conditions following the 8 min passive rest period (p = 0.891 – 0.474). Following the 8 min passive rest period, mean isometric PAP CMJ height was 6.9% higher than the baseline (p = 0.013).

4.3.6 Blood lactate

A significant main effect of time was found on blood lactate (F = 21.353, p < 0.001). Compared to the baseline, mean blood lactate was 86.9% higher after the WU (p = 0.014) and 142.7% higher following the 20 m maximum effort swim (p < 0.001). No significant main effect of condition was found on blood lactate (F = 1.202, p = 0.317; Table 4.2) and no significant time*condition interaction was found (F = 1.695, p = 0.165).

Table 4.2 Start performance, blood lactate, rate of perceived exertion (RPE) and the readiness to compete questionnaire results for all three conditions (mean ± standard deviation).

	Control	**Ballistic PAP**	**Isometric PAP**
Block time (s)	0.63 ± 0.05	0.64 ± 0.05	0.62 ± 0.06
Flight time (s)	0.35 ± 0.13	0.35 ± 0.12	0.36 ± 0.11
Start time (s)	6.71 ± 0.78	6.68 ± 0.69	6.71 ± 0.73
Post-swim lactate (mmol/L)	2.39 ± 0.75	2.77 ± 0.91	2.36 ± 0.93
Post-swim RPE	13 ± 2	13 ± 2	14 ± 1
My thoughts are	2 ± 1	3 ± 2	3 ± 2
My Body Feels	5 ± 2	6 ± 2	5 ± 2
I am feeling	3 ± 1	3 ± 2	3 ± 2

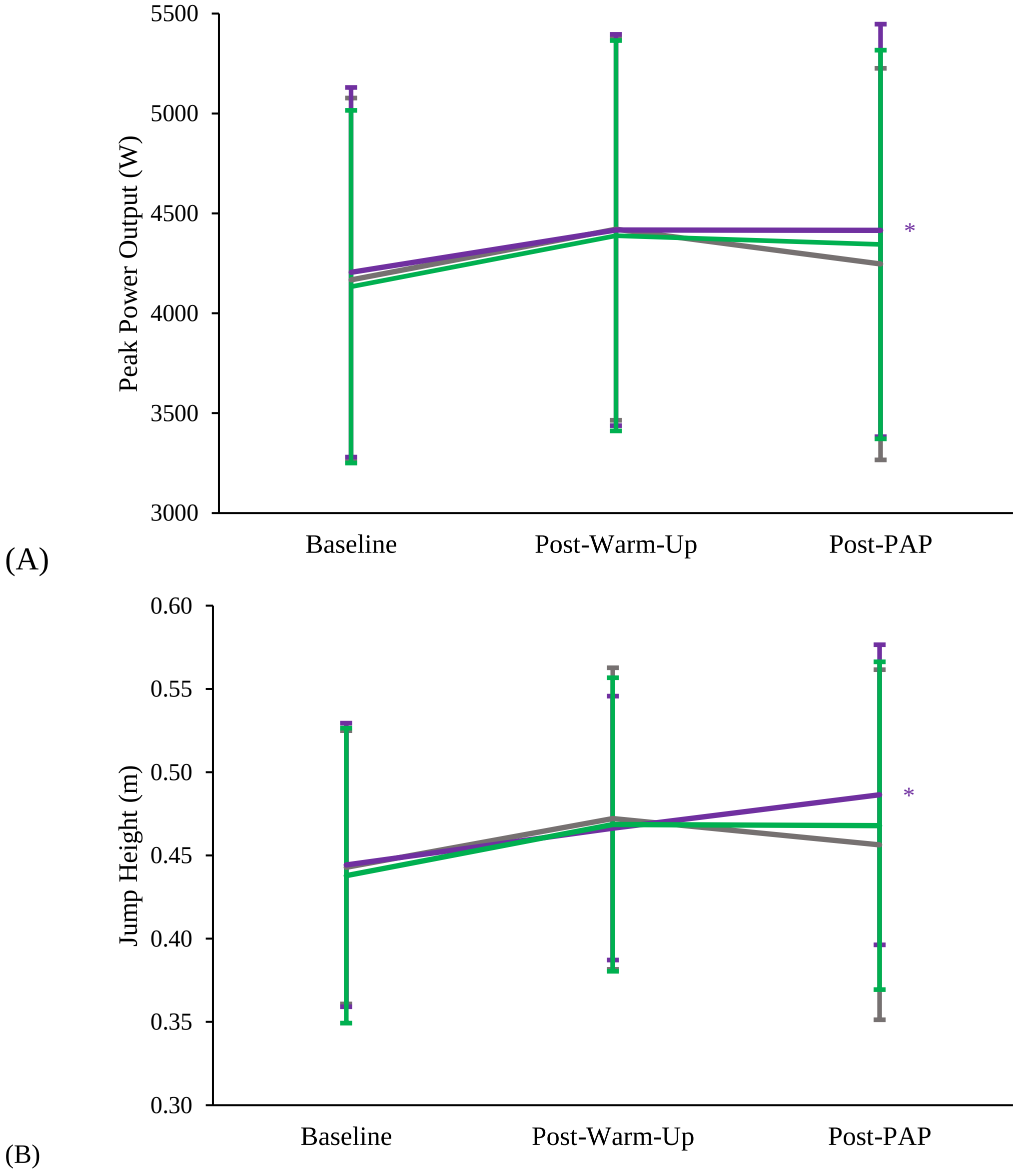

Figure 4.4 Peak power output (A) and jump height (B) means ± standard deviations (error bars) at all time points for the control (grey), ballistic PAP (purple) and isometric PAP (green) conditions.

*Indicates a significant difference from control after the 8 min passive rest period.

4.3.7 Individual results

To determine each swimmer's ability to harness PAP, individual responses between each condition were analysed and compared to the group mean for start time (Figure 4.5A), CMJ height (Figure 4.5B) and PPO (Figure 4.5C). Start times varied amongst individuals and between conditions, with 36% of swimmers achieving their fastest start time following ballistic PAP, 36% following isometric PAP and 29% during the control. Worthwhile changes ($\geq$ 0.18 s) were achieved following isometric PAP for two (14%) swimmers; all changes in start time following ballistic PAP were less than the SWC value.

4.3.8 Baseline and change in peak power output correlation results

A very large significant positive correlation was found for baseline PPO and change in ballistic PAP PPO (r = 0.805, $p < 0.001$). No significant correlation was found for baseline PPO and change in isometric PAP PPO (r = 0.371, $p = 0.096$).

4.3.9 Swimming performance and peak power output correlation results

No significant correlations were found between baseline PPO and change in start time following ballistic PAP (r = 0.155, $p = 0.298$) or following isometric PAP (r = -0.179, $p = 0.270$).

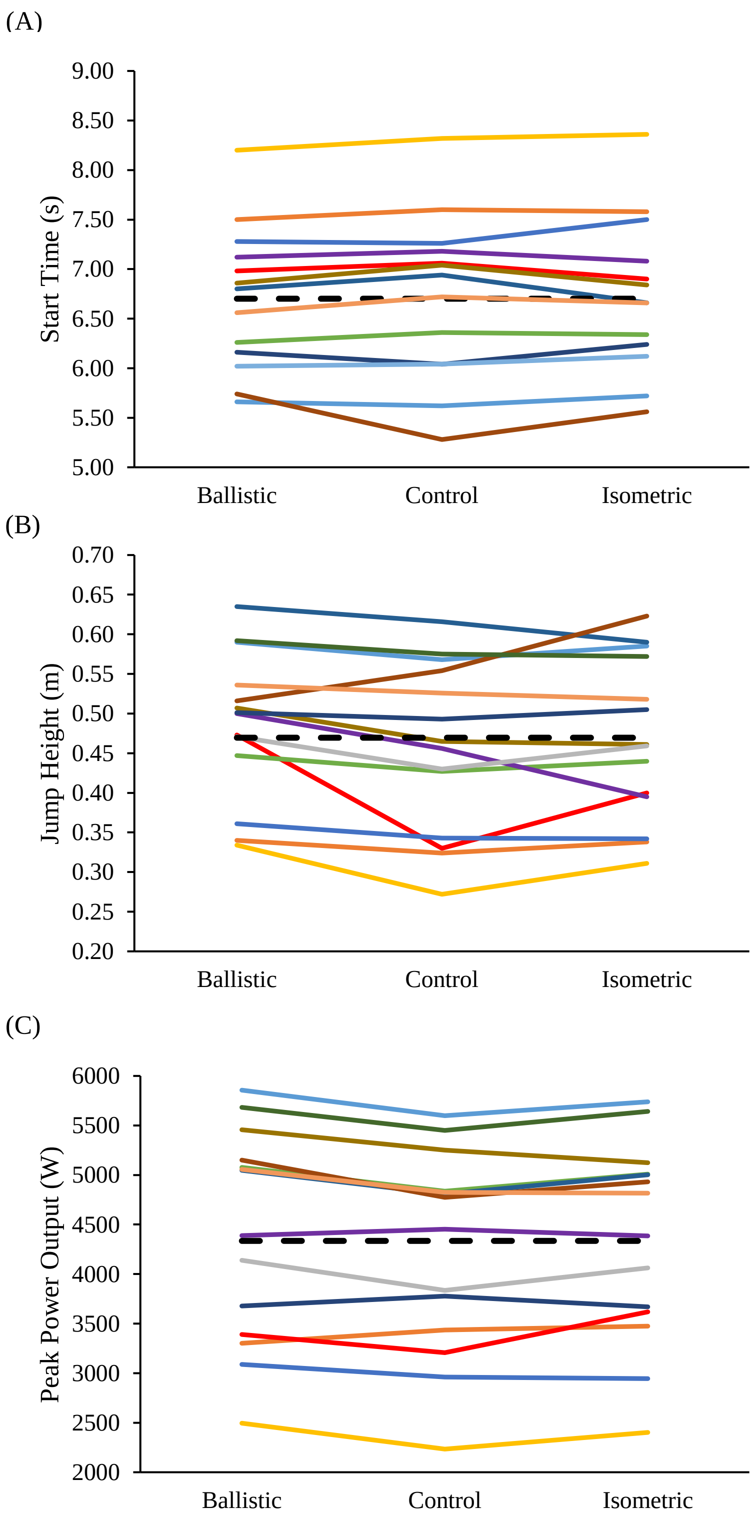

Figure 4.5 Individual results for start time (A), jump height (B) and peak power output (C) across all three conditions post-PAP. The dashed line indicates the group mean for each variable.

4.4 Discussion

The current study aimed to assess the effects of ballistic PAP and isometric PAP protocols on swimming start and CMJ performance within a group of national-level swimmers. Although swimming start performance did not significantly improve, CMJ height and PPO following ballistic PAP were significantly higher compared to the control condition (Figures 4.4A and 4.4B). Isometric PAP led to CMJ height and PPO increases between baseline and after the 8 min passive rest period, but this was not significantly different to the control. Participants experienced fewer calm thoughts during both PAP conditions than the control, although the additional two questionnaire scores (my body feels and I am feeling) and 20 m maximum effort swim RPE were not significantly different between conditions (Table 4.2). Correlation findings found participants with greater baseline PPO experienced a greater change in PPO following PAP; this supports previous results concluding more powerful individuals can harness PAP more effectively, thus increasing subsequent PPO. Isometric PAP led to worthwhile changes in start time (SWC $\geq$ 0.18 s) for two individuals (Figure 4.5A). In summary, these results support previous findings that ballistic PAP can increase PPO, however further research is needed to determine the effectiveness of isometric PAP on CMJ height and PPO.

A wealth of research has been conducted assessing the benefits of PAP conditioning activities on subsequent performance of power-based movements, such as jumping and sprinting (Beato et al., 2019; Cuenca-Fernández et al., 2015; Gołaś et al., 2016). Previous correlation results by West et al. (2011) found a significant relationship between start time and CMJ lower-body power output, therefore, it was anticipated that if a swimmer could harness PAP, start performance should improve, providing the PAP conditioning activity was biomechanically similar. Previous studies have focused on eccentric and concentric conditioning activities, using weightlifting equipment to harness PAP. For example, Bevan et al. (2009) completed a heavy resistance training PAP conditioning activity using a bench press to improve bench press performance in 26 professional rugby players. Despite studies supporting eccentric and concentric PAP, these types of contractions are thought to induce EIMD more severely compared to isometric contractions (Clarkson & Sayers, 1999). Therefore, the current study focused on ballistic and isometric PAP conditioning activities that are more readily available during competitions and require limited equipment. Providing maximal effort is exerted when performing the ballistic exercises, a PAP response should be achieved because higher-order motor units are recruited (Desmedt & Godaux, 1977), with past findings supporting this mode of PAP to enhance subsequent performance (Hester et al., 2017; Thapa et al., 2020). Although the current study did not find a significant or worthwhile change in start time following ballistic PAP (Table 4.2), a significant improvement in CMJ height and PPO was achieved (Figure 4.4). Previous research has supported relationships between CMJ height, PPO and start performance (Cossor et al., 2011; West et al., 2011), and can provide a direct observation of how interventions such as PAP can change PPO, without the additional variables which can impact start performance, such as underwater fly kick technique during the underwater phase (Figure 2.2). Therefore, although no SWC was identified for the group mean for start time, significant CMJ PPO improvements were found following ballistic PAP, which may have contributed to the 0.03 s faster start time during this condition, because of this relationship between start and CMJ performance and the transference of PPO. Similar results were found by McGowan et al. (2016) who found a small improvement in start time following ballistic PAP, although this was also not significant. 100 m time trial performance was significantly faster than the control during the PAP condition, suggesting that the small increase in start performance can contribute to the remaining 75 m of the race and aid the swimmer. Therefore, although start time was not significantly faster in the current study, the increased PPO may have led to faster overall times if longer distances were measured, however, this may have been due to other factors and further research is necessary to confirm this.

Although isometric exercise is considered to limit EIMD, isometric PAP has received limited attention; nonetheless, previous findings have concluded that isometric PAP is as effective at improving power-based movements as eccentric, concentric and ballistic PAP conditioning activities (Esformes et al., 2011). Although the current study only found a significant time interaction for isometric PAP CMJ height and PPO, individual differences revealed that 36% of swimmers achieved their fastest start time during this condition, and 14% of swimmers had a worthwhile change in start performance. One of the possible explanations behind the varying individual responses can be attributed to the experience in performing the isometric squat on the custom-built rig used within the current study. Previous research has found that those with more experience performing a PAP conditioning activity can harness a greater PAP response than those with less experience with the conditioning activity (Chiu et al., 2003; Hamada et al., 2000). This ability to successfully harness PAP is likely due to the adaptations of motor unit recruitment that occur due to training level and experience (Gullich & Sehmidtbleicher, 1996; Henneman, 1985). Although a familiarisation period was given for the isometric PAP conditioning activity across a five-month period before the current study, four swimmers had also utilised it at a competition, and three of these achieved their fastest start time during the isometric condition within the current study, one of these being a worthwhile change compared to the control. This increased exposure to the isometric PAP conditioning activity could explain why a SWC was only achieved for 14% of swimmers. The ballistic PAP condition had been used on multiple occasions before the current study, and although no SWC was found, 36% of swimmers experienced their fastest start time during this condition. This increased experience with ballistic PAP supports the increased CMJ height and PPO observed during the ballistic PAP condition, as swimmers could harness PAP more effectively due to previous exposure and therefore improve their start performance, even with minimal changes. Further research is necessary to determine whether isometric PAP can significantly improve CMJ and start performance further when a longer familiarisation period is given before data collection.

An additional explanation for the individual variation to the PAP conditioning activities is strength level. Further investigation into the two swimmers who achieved a SWC revealed that one had the highest relative strength testing results of all participants tested (APPENDIX D); strength testing results for the other participant could not be obtained. Likewise, correlation analysis revealed a relationship between baseline PPO and change in PPO following ballistic PAP. Although no SWC was achieved during the isometric PAP condition, these findings align with previous research that stronger individuals can achieve a larger PAP response and demonstrate significantly higher PPO values during the subsequent activity (Gourgoulis et al., 2003). This response is likely because stronger athletes are more capable of recruiting higher-order motor units (Sale, 2002), thus increasing the contraction stimulation during subsequent performance, as these motor units are already recruited.

Differences in muscle fibre type also impact the ability to harness PAP. Studies have found more significant phosphorylation of myosin light chains within fast-twitch muscle fibres and performance enhancements in events where fast-twitch muscle fibres are preferred (Hamada et al., 2000; Moore & Stull, 1984). Fast-twitch fibres are often associated as beneficial to speed-based activities, including swimming, because of their physiological properties including high phosphofructokinase activity, which is heavily involved during glycolysis, compared to slow-twitch muscle fibres which are considered to favour endurance activities because of their increased capillary supply enabling increased blood flow to the fibres for oxygen delivery (Qaisar et al., 2016). Since previous research has found increased fast-twitch muscle fibres following a sprint training programme (Jansson et al., 1990), it can be hypothesised that sprint-based swimmers would have a higher fast-twitch muscle fibre count, and therefore, be able to harness PAP more effectively.

Previous literature has outlined that conditioning intensity should be high to obtain a PAP response, with studies reporting a significant performance improvement when repetitions were completed at 75% 1RM or above (Kilduff et al., 2007; Tillin & Bishop, 2009). A PAP response was expected for the two conditions as both PAP conditioning activities within the current study required swimmers to exert maximal effort; however, this was only observed for mean CMJ height and PPO after ballistic PAP. Although research surrounding PAP intensity has been completed in-depth, results assessing the number of sets and repetitions is limited, and studies have used alternative PAP protocols, so direct comparisons cannot be made. The isometric PAP conditioning activity within the current study was designed as three repetitions of 5 s, with 1 min rest between each repetition. This conditioning activity was designed to be executed at maximal effort as it was anticipated that it would elicit the phosphorylation of myosin light chains (Blazevich & Babault, 2019), as well as recruiting higher-order motor units (Folland et al., 2008), two of the theorised mechanisms of PAP. However, there was no change in CMJ performance between the WU and after the 8 min passive rest period; therefore, the protocol may have only maintained the enhancements achieved from the pool WU, with more repetitions needed to ensure a PAP response is obtained. Comparisons between conditioning activity set and repetition frequency are needed to optimise the isometric PAP conditioning activity to enhance subsequent performance.

A period of fatigue is usually experienced following a PAP conditioning activity, meaning performance is temporarily compromised. The recovery period between the PAP conditioning activity and subsequent performance must be sufficient to enable the participant to overcome fatigue, but not too long that the PAP response is diminished. A rest period of 8 min was chosen for the current study as previous research has recorded the highest PPO at 8 min following a PAP conditioning activity (Bevan et al., 2009; Dello Iacono et al., 2018; Kilduff et al., 2011; Wilson et al., 2013). Ballistic PAP significantly improved CMJ height and PPO following the 8 min passive rest period compared to the control (Figure 4.4), supporting this recovery duration to enhance CMJ performance following ballistic PAP. Isometric PAP was not significantly different from WU to after the 8 min passive rest period for CMJ height and PPO. As limited research surrounds isometric PAP, it is not currently known what the optimal recovery time is between this PAP conditioning activity and subsequent performance, therefore this could explain why CMJ and start performance did not significantly improve, especially when most recovery duration studies have used eccentric PAP conditioning activities, as the findings may not apply to isometric PAP. Considering CMJ height and PPO were maintained following the 8 min passive rest period, additional recovery time may have been required to further enhance the PAP response and therefore observe a significant improvement. Previous research has found that increased exposure to a conditioning activity can enhance the PAP response (Comyns et al., 2010), potentially because of a decrease in the necessary recovery time following PAP. Therefore, because some participants were less familiar with the isometric PAP conditioning activity, the PAP response may have been less and they may have been unable to recover as quickly, therefore reducing the improvements in CMJ height and PPO 8 min after the conditioning activity. Similar to the above comment, one of the participants who achieved a SWC during the isometric condition had utilised the isometric PAP conditioning activity regularly during training and at competitions, supporting the theory that those more familiar with the PAP conditioning activity do not need as long a recovery duration to harness a PAP response. Nonetheless, further research is necessary to determine the ideal recovery time for isometric PAP. Previous research has also found that recovery time varies between individuals, based on participant-specific factors detailed above (Beato et al., 2019; Bevan et al., 2009); 8 min is an average recovery time determined from past findings. This variation can also aid in understanding why the PAP response for some individuals was less than others and why 29% of swimmers achieved their fastest start time during the control condition (Figure 4.5A). As outlined above, fatigue may still be present within the muscles if the recovery duration is insufficient, limiting power output and therefore maximal performance.

The readiness to compete questionnaire assessed how comfortable the swimmers were feeling before performing the 20 m maximum effort swim. Although results showed two of the three questions were not significantly different between conditions, swimmers did experience more negative thoughts after completing the ballistic PAP and isometric PAP conditioning activities (Table 4.2), however, the mean difference was minimal. The current study was completed throughout the training cycle when the participants were working towards end of season competitions, with a particular focus on aerobic maintenance and race pace intensities, which was unable to be controlled. The effects of training, such as fatigue and muscle soreness, may have been present during data collection, which can negatively impact athlete mind-set (Balk & de Jonge, 2021) and this could explain the results within the current study. RPE was not significantly different between conditions after the 20 m maximum effort swim, suggesting fatigue had been overcome as the same level of effort was perceived during the swim.

Although the current study provided some insight into ballistic and isometric PAP on the swimming start and CMJ performance, some limitations were present. Time restraints restricted the ability to complete the study during the same week of each cycle, such as the rest week. Therefore the training season was unable to be controlled for, with data collection taking place over a four-week period when regular training was being completed. As a result, elements of fatigue may have been present during some trials for participants but not others. Nevertheless, if the time within each cycle had been controlled for, training adaptations would have occurred, which could have impacted the results due to differences in fitness and strength during data collection, leading to a change in the ability to harness PAP.

Swimmers completed their individual race WU within the current study to simulate a competition environment to ensure the results were relevant for future races. Despite each swimmer completing the same WU across the three trials, the effectiveness of these WUs was questionable. Variation in CMJ performance and lactate measurements following the WU were substantially different for some individuals between each trial, despite mean results identifying significant time effects for all conditions between the baseline and post-WU. CMJ height and PPO values were also lower than anticipated following the WU (Figure 4.4). T_m can significantly affect performance, especially power-based movements, with improvements in metabolic reaction rate and decreased muscle viscosity attributed to force output improvements following a WU (Hill, 1922; Ranatunga, 1984; Section 2.5.1). Both PAP conditioning activities within the current study required maximal exertion to harness PAP and enhance subsequent performance. Therefore, if force output was not maximised during the PAP conditioning activities due to an insufficient WU, this could explain the results and limited significant differences from the control for the PAP conditioning activities. During a WU T_m increases which has been found to significantly enhance the subsequent performance of power-based movements (Section 2.5.2). Therefore, if T_m can be maintained, or increased, following the WU through the use of heat maintenance garments, this could enhance the PAP response as muscles can contract more effectively (Section 2.5.1) and therefore potentially improve start performance.

4.5 Conclusions and future recommendations

The current study found significant improvements in CMJ height and PPO following a ballistic PAP conditioning activity participants were highly familiar with. No significant changes were found between the control and isometric PAP for CMJ height, PPO or start time, potentially due to the limited exposure to the isometric PAP conditioning activity compared to ballistic PAP. However, a SWC in start time was found for 14% of participants following isometric PAP, supporting the conditioning activity as a method to elicit a PAP response in some participants; these athletes had used the isometric PAP conditioning activity during training and at competitions. Additional research is needed to refine the isometric PAP conditioning activity to determine the ideal recovery time amongst individuals, which previous research has identified varies and is dependent on muscle fibre type, strength level and training history. Furthermore, if T_m can be maintained following a WU, this could enhance the PAP response based on the biochemical and physiological changes associated with increased T_m.

Chapter 5. Assessing how start performance is influenced by the heat maintenance strategy used during the transitional phase within swimming

5.1 Introduction

The WU elicits a rise in T_m which promotes several physiological responses that can aid the subsequent performance of power-based movements. For example, Sargeant, (1987) found maximal peak force and power output significantly increased after immersion in 44°C water compared to the control by approximately 11% and 10%, respectively. Compared to the control, maximal peak force and power output decreased by 12% following immersion in 18°C water and 21% following 12°C water immersion. T_m was significantly higher than the control following 44°C immersion by 7%, and significantly lower than the control following 18°C and 12°C immersion by 13% and 21%, respectively. It was concluded that this increased T_m elicited a decrease in muscle and joint viscosity, enabling a more efficient muscular contraction, thus permitting greater force and power outputs. Additionally, Febbraio et al. (1996) found changes in muscle metabolism and energy contribution following increased T_m. Muscle biopsies showed a 17% lower ATP concentration for the heat condition, and lactate concentration was significantly higher post-exercise than the control. Additionally, significantly lower muscle glycogen concentrations immediately following exercise for the heat condition than the control were found. These results demonstrate the muscle's increased ability to effectively utilise and resynthesise ATP when T_m is increased, likely due to faster metabolic reaction rates than colder T_m (Stienen et al., 1996). Muscle viscosity is also considered a beneficial change with increased T_m. It is theorised that changes in the muscle's structural properties are evoked when T_m is increased, and contraction resistance decreases accordingly (Buchthal et al., 1944; Hill, 1922).

Following the cessation of the WU, athletes enter the “transition phase”, which refers to the time between the end of the WU and the beginning of the race. Throughout the transition phase, T_m decreases rapidly, particularly during the first 5 min, with a return to baseline after approximately 20 min (Galbraith and Wilmott, 2018). This rapid decrease can be problematic when applying the WU to the elite sporting world. For example, within swimming, athletes are regularly required to attend a call room environment up to 20 min before their race begins; therefore, the physiological benefits of the WU may have been diminished by the start of the race. In an attempt to overcome this problem, specific garments have been developed and used to maintain or delay the deterioration of T_m achieved during the WU. These heat maintenance garments have predominantly been insulative/passive (e.g. Blizzard garments), aiming to extend the duration T_m is elevated (Kilduff et al., 2013); however, current advancements include components that heat up and actively provide additional warmth near key muscle groups. The active heat maintenance garments aim to maintain and reduce heat decay, but with the additional components could potentially increase T_m after the WU, which have the potential to benefit swimming performance when athletes are constrained to call room requirements if used appropriately. McGowan et al. (2016) assessed active heat maintenance garments on 100 m swim performance. Participants sat for 30 min in a standardised t-shirt and tracksuit bottoms and a top with integrated heated elements across the chest and lower back, which heated up to 51°C, or just the standardised clothing for the control. 100 m performances were faster for the heat condition by 0.5%, and blood lactate concentration increased by 19% following the heat condition. Despite 100 m performance improving, this was concluded to be a marginal effect. However, as mentioned throughout Section 2.2.1, even marginal enhancements in swim time can increase medal likelihood.

The use of active and passive heat maintenance garments to improve swimming performance and upper body power was investigated by Wilkins and Havenith (2017). Following a standardised WU, participants wore a tracksuit jacket and bottoms or a jacket with integrated heat elements for 30 min before completing a 50 m swim and four maximum effort plyometric press-ups. Stroke rate at 25 m was significantly higher for the heated jacket condition by 5%, and 4% for the stroke rate at 40 m. As a result, stroke counts were also significantly higher during the heated jacket condition by 5%. A 0.8% improvement in 50 m swim time was found after participants wore the heated jacket, however this was not significant. Maximal RFD and peak force during the maximal effort plyometric press-ups were also significantly higher following the heated jacket condition by 10% and 11%, respectively. Following the 30 min, upper body skin temperature was significantly higher for the heated jacket condition by 7%. These improvements are likely because of the physiological benefits outlined above when T_m is maintained following WU exercise cessation. Although only torso skin temperature was recorded, previous research has found a close association between skin and direct T_m (Hardaker et al., 2007). Therefore, the findings of Wilkins and Havenith (2017) support the use of heat maintenance garments to maintain T_m and consequently enhance the performance of power-based movements.

The swimming start can contribute up to 26% of total race time, as outlined in Chapter 3, therefore making it a key element for sprint swimming (200 m or less). Start performance has been closely associated with CMJ performance as both rely on high power outputs for enhanced performance (Cossor et al., 2011), therefore CMJ performance is regularly implemented to monitor start performance as CMJs are more sensitive to changes in power output and more easily accessible to measure because of portable force platforms. Despite a connection being apparent between T_m and power output, there is currently limited research assessing improvements in swim start performance and lower-body power output following the use of heat maintenance strategies. Therefore, the current study aimed to assess the use of active and passive heat maintenance strategies to enhance start performance. A secondary aim was to assess the use of active and passive heat maintenance strategies on CMJ performance, as this land-based movement is regularly implemented to monitor start performance accurately and provide a direct measure of lower-body PPO when this cannot be achieved during the start.

5.2 Methods

5.2.1 Participants

Following ethical approval from the Swansea University College of Engineering Research Ethics Committee, five female and ten male national level swimmers (Table 5.1) provided written informed consent (APPENDIX A) and volunteered to participate in the study, having received full information about the study protocols and potential risks involved (APPENDIX B). All participants were sprint-based (< 200 m) swimmers within the Swim Wales High-Performance Centres who completed approximately nine swim training sessions and three gym sessions each week. Stroke background included five backstroke, one breaststroke, six butterfly and three front crawl swimmers; the 20 m maximum effort swim was completed on the participant's best stroke. Data collection sessions were held at the Cardiff International Pool and the Wales National Pool, Swansea.

5.2.2 Pool calibration

Prior to each testing session, the same lane was calibrated using the method described in Section 3.2.2. Lane buoys were pushed along the lane rope until there was no further movement and clamped. 15 m was measured on both sides of the pool from the starting blocks and marked with tape. A photo of the two 15 m tape markers was taken, and a line was drawn between the two. The lane buoys this line crossed through was identified and used as the 15 m landmark. A video camera with a high-speed setting (Sony FDR-AX53 4K Camcorder, Tokyo, Japan) was placed on a tripod perpendicular to the 15 m landmark, and the field of view was adjusted to view the starting block as well as the 15 m marker without additional panning. The video was set to record at 100 Hz.

Table 5.1 Participant characteristics as mean ± standard deviation for the entire group, females and males.

	Group (n = 15)	**Females** (n = 5)	**Males** (n = 10)
Mass (Kg)	74.8 ± 9.7	65.9 ± 5.1	79.3 ± 8.3
Age (Years)	22 ± 2	20 ± 2	22 ± 2
Skinfolds (Sum of eight; mm)	63.2 ± 26.2	93.7 ± 29.6	51.0 ± 9.7
FINA Points	788 ± 54	768 ± 57	790 ± 49

5.2.3 Main trial procedures

Participants completed all three conditions (active heat maintenance (AHM), passive heat maintenance (PHM) and control (CON)) on separate days, one week apart at the same time of day to control for circadian rhythms in a randomised cross over design (Figure 5.1). A baseline blood lactate was measured from the index finger or earlobe using a lactate analyser (LactatePlus, Nova Biomedical, Cheshire, UK). Following a similar process to Flouris et al. (2015), iButtons (DS1922L, Maxim Integrated Products, CA, USA) were placed on the muscle belly of the right tibialis anterior, right rectus femoris and right biceps femoris using a self-adhesive pad, and recorded temperature at 5 s intervals. A line was drawn around each iButton site to ensure iButtons were placed in the same location when they were reapplied after the WU. A round neoprene disk (50 mm in diameter) was secured over each iButton using surgical tape (3M Transpore Surgical Tape, Gloucestershire, UK; Figure 5.2). Three CMJs were performed with arms akimbo whilst wearing swimwear and trainers on a portable force platform (Type 9260AA6, Kistler, Winterthur, Switzerland). As explained in Chapter 4, all participants regularly performed CMJs to self-selected depths, which is why this movement was chosen and CMJ depth was not prescribed. Participants were then given 20 min to complete self-prescribed stretches and land-based exercises before the WU whilst a baseline temperature was collected from the iButtons. These stretches and land-based exercises were consistent across each trial, with participants following the guidance from coaching staff received during early-season screening. Therefore, although stretches and land-based exercises may have varied between swimmers, they were consistent within individual swimmers during each trial.

The iButtons were then removed, and a standardised WU was completed (Figure 5.1). Immediately after the WU, a CMJ was performed, and a blood lactate and RPE score were measured (APPENDIX C). Surface area of the trunk region was measured using a FLIR i7 thermal imaging camera (FLIR systems, Oregon, USA). The iButtons were reattached to the same sites using the method described above. A 10 min period was given for participants to change into trainers and condition clothing: a standardised hooded top and tracksuit bottoms (CON), the standardised clothing underneath a custom-made hooded foil-lined survival jacket (PHM), or the standardised hooded top with a pair of HUUB trousers (HUUB, Derby, United Kingdom; AHM). The HUUB trousers had heated elements across the quadriceps, hamstrings, gluteus maximus and gastrocnemius that were switched on and heated to ~43°C 5 min before the end of the WU (Figure 5.3).

A 30 min passive rest period was completed to replicate the transitional phase of a swim meet, with scales used to rate thermal comfort (TC) (Bedford 1950; Appendix E) and thermal sensation (TS) (Zhang et al. 2010; Appendix F) every 5 min. After 25 min, participants gave final TC and TS scores and completed a readiness to compete questionnaire in Likert format (Krane 1994; Figure 4.3). After 30 min, condition clothing and iButtons were removed, and trunk temperature was measured before a final CMJ. Approximately 2 min after the CMJ, a 20 m maximum effort swim from a dive/backstroke start was completed. All swims were started using a timing light, preceded by a verbal "take your marks" signal and were recorded using the video camera perpendicular to 15 m. Blood lactate was measured immediately following the 20 m swim, and an RPE was scored. Participants then completed their own swim down.

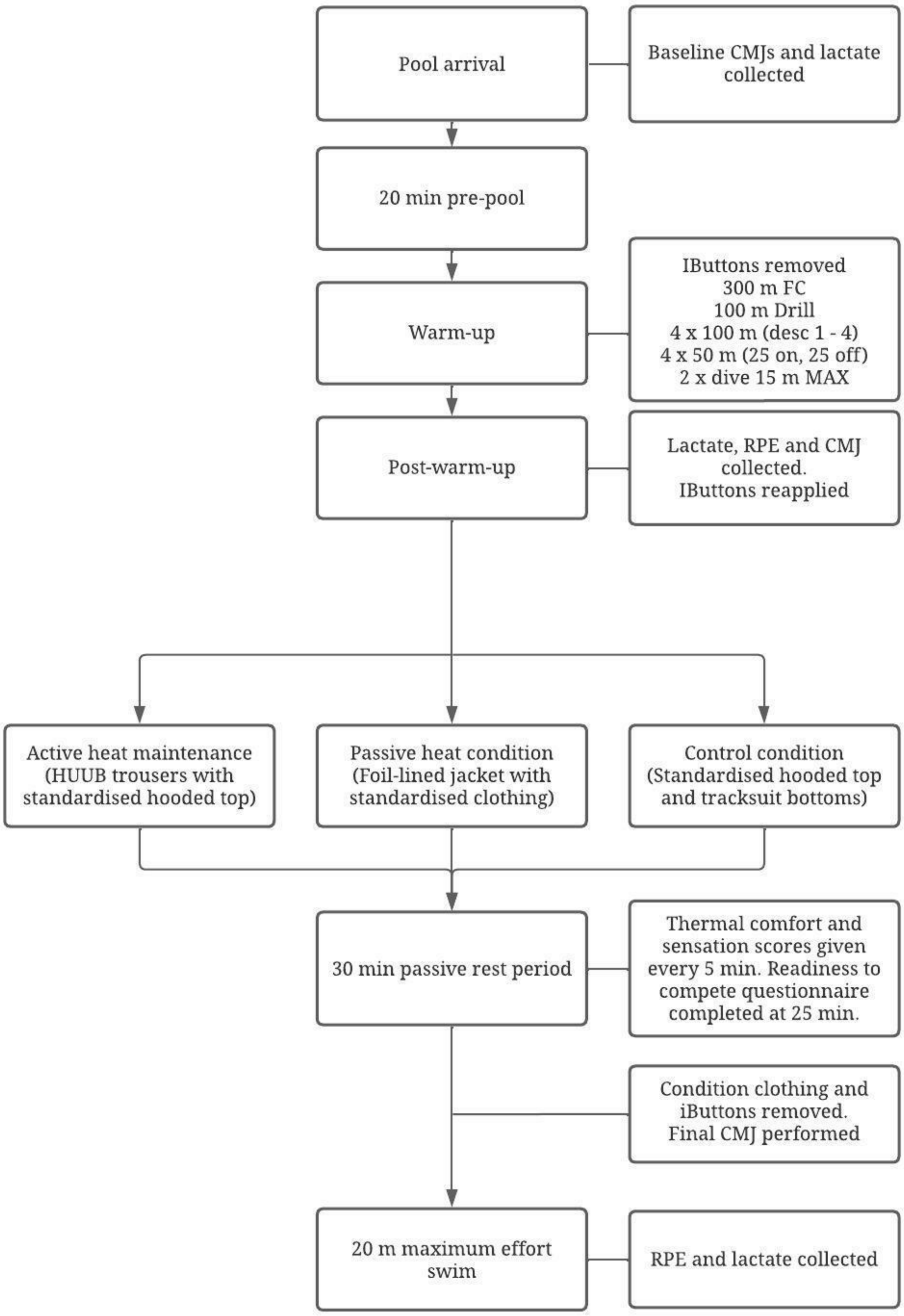

Figure 5.1 Flowchart of the main trial procedures, including the standardised warm-up.

Figure 5.2 Example of the placement and taping method used to cover the iButtons for the rectus femoris and the tibialis anterior. This method, previously used by Flouris et al. (2015), allowed for muscle temperature to be predicted.

A

B

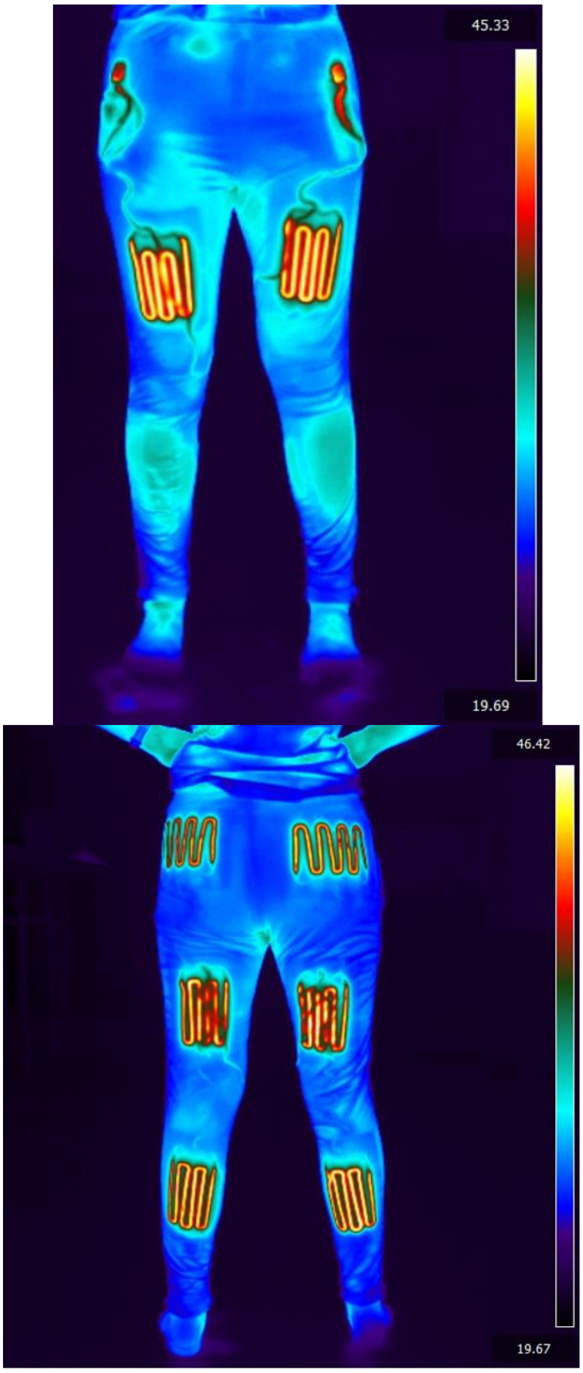

Figure 5.3 Image taken using the FLIR thermal imaging camera of the HUUB trousers when worn with elements heated at the front (A) and the back (B).

All 20 m maximum effort swims were analysed using Dartfish (Dartfish 10, Fribourg, Switzerland). Block time was defined as the first frame in which the timing light was illuminated until the final frame when the swimmer's foot was on the block/backstroke wedge. Flight time was defined as the end of block time until the centre of the swimmer's head entered the water. Start time was defined as the first frame in which the timing light was illuminated until the centre of the swimmer's head was at the 15 m landmark identified earlier during pool calibration. The SWC value for start time was 0.18 s, pre-determined using changes in start time from previous literature (Table 3.2).

BioWare 5.4.3.0 (Kistler, Winterthur, Switzerland) was used to collect the vertical component of the ground reaction force data for all CMJs. From this, CMJ height and PPO were calculated using bespoke CMJ analysis software as outlined by Owen et al. (2014; Table 2.5), for the baseline, post-WU, and post-passive rest period CMJs.

For all three muscles, the 5 s iButton measurements were calculated into 1 min averages by averaging all the measurements collected within the same min on the timestamp. These averages were converted into T_m using the T_m prediction equation (5.1), from the study of Flouris et al. (2015). The T_m prediction equation (5.1) used the four time points preceding each measurement to calculate T_m, meaning T_m could not be calculated for the first 4 min of the data collection once applied to each site. As iButtons took approximately 5 min to adjust to the environmental change once placed on the skin, the T_m prediction equation (5.1) was able to account for this.

$$(5.1)\ T_m = (\text{iButton}_{1\text{min}} \cdot 0.597) - (\text{iButton}_{2\text{min}} \cdot 0.439) + (\text{iButton}_{3\text{min}} \cdot 0.554) - (\text{iButton}_{4\text{min}} \cdot 0.709) + 14.767$$

$T_{mBaseline}$ was defined as the average across the first measurement period collected before the WU. T_{mWU} was defined as the average first 5 min of the passive rest period after the initial first 4 min when the iButton adjustment was taking place. T_{mFinal} was defined as the average last 5 min of the passive rest period.

5.2.4 Statistical analysis

All statistical analysis was completed using SPSS 28 (SPSS Inc., Chicago, IL, USA), and data is presented as mean ± SD. Significant interactions were set as $p \leq 0.050$.

Three linear mixed models were developed with start time, CMJ height and PPO included as the respective dependent variables to identify any significant differences between conditions and the contribution of covariates to the overall variance to the dependent variables. In all three models, a simple, fixed effects model was initially produced (first model), so successive iterations with random intercepts and additional covariates (added one at a time) could be compared for improvements in the model based on decreases in maximum log likelihood scores. Participant and sex were added as level one variables to all models after the first model was developed and included separately as random intercepts. Rectus femoris T_{mFinal}, tibialis anterior T_{mFinal}, biceps femoris T_{mFinal}, readiness to compete questionnaire results, TC and TS scores at each time point, age, FINA points, mass, skinfolds and WU lactate were included as covariates. Any covariate that did not significantly improve the overall strength of the model (based on critical values of the chi-square statistic; Appendix D) were removed from further analysis (Field, 2013). Once all covariates were added and evaluated based on chi-square statistics, this was deemed as the final model for each performance metric. Estimates of fixed effects and pairwise comparisons with a Bonferroni adjustment were used to identify any significant effects of condition and other covariates included within the final model. Unless stated, only the final model results are discussed.

A factorial repeated measures ANOVA was conducted to identify any significant differences between conditions for blood lactates and TC and TS score at each time point they were collected. This provided a condition, time and condition*time interaction. Any significant results were further explored through pairwise comparisons using a Bonferroni adjustment.

A repeated measures one-way ANOVA was performed to identify any significant differences between conditions for block time, flight time, RPE and readiness to compete questionnaire results. Post-hoc analysis was completed using pairwise comparisons with a Bonferroni adjustment when significant interactions were found.

Two additional mixed models were designed to identify any differences in T_m between conditions and at each time point, both modelling participant as a level one variable. One model had T_{mFinal} as the dependent variable with condition as the factor. The second model had T_{mFinal} for each condition as the dependent variable (e.g. AHM biceps femoris T_{mFinal}), with the factor set as time and significant interactions were investigated using pairwise comparisons and estimates of fixed effects.

5.3 Results

5.3.1 Start performance

No significant differences were found between conditions for block time (F = 2.650, p = 0.090) or flight time (F = 1.389, p = 0.267; Table 5.2).

In the final model, no significant differences were found for start time between conditions (p = 0.787). However, the covariates TS_{20min} (b = -0.034, t(21.065) = -2.281, p = 0.033) and baseline CMJ height (b = -2.122, t(31.257) = -2.348, p = 0.025) were identified as significant predictors of start time. Therefore, when TS_{20min} increased by one score, start time decreased by 0.03 s. Additionally, when baseline CMJ height increased by 1 cm, start time decreased by 0.02 s. While two further covariates (rectus femoris T_{mFinal} (b = 0.044, t(15.592) = 1.743, p = 0.101) and skinfolds (b = 0.011, t(16.075) = 1.859, p = 0.081)) had significantly improved the model's accuracy when initially included, they were no longer significant within the final model. When participant and sex were included as random intercepts at level one, a significant effect was found (β = 0.297, Wald Z = 2.513, p = 0.012), demonstrating significant individual variation within the results and the need to consider this within the final model.

5.3.2 Countermovement jump peak power output

In the first model, no significant differences were found for CMJ PPO between conditions (p = 0.961). However, when rectus femoris T_{mFinal} was included within the third model, a significant difference was found for PPO between conditions (p =

0.029). This indicated that a more accurate reflection of the differences between conditions was provided when the effects of rectus femoris T_{mFinal} were accounted for. In the final model, a significant difference was found for PPO between conditions (p = 0.047). Estimates of fixed effects found PPO was significantly higher for PHM than CON by 2% (p = 0.047). The covariates skinfolds (b = -15.247, t(13.948) = -3.706, p = 0.002) and mass (b = 68.968, t(13.824) = 6.086, p < 0.001) were identified as significant predictors of PPO. When skinfolds increased by 1 mm, PPO decreased by 15 W, and when mass increased by 1 kg, PPO increased by 69 W. While three further covariates (rectus femoris T_{mFinal} (b = 19.596, t(19.767) = 0.723, p = 0.478), tibialis anterior T_{mFinal} (b = 73.621, t(20.807) = 1.204, p = 0.242) and "I am feeling" (b = -30.498, t(19.253) = -1.912, p = 0.071)) had significantly improved the model's accuracy when initially included, they were no longer significant within the final model. When participant and sex were included as random intercepts at level one, a significant effect was found (β = 154554.315, Wald Z = 2.596, p = 0.009), demonstrating significant individual variation within the results and the need to consider this within the final model.

5.3.3 Countermovement jump height

In the final model, no significant differences were found for CMJ height between conditions (p = 0.284). However the covariates skinfolds (b = -0.002, t(14.054) = -3.761, p = 0.002), TS_{20min} (b = -0.017, t(21.426) = -3.831, p < 0.001) and TS_{15min} (b = 0.012, t(16.925) = 2.740, p = 0.014) were significant predictors of CMJ height. When participant and sex were included as random intercepts at level one, a significant effect was found (β = 0.003, Wald Z = 2.620, p = 0.009), demonstrating significant individual variation within the results and the need to consider this within the final model.

5.3.4 Blood lactate

A significant time effect was found on blood lactate (F = 21.803, p < 0.001). Blood lactate was significantly greater following the WU than baseline by 110 ± 115% (p = 0.008). Blood lactate was significantly greater following the 20 m maximum effort swim than baseline by 137 ± 109% ($p < 0.001$). There was no significant difference in blood lactate between post-WU and following the 20 m maximum effort swim (p = 1.000). No significant main effect of condition was found on blood lactate (F = 0.934, p = 0.409; Table 5.2) and no significant condition*time interaction was found (F = 0.818, p = 0.522).

5.3.5 Swimming rate of perceived exertion

No significant main effect of condition was found on post 20 m swim RPE (F = 1.762, p = 0.190; Table 5.2).

Table 5.2 Results for all three conditions during (block time, flight time, start time) and immediately after (blood lactate, rate of perceived exertion (RPE)) the 20 m maximum effort swim (mean ± standard deviation).

	Control	**Active Heat Maintenance**	**Passive Heat Maintenance**
Block time (s)	0.64 ± 0.06	0.66 ± 0.07	0.64 ± 0.06
Flight time (s)	0.35 ± 0.07	0.35 ± 0.08	0.34 ± 0.08
Start time (s)	6.94 ± 0.80	6.94 ± 0.84	6.89 ± 0.76
Blood lactate (mmol/L)	2.4 ± 0.9	2.6 ± 0.5	2.7 ± 1.0
RPE	13 ± 2	13 ± 1	14 ± 2

5.3.6 Readiness to compete questionnaire

No significant main effects of condition were found for any of the readiness to compete questionnaire results ($F \geq 0.924$, $p > 0.05$; Table 5.3).

5.3.7 Thermal comfort

A significant main effect of condition was found for TC ($F = 8.045$, $p = 0.002$). Pairwise comparisons found significantly higher TC scores for AHM than CON by 14 ± 18% ($p = 0.028$). PHM had significantly higher TC scores than CON by 21 ± 21% ($p = 0.017$). No significant differences were found between AHM and PHM ($p = 0.415$).

A significant time effect was found on TC ($F = 8.544$, $p < 0.001$). Pairwise comparisons found TC_{5min} had significantly lower scores than TC_{15min} by 8 ± 12% ($p = 0.013$), TC_{20min} by 9 ± 14% ($p = 0.016$) and TC_{25min} by 9 ± 16% ($p = 0.001$). No significant condition*time interaction was found for TC ($F = 1.339$, $p = 0.273$).

5.3.8 Thermal sensation

A significant main effect of condition was found for TS ($F = 8.505$, $p = 0.001$). Pairwise comparisons found significantly higher TS scores for AHM than CON by 26 ± 26% ($p = 0.008$). PHM had significantly higher TS scores than CON by 30 ± 33% ($p = 0.025$). No significant differences were found between AHM and PHM TS scores ($p = 1.000$).

A significant time effect was found on TS ($F = 4.210$, $p = 0.035$), however pairwise comparisons did not find any significant differences ($p > 0.005$). No significant condition*time interaction was found for TS ($F = 0.860$, $p = 0.477$).

Table 5.3 Results for all three conditions from the readiness to compete questionnaire (mean ± standard deviation).

	Control	Active Heat Maintenance	Passive Heat Maintenance
My thoughts are	3 ± 1	3 ± 1	3 ± 2
My body feels	4 ± 2	3 ± 1	4 ± 2
I am feeling	3 ± 1	3 ± 1	4 ± 2

5.3.9 Muscle temperature

Biceps femoris

Linear mixed model results for biceps femoris T_{mFinal} found a significant difference between conditions (p < 0.001). Pairwise comparisons found significantly higher T_{mFinal} for AHM than PHM by 4.8% (p < 0.001) and CON by 5.5% (p < 0.001). No significant difference was found between PHM and CON (p = 0.721).

A significant time interaction was found for biceps femoris T_m during AHM (p < 0.001; Figure 5.4). Pairwise comparisons found T_{mFinal} was significantly greater than $T_{mBaseline}$ by 7.7% (p < 0.001) and T_{mWU} by 6.9% (p < 0.001).

A significant time interaction was found for biceps femoris T_m during PHM (p < 0.001; Figure 5.4). Pairwise comparisons found T_{mFinal} was significantly greater than $T_{mBaseline}$ by 2.1% (p = 0.001) and T_{mWU} by 4.4% (p < 0.001).

A significant time interaction was found for biceps femoris T_m during CON (p < 0.001; Figure 5.4). Pairwise comparisons found T_{mFinal} was significantly greater than $T_{mBaseline}$ by 2.5% (p < 0.001) and T_{mWU} by 4.5% (p < 0.001).

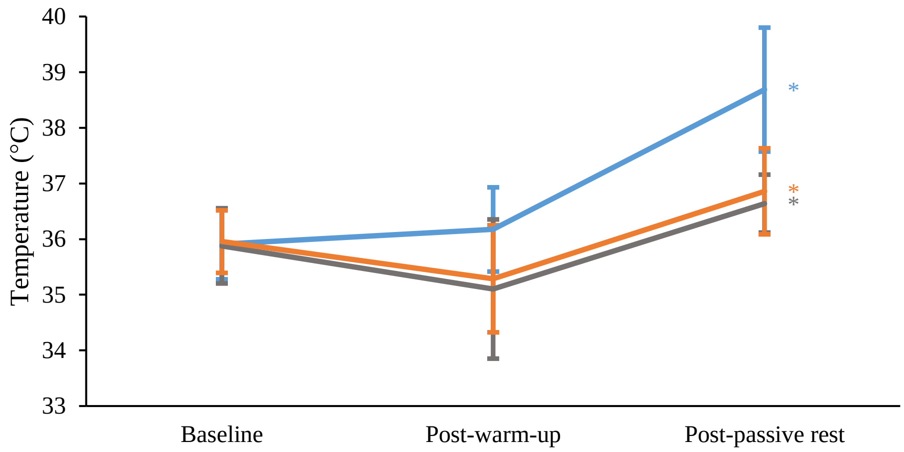

Figure 5.4 Mean (± standard deviation) muscle temperatures for the biceps femoris at baseline, post-warm-up and post-passive rest period for active heat maintenance (blue), passive heat maintenance (orange), control (grey).

* indicates a significantly higher muscle temperature than baseline and post-warm-up.

Tibialis anterior

Linear mixed model results for tibialis anterior T_{mFinal} found a significant difference between conditions (p = 0.011). Pairwise comparisons found significantly higher T_{mFinal} for AHM than CON by 0.6% (p = 0.010) No significant differences were found between PHM and CON (p = 0.253), or AHM and PHM (p = 1.000)

A significant time interaction was found for tibialis anterior T_m during AHM (p < 0.001; Figure 5.5). Pairwise comparisons found T_{mFinal} was significantly greater than T_{mWU} by 2.5% (p < 0.001). No significant difference was found between T_{mFinal} and $T_{mBaseline}$ (p = 1.000).

A significant time interaction was found for tibialis anterior T_m during PHM (p < 0.001; Figure 5.5). Pairwise comparisons found T_{mFinal} was significantly greater than T_{mWU} by 2.8% (p < 0.001). No significant difference was found between T_{mFinal} and $T_{mBaseline}$ (p = 1.000).

A significant time interaction was found for tibialis anterior T_m during CON (p < 0.001; Figure 5.5). Pairwise comparisons found T_{mFinal} was significantly greater than T_{mWU} by 2.1% (p < 0.001). No significant difference was found between T_{mFinal} and $T_{mBaseline}$ (p = 0.619).

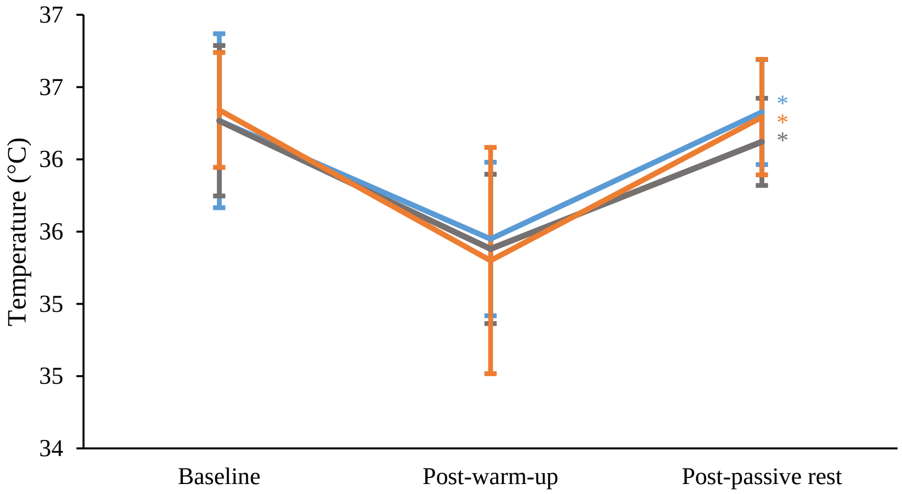

Figure 5.5 Mean (± standard deviation) muscle temperatures for the tibialis anterior at baseline, post-warm-up and post-passive rest period for active heat maintenance (blue), passive heat maintenance (orange), control (grey).

* indicates a significantly higher muscle temperature than post-warm-up.

Rectus femoris

Linear mixed model results for rectus femoris T_{mFinal} found a significant difference between conditions ($p < 0.001$). Pairwise comparisons found significantly higher T_{mFinal} for AHM than CON by 2.7% ($p < 0.001$). PHM also had significantly higher T_{mFinal} than CON by 2.1% ($p = 0.003$). No significant difference was found between AHM and PHM ($p = 0.791$).

A significant time interaction was found for rectus femoris T_m during AHM ($p < 0.001$; Figure 5.6). Pairwise comparisons found T_{mFinal} was significantly greater than $T_{mBaseline}$ by 5.4% ($p < 0.001$) and T_{mWU} by 6.7% ($p < 0.001$).

A significant time interaction was found for rectus femoris T_m during PHM ($p < 0.001$; Figure 5.6). Pairwise comparisons found T_{mFinal} was significantly greater than $T_{mBaseline}$ by 5.0% ($p < 0.001$) and T_{mWU} by 5.9% ($p < 0.001$).

A significant time interaction was found for rectus femoris T_m during CON ($p < 0.001$; Figure 5.6). Pairwise comparisons found T_{mFinal} was significantly greater than $T_{mBaseline}$ by 2.8% ($p < 0.002$) and T_{mWU} by 4.5% ($p < 0.001$).

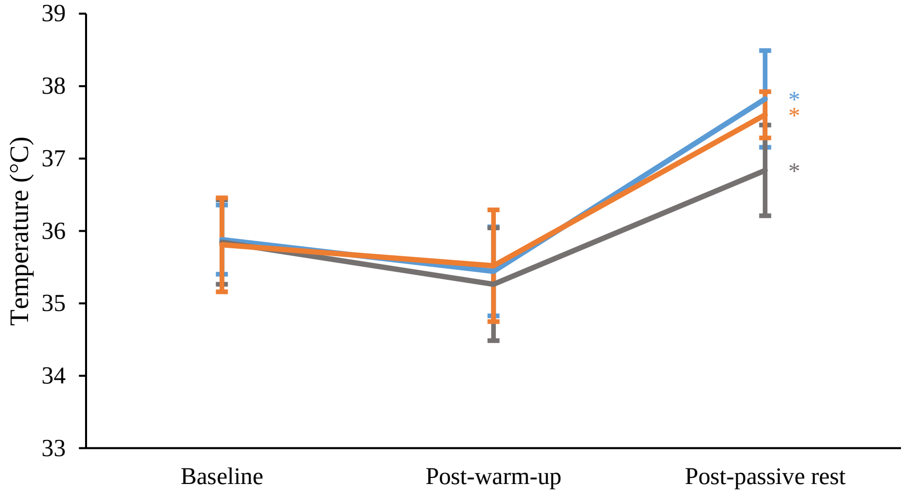

Figure 5.6 Mean (± standard deviation) muscle temperatures for the rectus femoris at baseline, post-warm-up and post-passive rest period for active heat maintenance (blue), passive heat maintenance (orange), control (grey).

* indicates a significantly higher muscle temperature than baseline and post-warm-up.

5.3.10 Individual results

As described throughout this results section, individual differences for CMJ height, PPO and start time were assessed within the linear mixed models to determine whether there were significant differences between individuals and their responses to AHM and PHM. A significant effect was found for all three models when participant was added as a random intercept ($p < 0.005$), which led to individual responses being compared to the respective group mean values for start time (Figure 5.7A), CMJ PPO (Figure 5.7B) and CMJ height (Figure 5.7C). 13% of participants achieved their fastest start time following AHM, and 40% achieved their fastest start time following PHM. Separately, 13% of participants achieved their joint fastest start time following both AHM and PHM. Worthwhile changes (> 0.18 s) were achieved by three participants (20%), two during PHM and one during AHM. None of the participants who achieved their joint fastest start times during both conditions achieved a worthwhile change.

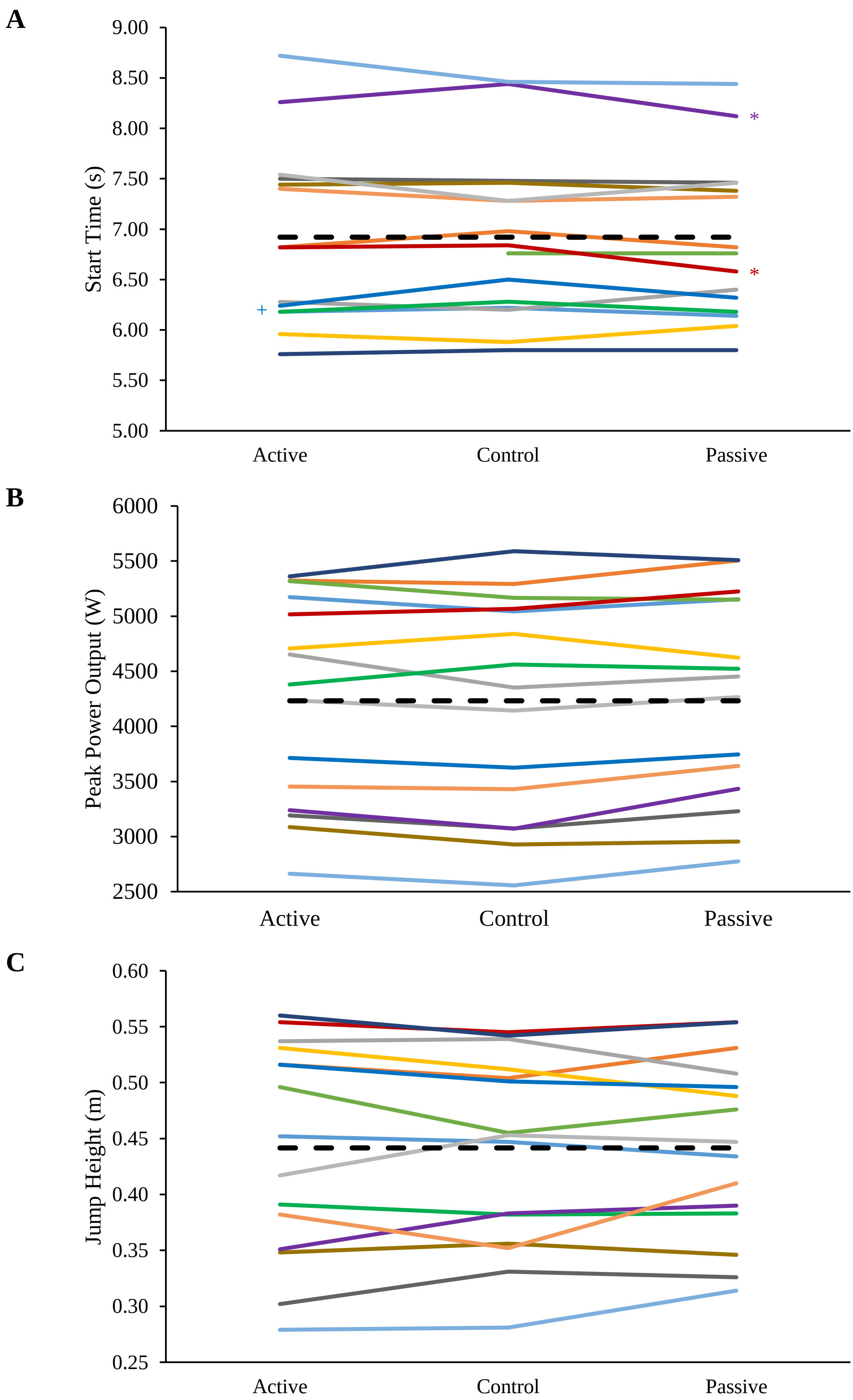

Figure 5.7 Individual results for start time (A), peak power output (B) and jump height (C) across all three conditions. The dashed line indicates the group mean for each variable.

* represents a smallest worthwhile change (> 0.18 s) for passive heat maintenance.

+ represents a smallest worthwhile change (> 0.18 s) for active heat maintenance.

5.4 Discussion

The current study investigated differences in T_m, CMJ performance and swimming start time when heat maintenance strategies were implemented for 30 min before performance. Following PHM, PPO was significantly greater than CON. No significant PPO increase was found for AHM compared to CON, and CMJ height and start time were not significantly different between the three conditions. For all muscles, T_{mFinal} was significantly higher for AHM than CON, and rectus femoris T_{mFinal} was significantly greater for PHM than CON (Figure 5.6). Biceps femoris T_{mFinal} was significantly greater for AHM than PHM (Figure 5.4). To summarise, despite significant increases in T_{mFinal} following AHM, PHM was the only condition to significantly enhance PPO.

Within the start time linear mixed model, rectus femoris T_{mFinal} enabled a more accurate reflection of the differences between the conditions when this covariate was included and helped to explain some of the model's variance. Although this covariate was not a significant predictor within the final model, it still aided in increasing the accuracy of the model to explain the differences between the three conditions. This finding suggests that increasing rectus femoris T_m is an important consideration for enhancing start time compared to the two additional muscles measured. Nonetheless, the significant predictors for the start time model were TS_{20min} and baseline CMJ height ($p < 0.050$), with increases in both covariates being associated with a decrease in start time. Therefore, although rectus femoris T_{mFinal} is an important consideration, the ability to obtain a large CMJ height at baseline is a significant predictor of start performance, as previous research has identified (Cossor et al., 2011; West et al., 2011). Interestingly, TS_{20min} was a significant predictor of start time, suggesting that it is crucial for participants to feel the effects of the heat maintenance strategies before competing. Similarly, rectus femoris and tibialis anterior T_{mFinal} significantly improved the PPO linear mixed model's accuracy, but only skinfolds and mass were significant predictors within the final model ($p < 0.050$), with a decrease in skinfolds and an increase in mass enhancing PPO. This finding is supported by previous literature, which has found that power output is associated with increases in muscle mass and cross-sectional area (Kanehisa et al., 1994; Masuda et al., 2003; Maughan et al., 1983) due to the muscular contraction mechanisms outlined in Section 2.4.2. Therefore, increased muscle mass and cross-sectional area, which can be monitored through skinfolds and body mass, aids the muscle's ability to produce power and is a significant predictor of PPO.

The current study selected CMJ as an additional performance metric because of its close association with start performance and the ability to relate improvements in CMJ performance to start time (Cossor et al. 2011; West et al. 2011; Section 2.3.3). Various technical aspects have been studied to assess their impact on start performance and how they aid in generating velocity on the block or help to maintain velocity throughout the underwater phase until the breakout (Section 2.3.1). As the underwater phase is the longest phase within the start and is the phase which can determine the start’s success (Tor et al., 2015b), any small variation in the underwater phase can have a substantial impact on start time, both positively and negatively. Therefore, the effectiveness of the intervention to improve PPO during start performance may not be accurately represented unless the underwater phase remains consistent across the three trials, something which was not monitored within the current study. Nonetheless, as PPO significantly increased following PHM, it also suggests an improvement in power off the block would likely have been achieved. Similar results were obtained by McGowan et al. (2016), who found a marginal improvement in start time following PHM, despite significantly higher skin temperatures during this condition. Within the same study, a combination of PHM and a priming routine was studied, which aimed to elicit a PAP response based on the mechanisms outlined in Section 2.4.2. The combination of heat maintenance and PAP before racing was later supported by McGowan et al. (2017). They found a 1% improvement in start time, as well as significantly higher skin and core temperatures when a combination of AHM and PAP were used before racing. These previous findings could offer some explanation for the non-significant change in start time that was observed during the current study. As no significant improvement in start time was found within the current study, despite significantly higher T_{mFinal}, this could suggest that AHM as a sole intervention is insufficient to enhance PPO or start performance. As described in Section 2.5.1, increased T_m can provide an enhanced environment for muscles to contract maximally through increased motor unit recruitment (McGowan et al., 2015) and faster metabolic reaction rates (Ranatunga, 1984). Consequently, heat maintenance may promote a greater PAP response through this enhanced internal environment for the muscles to contract maximally, enhancing the subsequent performance of power-based movements. Therefore, further work may be necessary to combine the findings from Chapter 4 as well as the current results to ensure maintaining T_m benefits PAP conditioning activities, enabling a larger PAP response and thus greater PPO during subsequent performances.

Although no significant differences were found for start time between the three conditions, modelling participant as a random intercept within all three linear mixed models was significant and highlighted the importance of investigating changes within participants. Across the three conditions, 66% of participants achieved their fastest start time following a heat maintenance condition, with 40% following PHM, 13% following AHM and 13% having their joint fastest start time following both heat maintenance conditions. A worthwhile change (> 0.18 s) was achieved by 20% of participants, two during PHM and one during AHM (Figure 5.7A). These results represent the individual variation in response to heat maintenance and suggest it is more beneficial for certain athletes than others, despite the overall increase in T_{mFinal} for all three muscles following AHM and in the rectus femoris for PHM. All participants completed a standardised WU for all three trials, reducing any variation in T_m through different WU modes, intensities and durations. Likewise, the passive rest period was standardised; all participants were given 30 min and were required to remain seated, removing methodological differences as an explanation for individual variation. The foil-lined survival jacket (PHM) strategy had been previously used by 40% of participants from the current study, which could explain some of the individual variation; no participants had used the HUUB trousers (AHM) before data collection. During the passive rest period, TC and TS scores were significantly higher for AHM and PHM compared to CON, which does suggest the heat maintenance strategies are effectively maintaining heat, but could be detrimental if TC scores become too uncomfortable for the participant, particularly when the poolside environment was also 29°C. Since TS_{20min} was a significant predictor within the start time model it would seem this covariate needs to remain elevated. This individual variation in results and previous use of PHM suggests that a familiarisation period may have been beneficial for participants to experience the novel feelings of TC felt throughout the study, but within a rest condition before any additional data collection, or with the addition of cooling strategies.

The readiness to compete questionnaire and RPE scores after the 20 m maximum effort swim were recorded to determine whether participants favoured one condition over another. Despite significant differences in TC and TS scores, no significant differences were found for the readiness to compete questionnaire or post-swim RPE scores (Tables 5.2 and 5.3), suggesting AHM and PHM do not impact a participant's readiness before racing, or the exertion required to perform. This finding supports the use of heat maintenance as a pre-race intervention because of the increased $T_{m,}$ which can elicit several physiological responses that can aid the performance of power-driven movements without being detrimental to a swimmer's mind-set and race preparation. Supporting this, multiple participants expressed their interest in including AHM as a pre-race intervention following the study because of the intrinsic benefits they experienced during this condition.

A significantly greater PPO was found following PHM compared to CON, however no additional significant improvements were found for swim performance measures between the three conditions, demonstrating that although PPO increased during this condition, because of the additional variables within start performance (e.g. underwater technique), start time did not improve. Despite no significant increase in PPO after AHM, there were significant increases in T_{mFinal} following this condition (Figures 5.4, 5.5 and 5.6). These results do not support previous literature, which has found a close association between increased T_m and improved PPO during sporting performance (Galbraith and Willmott 2018; Sargeant 1987; Shellock 1983; West et al. 2016). In the current study, the T_m prediction equation (5.1) used the four preceding skin temperature measures to predict T_m for every min (hence why T_m was not available for the first 4 min of data collection). The T_m prediction equation (5.1) was devised by Flouris et al. (2015) when they used regression analysis to develop equations that could predict T_m when iButtons were insulated with a neoprene disk. Although Flouris et al. (2015) found significant differences between T_m and the T_m prediction equation, these were small, with an average standard error of estimate reported as 0.36 °C. Prior to study completion, the standard error of estimate was not considered to be large enough to affect the results, however due to the results within the current study not supporting previous literature which has found increases in T_m typically increase PPO, a decision was made to assess the impact the T_m prediction equation had on the results by repeating the analysis with the original skin temperature values. Following this, the same significant differences were found; although skin temperature was 2% lower than predicted T_m across all conditions this was likely due to the adipose tissue surrounding the muscle, which prevents heat transfer to the skin (Brajkovic et al., 2006; Henschel, 1967). Nonetheless, because skin temperature and T_m followed the same pattern, the T_m prediction equation (5.1) was concluded to not be the primary cause for the contradictory findings.

Due to the participants within the current study, a non-invasive, thermometric measure of T_m was necessary; as national-level swimmers, any muscular injury or damage through T_m measurement may have impacted training and their ability to compete in upcoming competitions. Because of their non-invasive nature, iButtons were selected as research has also outlined how skin temperature recorded through the iButtons can predict T_m through regression analysis previously completed by Flouris et al. (2015), who also validated the iButtons and their associated T_m prediction equations at rest, before exercise, after exercise, and within different environmental conditions; however, heat maintenance garments were not a condition included within this validation. Due to the sensitivity of iButtons to environmental change (van Marken Lichtenbelt et al., 2006), it is possible that the iButtons measured skin temperature and the temperature emitted from the AHM trousers during the current study, thus causing increases in predicted biceps femoris T_{mFinal} and rectus femoris T_{mFinal}, whose iButton sites were directly underneath the heated elements (Figures 5.2 and 5.3). Additionally, as the AHM trousers were tight around the thigh and participants remained seated during the passive rest period, this may have restricted heat dissipation from the heated elements, causing a significant increase in T_m; this impact was also evident from the markings of the heated elements on the participant's skin once the trousers were removed. Likewise, the lack of a significant change in tibialis anterior T_m during AHM supports this suggestion, as no heated element directly covered this muscle (Figures 5.2 and 5.5). As a result, it is possible that the AHM T_m results are not an accurate reflection of the real T_m and are instead a combination of the heated element and skin temperatures; hence why no significant increase in CMJ or start performances were observed, despite seemingly significant increases in T_{mFinal}. Results also found a significant increase in rectus femoris T_{mFinal} following PHM. As the foil-lined survival jacket did not include any heated elements that could interfere with the iButton measurements, as outlined above, this implies that the iButton T_m results were representative of the actual T_m and were not affected by any environmental change, except when applied to the skin, which is controlled for through the T_m prediction equation (5.1). Therefore, this implies that T_m had increased due to PHM eliciting a physiological response which enabled PPO to increase, supporting the use of PHM following a swim WU to maintain T_m.

For all three conditions, T_{mWU} was significantly lower than T_{mFinal} across all three muscles (Figures 5.4, 5.5 and 5.6), which was not anticipated, as previous research has found significant increases in T_m throughout the WU, which rapidly decrease once the WU has ceased, usually returning to baseline after approximately 20 min (Altavilla et al., 2018; McGowan et al., 2017; Mohr et al., 2004; Price & Campbell, 1997). Throughout previous research, core temperature has been selected as a method to measure the thermoregulatory response to exercise, however the current study used iButtons which, through the T_m prediction equations developed by Flouris et al. (2015), can predict T_m through skin temperatures collected by the iButtons. The current study utilised iButtons as they enabled the individual thermoregulatory response of key muscles within the start to be predicted, instead of generalising core temperature findings across the entire body, which could affect the validity of the results if core temperature does not align with T_m within the specified muscles. As the current study focussed on the lower extremities because of their contribution to start and CMJ performance, it was important to observe the direct changes in T_m of the lower limbs, as these may not have been accurately represented from core temperature measurements. During a swim WU skin temperature decreases because of the change in temperature, where the pool is often colder than the poolside environment, as was the case in the current study, with an average water temperature of 27°C and a poolside temperature of 29°C for the two locations used. This change in temperature can also address the decrease in T_{mWU} from $T_{mBaseline}$, a contradictory finding to previous research which has found increases in T_m following a WU because heat is generated as a by-product during muscular contractions and is dissipated into the bloodstream (Gleeson, 1998). The T_m prediction equation (5.1) used within the current study was reliant on skin temperature, therefore any changes to skin temperature would impact the predicted T_m results, regardless of actual T_m. With a decrease in skin temperature resulting from the colder water temperature compared to the poolside environment, the predicted T_m results would therefore also be lower, as a direct measure of T_m could not be collected. This change in skin temperature during a swimming WU is supported by Brandt and Pichowsky (1995), who found skin temperature decreased by 18%

during the first 10 min of swimming within 15 male university swimmers, until an equilibrium was reached which was approximately the same as the water temperature (27°C). Within the current study, skin temperature was 32 ± 0.3°C after the WU, however this was approximately 10 min after the WU had ceased, as time was given for participants to dry off before the iButtons were reapplied, as well as accounting for the time delay the iButtons required to adapt to the new environment. However, skin temperature decreased by 9% from baseline to post-WU for all three muscles, and T_m decreased by 2% on average. Therefore, it is possible that T_m did increase during the WU as a result of the thermoregulatory mechanisms, but because T_m predictions were dependent on the skin temperature readings, this potential increase in T_m was not found, and therefore $T_{mBaseline}$ appeared greater than T_{mWU}. Likewise, once the WU had ceased and skin temperature began to adjust to the warmer poolside environment, T_{mFinal} would appear greater than T_{mWU} because of this change in skin temperature to the external environment, instead of reflecting the potential changes in actual T_m. This is especially true, given that T_{mFinal} was significantly greater than T_{mWU} for all three conditions, suggesting that all the clothing worn throughout the 30 min passive rest period was effective at increasing skin temperature, and therefore predicted T_m, because of the causal relationship between skin and T_m throughout the T_m prediction equation (5.1). As PHM and AHM had significantly higher T_{mFinal} than CON, these interventions would appear to be more effective at heat maintenance and generation following a swim WU.

Participants were completing their regular training sessions throughout the data collection period of the current study. As national-level swimmers who volunteered for this study, their training plans were unable to be adapted to ensure the same volume and intensity of training was completed before each data collection session, as this could have been detrimental to future competitions and training goals. However, the weekly training timetable remained unchanged throughout the data collection period, which ensured participants had the same recovery time by scheduling testing sessions for the same time and day each week; this also allowed differences from circadian rhythms to be controlled for. Conditions were also randomly assigned to participants each week, aiming to limit the group-wide effects of fatigue that may have been present across the three weeks resulting from variations in their training load.

As multiple studies have assessed the changes in core temperature following the use of heat maintenance garments, this study originally planned to take a core temperature measurement, as well as T_m using the iButtons. Core temperature has been found to influence muscle function and power production, which could have provided more detail into the contradictory findings within the current study. Unfortunately, due to time restrictions and availability to the participants during the data collection period, the equipment to measure core temperature was unavailable, and only T_m could be measured at the time. Further research assessing the changes in core and T_m within swimming could explain the changes experienced by the body when a swim WU is completed, and the influence of active and passive garments to aid with heat maintenance.

During the current study, one methodological choice made, and agreed to by the coaching team following feedback from Chapter 4, was to standardise the WU. Following Chapter 4, it was deemed that some of the individual WUs were insufficient to physiologically prepare the participant to race, based on the post-WU lactate and CMJ results. Therefore, a standardised WU was applied during the current study to ensure participants had increased T_m and CMJ performance to the expected standards following a WU (approximately 8-10% PPO increase). Some subjective feedback following the trial and observing the post-WU RPE scores would suggest that some participants found the WU too difficult and challenging before the passive rest period and 20 m maximum effort swim. Fatigue may have been induced following the WU, limiting the ability to perform maximally after the passive rest period, regardless of the physiological benefits AHM or PHM could have elicited. Nonetheless, as the same WU was completed across all three conditions, this should have limited the variation in performance following the WU from different WU protocols. Using heat maintenance strategies alongside the individual race WU would enable swimmers to practise their pre-race routine and familiarise themselves with the protocols and TC/TS feelings of the heat maintenance garments.

5.5 Conclusions

The current study found PPO was significantly greater following PHM than CON. CMJ height and start time were not significantly different between any of the three conditions. Individual variation was found across the three conditions and worthwhile changes were found for one participant following AHM and two following PHM, which may have been due to the familiarisation some participants had with PHM before the current study. Therefore a familiarisation period may be necessary for all participants to experience heightened TC and TS in a resting trial before racing. For all three muscles, T_{mFinal} was significantly greater after AHM than CON, however this could be a result of the systematic error of the iButtons which rely on skin temperature measurements to predict T_m. Rectus femoris T_{mFinal} was significantly greater after PHM compared to CON. No significant differences were found in the readiness to compete questionnaire answers for the three conditions, implying that neither intervention impacted the swimmer's psychological mind-set. Therefore, AHM and PHM are effective interventions for maintaining T_m after a swim WU, and PHM can elicit a significant increase in PPO after a 30 min passive rest period.

Chapter 6. General Discussion

6.1 Discussion of key findings

This thesis aimed to determine the accuracy of start times measured using a single panning camera analysis system, to quantify start times to total race time and investigate pre-race interventions which could enhance start performance. Four specific research objectives were developed to achieve this aim, and the key findings for each will now be discussed in turn.

6.1.1 Accuracy and reliability of a single panning camera set-up to measure start time

In Chapter 3, the single panning camera analysis set-up method commonly used within swimming was validated to measure the system's accuracy and reliability when measuring start times. This was considered within the context of a SWC (0.187 s), developed from changes in start time from previous swimming literature (Table 3.2).

The single panning camera analysis system was accurate within the context of the SWC, with 200 m breaststroke having the smallest systematic error and 100 m butterfly having the largest systematic error (Table 3.4). Findings from this chapter suggest that caution should be applied when conducting analysis within a 10-lane pool as the highest systematic error across the 10 lanes was found for lanes 0 and 9, although these were still smaller than the SWC and competitions tend to only use the eight lanes within the middle of the pool, which had an even lower systematic error. As well as this, no significant differences were found between start times and lane number, stroke, distance, heat number or round type and excellent reliability (ICC = 1.000, $p < 0.001$) was found for the single panning camera analysis system. The current study concluded that the single panning camera analysis system provides a sufficiently accurate and reliable measure of start time, and enabled the retrospective results collected from 2010 to be used to quantify the contribution of start time to the overall race. As excellent reliability was also found for the gold standard analysis system, this set-up was used throughout Chapters 4 and 5 to measure start time with higher spatial and temporal precision within a training environment, where access restrictions were not an issue.

The current study supported the previous findings of Kelley (2014), who assessed the use of the single panning camera analysis system against multiple perpendicular cameras across an entire 50 m pool. Kelley (2014) used a sample size which was seven times smaller than the sample used within the current study. This is problematic because results from small samples may not reflect the true accuracy of the single panning camera analysis system, and lead to false conclusions about the validity of the system to measure start time, ultimately lowering the statistical power of the study (Button et al., 2013). With a larger sample size, the current study had smaller systematic errors compared to Kelley (2014) and therefore further supports the single panning camera analysis system to measure accurate start times across a range of events and swimmers. Additionally, the current study was conducted across four different venues compared to the singular venue used by Kelley (2014). There are a range of considerations when conducting analysis within different environments, such as lighting and camera distance from the pool. As outlined by Stephens et al. (2019), placing the single panning camera at the greatest distance possible away from the swimmer enables perspective error to be minimised, but this distance varies between environments. However, distance away from the pool and lighting still need consideration when assessing camera placement to ensure perspective error is minimised and video quality is enhanced, which can affect the accuracy of the single panning camera analysis system. Therefore, similar to sample size, completing the validation across multiple environments accounted for these potential increases in error and provide reassurance to coaches and support staff that start times are accurate for the single panning camera analysis system regardless of setting.

Perpendicular analysis cameras are often unrealistic within the applied setting, particularly during competitions where access restrictions are applied. Therefore, the accuracy of the single panning camera analysis system gives confidence to coaches and support staff that an accurate reflection of the swimmer’s race is presented and worthwhile changes are genuine rather than a result of random errors within the analysis system. Therefore, the results from Chapter 3 are applicable within the applied setting and support the continuation of the single panning camera analysis system when a gold standard method cannot be utilised, provided measures are taken to reduce perspective error. As a result, the single panning camera analysis system database was subsequently obtained and used to calculate the contribution of start time for every event and for both sexes in order to determine the contribution of the start to overall race time.

6.1.2 The quantification of start time to overall race time

As a result of the single panning camera being deemed accurate and reliable within the context of a SWC for start time, previous start times measured using this method were extracted from a large race analysis database and used to quantify the start in relation to total race time. This type of analysis had not been comprehensively completed as Morais et al. (2018) had only quantify start times for 100 m; they did, however, account for sex, which previous start quantification studies had failed to do (Slawson, 2010). Likewise, any studies which collected data from races before 2009 may not accurately represent the contribution of the start to total race time, as the new start block with the back plate had not been implemented. Therefore, the current study aimed to quantify start time for all strokes and distances, and account for sex, competition and other variables which could potentially impact the contribution of the start to total race time since 2010, which would enable coaches and support staff to make informed decisions about the importance of the start within each individual swimmer's event.

Start times were found to contribute up to 26.07% of total race time, with females' 50 m backstroke having the largest contribution from the start and the males' 1500 m freestyle having the smallest contribution (0.73%). Since 2010, start times have decreased by 0.112 s on average across all distances and strokes, but events did not all follow the same rate of change. This is likely due to additional changes since 2010. For example, the backstroke wedge was introduced in 2014, five years after the back plate on the start block, this could explain why backstroke had a different rate of change compared to other strokes. Research found that the backstroke wedge increased horizontal velocity and reduced start times (Ikeda et al., 2017; Sinistaj et al., 2015), therefore it was expected that an improvement in start performance would be observed shortly after the introduction of the wedge, which would not apply to the three other strokes which use the start block during the dive. Therefore, the current study gives insight into some of the changes new equipment has had on start performance and detailed how the start contribution to total race time decreased for all events except 1500 m freestyle, which has seen a 18.60 s decrease in total race time since 2010. Additionally males had significantly faster start times on average than females across all events, and international competitions had faster start times on average than national competitions. Morning swims were significantly slower than afternoon/evening swims and short-course pools (25 m) had faster start times than long-course (50 m) pools, although short-course competitions have faster overall times because of the additional turns enabling swimmers to use the wall to increase power output and obtain higher velocities (Keskinen et al., 2007). Significant differences were also found between nationalities, and British swimmers were found to have slower start times than other nations across all events.

The current study furthered the work of Morais et al. (2018) and Slawson (2010), who assessed the contribution of start time to 100 m events and 50 m freestyle, respectively. However, the quantification within Chapter 3 was more thorough by investigating the differences between all events and both sexes, which led to the finding that female swimmers spend longer within the start phase than their male counterparts within the same event. Because the times used within the current study were obtained from retrospective race analysis data where no biomechanical metrics were obtained, kinematic and kinetic differences between sexes can only be theorised rather than confirmed as the causal factor of these results. Nonetheless, this finding suggests that although males can typically produce higher PPO values than females due to a greater muscle mass (Perez-Gomez et al., 2008), which predisposes them to faster start times, there may also be differences when coaching each sex, which are further considered in Section 6.3. Likewise, the same suggestion can be considered for British swimmers and why other nationalities are achieving faster start times, although this is also unable to be confirmed.

Results found that morning races produced slower start times on average than evening races. Although morning races are typically heat swims, which are typically slower than finals (FINA, 2022a), these longer start times are likely due to changes in body temperature and the fluctuations that occur throughout the day and typically peak in the early evening (Monk et al., 1997). During Chapter 3, it was suggested that swimmers should utilise pre-race interventions to compensate for this diminished T_m

during morning races to decrease start time and increase the likelihood of final qualification, which led to the development of Chapters 4 and 5 to investigate two pre-race intervention methods to enhance PPO during subsequent performance. PAP was investigated as this pre-race intervention is considered to elicit increased motor unit recruitment which results in increased PPO (Section 2.4.2) and heat maintenance garments and whether these can enhance start times when worn 30 min before racing, as higher body temperatures enable the muscles to contract more effectively (Section 2.5.1).

Overall the current study provided a clear rationale for investigating start performance for sprint swimmers, where the start contributes a substantial portion of total race time. The current study has outlined the contribution of the start for every event and for both sexes, which has not been knowingly completed in previous research or since new start equipment was introduced, and how start times have changed since then.

6.1.3 The effects of ballistic and isometric postactivation potentiation on the swimming start

As Chapter 3 reaffirmed the start as a key component of sprint swimming, which comprises up to 26.07% of total race time, Chapter 4 aimed to identify if a ballistic or isometric PAP conditioning activity could improve start performance. Owing to the challenges of identifying SWCs in start time, because of additional factors other than PPO which can impact start performance, such as the technique adopted during the underwater phase, a CMJ was also performed to investigate whether there were any significant differences in PPO after the PAP conditioning activities; this movement was selected as it has been previously linked to the start and could isolate lower-body PPO (Cossor et al., 2011; West et al., 2011). PAP was investigated because it is a physiological phenomenon which can elicit an increase in power output through the phosphorylation of myosin light chain units (Manning & Stull, 1982) and the recruitment of higher-order motor units (Henneman, 1985), as outlined throughout Section 2.4.2. As power output is a key determinant of start performance (West et al., 2011; Section 2.3.2), it was theorised that a PAP conditioning activity could enhance start performance. Previous research has found ballistic and isometric PAP conditioning activities can recruit higher-order motor units and therefore increase PPO during subsequent performance (Bogdanis et al., 2014; Desmedt & Godaux, 1977; Esformes et al., 2011; Wilcox et al., 2006). Both of these PAP modes require limited equipment, which can benefit international athletes due to travel restrictions, but isometric PAP is also considered to reduce EIMD, which could be more beneficial to swimmers competing across an extended competition period (Clarkson et al., 1986). Therefore Chapter 4 aimed to investigate the differences in start time and CMJ performance following a ballistic or isometric PAP conditioning activity.

No significant differences were found for start time between conditions. However, ballistic PAP had significantly larger CMJ height and PPO values than the control, which suggests that despite a probable increase in PPO following ballistic PAP, additional variables during the start, e.g. underwater technique, were not consistent across trials. Despite 36% of participants achieving their fastest start time following isometric PAP and 36% achieving their fastest start times following ballistic PAP, only two participants had a worthwhile change (≥ 0.18 s) following isometric PAP; no worthwhile changes were found for ballistic PAP. One of these swimmers had the highest relative strength testing results (APPENDIX D) which supports previous findings that stronger individuals are able to obtain a greater PAP response (Section 2.4.5). Another participant factor considered to contribute to the PAP response is training level. With a similar theory to strength level, those who have a higher training level can recruit higher-order motor units and experience an increased motor unit firing rate (Xenofondos et al., 2010). As all participants within the current study were national-level swimmers, they were also considered to have a high training level, however, FINA points revealed that one of the participants who achieved a worthwhile change had the second-highest FINA points value out of the entire cohort; the other participant who achieved a worthwhile change was ranked sixth-highest. Therefore, these higher training levels and increased exposure both participants had to the isometric PAP conditioning activity through multiple competitions and training before data collection, could explain why both participants achieved a worthwhile change when others could not. This consideration is supported by Hamada et al. (2000), who found that the PAP response increased with training level, providing the trained muscles are the predominant muscles contracting during the PAP conditioning activity, suggesting a familiarisation period to the PAP conditioning activity is critical. These participant factors also suggest the need to assess swimmer strength and performance levels before introducing a PAP conditioning activity into their race preparation, and to use these results as potential identifiers for PAP capabilities to ensure a performance enhancement is achieved.

As well as additional variables which influence start time but not PPO, such as underwater technique, the lack of a significant difference in start time could also result from the standardised recovery time set for all participants across the current study. Despite recovery time being deemed highly individual, previous research has outlined 8 min as the average recovery time necessary to overcome fatigue but still experience PAP within the muscles (Kilduff et al., 2011; Wilson et al., 2013). Although the CMJ was completed 8 min after the PAP conditions, the 20 m maximum effort swim was completed approximately 2 min after the CMJ; this was to give participants time to change from their CMJ footwear into swimming caps and goggles. Therefore, it is possible that had the swim been completed close to the 8 min time point, either before or immediately after the CMJ, a significant change in start time may have been observed. Due to the applied nature of this thesis and the restriction to conduct data collection with the swimmers, the current study aimed to identify whether a change in start and CMJ performance could be achieved following ballistic and/or isometric PAP, instead of identifying individual protocol differences; this is a consideration outlined below for future research needs.

Additionally, no significant differences were found for the RPE scores or the readiness to compete questionnaire. Although an initial significant main effect was found for the participants' thoughts, no significant pairwise comparisons were found. These scores aimed to assess the athletes' perception of the PAP conditioning activities and ensure these were not negatively impacting the athletes' mindset before performing. Therefore, both PAP conditioning activities can be implemented before racing without negatively impacting a swimmer's mindset, but with the possibility that performance could increase.

6.1.4 Assessing how start performance is influenced by the heat maintenance strategy used during the transitional phase within swimming

As outlined above, start time can contribute up to 26.07% of total race time, with small changes in overall performance potentially leading to significant changes in medal likelihood and podium position. Therefore coaches and practitioners seek pre-race interventions to improve PPO during the start and achieve worthwhile changes in start time to impact total race performance. The final pre-race intervention investigated during this thesis was heat maintenance, as previous research has demonstrated how increases in T_m can significantly enhance PPO and therefore improve performance (Asmussen & Bøje, 1945; Sargeant, 1987). During exercise, T_m increases due to metabolic reactions within the muscles, resulting in heightened T_m following a WU compared to baseline values (Gleeson, 1998; McGowan et al., 2015). As the start is a power-based movement (Cossor et al., 2011; West et al., 2011), if T_m can be maintained following a WU, then PPO and therefore start time should improve. Therefore, Chapter 5 aimed to assess the effectiveness of two heat maintenance garments to maintain or increase T_m and enhance start time. Similarly with Chapter 4, CMJ performance was also monitored to assess changes in PPO which could not be monitored on the block and to also remove the extraneous variables accompanied with start performance, such as underwater technique.

No significant differences in start time or CMJ height were found between conditions, but PPO was significantly greater than CON after PHM. TS_{20min}, baseline CMJ height, participant and sex were all variables which explained some of the variance within start time. This suggests that TS needs to be increased for start time to improve, although based on the findings of Kroesen et al. (2022), too high a TS score can result in a performance deficit, therefore monitoring TS is vital when utilising heat maintenance strategies to ensure TS scores are appropriate. Similarly, TC_{15min} and TS_{20min} were variables which explained some of the variance in CMJ height. Skinfolds, mass, participant and sex explained some of the variance for CMJ PPO. As those with greater muscle masses are capable of increased force production, and potentially increased power output, this result was as expected and also demonstrates why sex was a significant variable for all performance measures, as females typically have lower muscle masses than males (Perez-Gomez et al., 2008). Worthwhile changes were found for two participants following PHM and one participant following AHM. Start times were fastest following AHM for 13% of participants, and 40% of participants following PHM; 13% of participants had their joint fastest start time during both heat maintenance conditions and 34% had their fastest start time during CON.

Despite no significant increases in performance, T_m was significantly higher following AHM for all three muscles compared to CON. During the current study, iButtons were used to measure skin temperature, which could be used to predict T_m based on regression equations developed by Flouris et al. (2015). However, following the results during the current study, it was considered that the iButtons were impacted by the heated elements within the HUUB trousers used during AHM. As iButtons are extremely sensitive to their surroundings, the iButtons may have recorded the heat emitted by the heated elements, as well as skin temperature, thus providing an inaccurate reading of skin temperature. This would explain how, despite a significant increase in T_m, no significant differences in performance were observed, as expected based on previous research correlating increased T_m with enhanced performance (Section 2.5.2).

Although the current study was conducted within the applied setting, which can increase the ecological validity of the results compared to a laboratory setting, a standardised WU was implemented during the current study, compared to the individualised approach taken during Chapter 4. This decision was made because the results in Chapter 4 suggested the quality of the swimmers' individual race WUs were insufficient to achieve the expected change in CMJ height and PPO following the WU. Therefore a standardised WU was used within Chapter 5. Although RPEs were higher following this WU, compared to Chapter 4, the changes in CMJ height and PPO from baseline to WU were greater, suggesting that the WU was more effective within the current study. Unfortunately, the applied setting of the current study also reduced the controllability of the participants' training status and readiness before data collection. Because all swimmers were members of a Swim Wales High-Performance Centre, requesting a cessation or modification in physical activity at any time prior to data collection was not an option because of training commitments. Therefore, for the current study and Chapter 4, the same day and time were used throughout all data collection periods to reduce the differences in training load, fatigue and circadian rhythms as much as possible. Additionally, each study was completed in a randomised design to try and reduce the fatigue effect.

6.1.5 Summary

This thesis aimed to understand the importance of the swimming start and identify pre-race interventions which could enhance start performance. Because of the high calibre of swimmers used within these studies (FINA points for Chapters 4 and 5 participants: 783 ± 55), the results were more easily applicable to other elite swimmers, but also support any significant results being a true change rather than a learning effect which may have occurred if non-swimmers were used, as participants in Chapters 4 and 5 could already successfully perform a high-level swimming start. Due to the applied nature of this thesis, the ecological validity was high for all studies, and the results from Chapters 4 and 5 had direct impacts on the swimmers during future competitions. For example, several participants from Chapters 4 and 5 attended the Birmingham 2022 Commonwealth Games and utilised these pre-race interventions based on their individual findings from this thesis. One participant who achieved a worthwhile change following isometric PAP achieved a personal best time at the Birmingham 2022 Commonwealth Games for 50 m backstroke, and they achieved their 100 m backstroke personal best time during a qualifying meet for the Commonwealth Games four months earlier, after data collection for Chapter 4. The other participant to achieve a worthwhile change in Chapter 4 also attended the Birmingham 2022 Commonwealth Games and achieved a 100 m breaststroke season's best time. Their personal best for the 50 m breaststroke was achieved a year earlier, shortly following the data collection for Chapter 4. Although it is unlikely that the change in PAP mode caused these results alone, it does support the use of PAP to improve performance alongside other possible interventions, such as training and strength enhancements.

6.2 Practical Applications for swimming

Based on the findings from each chapter, practical applications and their use within swimming were considered and will now be outlined.

- A single panning camera analysis system can provide an accurate measure of start time, providing an experienced analyst is used and protocols which reduce perspective error are implemented. This system can monitor changes in start time and confidently identify worthwhile changes that are due to interventions and potential fluctuations due to training load, rather than systematic errors within the analysis system.

- It is recommended that support staff completing analysis using the single panning camera analysis system should be fully trained and complete a reliability check before any official analysis is conducted. It is also recommended that future analysts are made aware of the potential difficulties with analysing breaststroke and butterfly, as the swimmers head is not always visible during these strokes due to vertical displacement, or when white water is present, and care should be taken when analysing the outer lanes of the pool.

- The swimming start is a key component of sprint swimming. Coaches with sprint athletes should therefore seek opportunities to enhance start performance. If PPO cannot be monitored on the block, CMJ performance can also be monitored, and any changes in CMJ height and PPO can be applied to the start.

- As females have a greater total start contribution by 0.55% compared to their male counterparts, there may be some technical or physical differences between sexes which result in males having a lower start contribution. This difference could be associated with anthropometric differences, as males are typically able to produce more power due to increased muscle mass, or potentially a difference in start technique. Nonetheless, some consideration of this difference is necessary when coaching to ensure the start is enhanced regardless of sex.

- The results from Chapter 4 suggest that participant factors can impact an individual’s ability to harness PAP. Before implementing a PAP conditioning activity into a swimmer’s pre-race routine, it is important to investigate the swimmer’s strength and training level to determine their potential ability to harness a PAP response and therefore benefit from this intervention.

- The results from Chapter 4 suggest that a greater training history with the PAP conditioning activity may be necessary for individuals to increase their PAP response. Therefore, swimmers intending to use PAP conditioning activities should practice such routines throughout the training period and at competitions to enhance performance following this intervention.

- Familiarisation with heat maintenance garments should be considered for swimmers before competitions, to enable them to become accustomed with the TC and TS associated with the garments. This would also enable any cooling strategies, such as cold towels and ice drinks to be trialled and practiced before competing.

- The results from Chapter 5 suggest that PHM is an effective pre-race intervention and can be implemented prior to racing to enhance PPO. Providing underwater technique remains consistent, PHM could potentially enhance start time also.

- Based on the changes made between Chapters 4 and 5, where the WUs were changed from individual to standardised, it would seem that an education piece around effective WUs may be necessary within this particular cohort of elite swimmers. To ensure the WU and its physiological adaptations are maximised, coaches and support staff may need to outline the appropriate intensity and duration for swimmers. This change could further increase T_m and performance of PAP conditioning activities if this increased T_m can be maintained.

6.3 Future research directions

Throughout each chapter, additional research needs were identified. These aim to further the knowledge gaps within different areas discussed throughout each chapter and detail any methodological limitations where research may benefit the findings of future studies. These will now be outlined.

- Although Chapter 3 identified that females have a greater contribution from the start to the overall race, it was unclear why. Therefore, investigating the start for both sexes, including a biomechanical approach and assessing differences in strength and PPO, could give an understanding of whether there are any technical differences between males and females and how these can be manipulated to enhance start performance for both sexes.

- Chapter 3 also found that other nationalities have faster start times than British swimmers. This difference could be due to power differences or a greater understanding of the determinants of the start and how these can be manipulated through the new equipment by other nationalities, but regardless, the finding suggests that further investigation is required within Britain to improve start performance and achieve start times similar to or better than other nationalities, as even small changes to performance could increase medal likelihood.

- The isometric PAP conditioning activity has been implemented within the Swim Wales environment because isometric exercise reduces EIMD, and could be more beneficial during multi-day competitions. However, limited research into the volume of an isometric PAP conditioning activity has been completed, and the repetitions and rest periods set within Chapter 4 may have been insufficient to achieve a PAP response for all participants. Therefore, understanding the appropriate volume for an isometric PAP conditioning activity to elicit a response would ensure that isometric PAP can enhance start performance for more swimmers.

- Although 8 min has been concluded within research as the average recovery time from a PAP conditioning activity to achieve PPO, it has also been discussed that the PAP response is highly individual. Therefore an 8 min recovery time is not appropriate for all. For the participants in Chapter 4 to have a greater likelihood of enhanced performance following PAP, a more bespoke timeline is required. Further research into individual recovery times could help achieve this.

- It is recommended that a validation study is completed with the iButtons when used in conjunction with heat maintenance garments, particularly those with heated elements. Throughout Chapter 5, it was unclear why T_m increased but no increase in performance was also observed, and it was theorised to be a measurement error with the iButtons, recording a combination of the heat emitted from the heated elements and skin temperature. A specific validation which investigates the skin temperatures measured using iButtons when heat maintenance garments are worn, particularly those with heated elements, would give insight into the iButton's ability to measure skin temperature accurately and predict T_m and whether this is a valid method to use in future heat garment studies.

- Measuring core temperature alongside T_m whilst wearing heat maintenance garments would offer further insight into the changes experienced by the body during these interventions. As Chapter 5 produced some contradictory findings, such as the increase in T_m but no increase in performance, core temperature could provide an explanation into the effectiveness of the heat maintenance garments, without the possible methodological limitation outlined above when using the iButtons. Therefore, it is recommended that additional research into the use of heat maintenance garments as a pre-race intervention is completed, assessing both core and T_m.

6.4 Thesis summary

This thesis has determined the accuracy of a single panning camera analysis system to measure start times within the context of a pre-determined SWC for start time, derived from previous literature, and assessed the reliability of the analysis system. This thesis has quantified start times in relation to total race time and accounted for changes in equipment since 2010. This process was completed across all events and between additional variables including sex to assess differences and identify future research needs accordingly. Ballistic and isometric PAP strategies were investigated to understand how they enhance start time. CMJ performance was also measured to assess direct changes in PPO whilst removing additional variables which can impact start time if inconsistent. Ballistic PAP significantly improved CMJ height and PPO, but neither PAP intervention significantly improved start time. SWCs were identified for two swimmers and support the need to assess changes in PPO following PAP on an individual level. Active and passive heat maintenance strategies were examined on how they impact start and CMJ performance, and the changes in T_m. Despite significant increase in T_m, no significant changes in performance metrics were found for AHM compared to CON. PHM significantly improved CMJ PPO compared to CON. In summary, the start remains a key component of sprint swimming, and SWCs can be confidently identified using a single panning camera analysis system. Both PAP and heat maintenance strategies can be successful pre-race interventions on an individual basis, but it is suggested that coaches and support staff consider individual characteristics, such as strength level, before implementing these into a swimmer's race day timeline.

APPENDICIES

Appendices A and B redacted due to inclusion of personal information
Library Research Support / Open Access Team (13/09/2023)

Appendix C: Rate of perceived exertion scale

Score	Perceived Exertion
6	No exertion at all
7	Extremely light
8	
9	Very light
10	
11	Light
12	
13	Somewhat hard
14	
15	Hard (heavy)
16	
17	Very hard
18	
19	Extremely hard
20	Maximal exertion

Appendix D: Mean (± standard deviation) strength testing results for chapter 4 participants

	Group (n = 14)	Female (n = 3)	Male (n = 11)
1RM Back Squat (kg)	99.6 ± 21.2	74.2 ± 13.6	108.1 ± 15.8
1RM Leg Press (kg)	294.0 ± 80.8	214.2 ± 49.0	318.0 ± 72.6
1RM Bench Press (kg)	81.3 ± 21.8	48.3 ± 2.4	91.3 ± 13.8
1RM Lat Pulldown (kg)	85.2 ± 19.2	60.0 ± 6.1	92.8 ± 14.9
1RM Prone Pull (kg)	77.9 ± 19.7	50.8 ±4.7	86.0 ± 14.6

Appendix E: Thermal comfort scale

3	Much too warm
2	Too warm
1	Comfortably warm
0	Comfortable
-1	Comfortably cool
-2	Too cool
-3	Much too cool

Appendix F: Thermal sensation scale

4	Very hot
3	Hot
2	Warm
1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold
-4	Very cold

BIBLIOGRAPHY

Ahmad, N., Ghazilla, R. A. R., Khairi, N. M., & Kasi, V. (2013). Reviews on Various Inertial Measurement Unit (IMU) Sensor Applications. *International Journal of Signal Processing Systems*, *1*(2), 256–262. https://doi.org/10.12720/ijsps.1.2.256-262

Altavilla, G., di Tore, A., & D'Isanto, T. (2018). Physiological Effects of Warm-Up and Problems Related to Team Sports. *Sport Science*, *11*(1), 83–88.

Anthi, X., Dimitrios, P., & Christos, K. (2014). On the mechanisms of post-activation potentiation: The contribution of neural factors. *Journal of Physical Education and Sport*, *14*(2), 134–137. https://doi.org/10.7752/jpes.2014.02021

Arellano, R., Cossor, J., Wilson, B., Chatard, J.-C., Riewalds, S., & Mason, B. (2001). Modelling competitive swimming in different strokes and distances upon regression analysis: A study of the female participants of Sydney 2000 Olympic Games. *Biomechanics Symposia*, 53–56.

Argüelles-Cienfuegos, J., & de La Fuente-Caynzos, B. (2014). XVth World Swimming Championships race phases' contribution to the overall performance and the gender differences. *NSCA IV International Conference. Human Performance Development through Strength and Conditioning*. http://www.swim.ee/competition/index.html.

Asmussen, E., & Bøje, O. (1945). Body Temperature and Capacity for Work. *Acta Physiologica Scandinavica*, *10*(1), 1–22. https://doi.org/10.1111/j.1748-1716.1945.tb00287.x

Bach, A. J. E., Stewart, I. B., Disher, A. E., & Costello, J. T. (2015). A comparison between conductive and infrared devices for measuring mean skin temperature at rest, during exercise in the heat, and recovery. *PLoS ONE*, *10*(2), 1–13. https://doi.org/10.1371/journal.pone.0117907

Balk, Y. A., & de Jonge, J. (2021). The "underrecovery trap": When physical fatigue impairs the physical and mental recovery process. *Sport, Exercise, and Performance Psychology*, *10*(1), 88–101. https://doi.org/10.1037/spy0000249

Barbosa, A. C., Barroso, R., & Andries, O. (2016). Post-activation Potentiation in Propulsive Force after Specific Swimming Strength Training. *International Journal of Sports Medicine*, *37*(4), 313–317. https://doi.org/10.1055/s-0035-1565050

Barbosa, T. M., Bragada, J. A., Reis, V. M., Marinho, D. A., Carvalho, C., & Silva, A. J. (2010). Energetics and biomechanics as determining factors of swimming performance: Updating the state of the art. *Journal of Science and Medicine in Sport*, *13*(2), 262–269. https://doi.org/10.1016/j.jsams.2009.01.003

Barlow, H., Halaki, M., Stuelcken, M., Greene, A., & Sinclair, P. J. (2014). The effect of different kick start positions on OMEGA OSB11 blocks on free swimming time to 15m in developmental level swimmers. *Human Movement Science*, *34*, 178–186. https://doi.org/10.1016/j.humov.2014.02.002

Barris, S., & Button, C. (2008). A Review of Vision-Based Motion Analysis in Sport. *Sports Medicine*, *38*(12), 1025–1043.

Beato, M., Bigby, A. E. J., de Keijzer, K. L., Nakamura, F. Y., Coratella, G., & McErlain-Naylor, S. A. (2019). Post-activation potentiation effect of eccentric overload and traditional weightlifting exercise on jumping and sprinting performance in male athletes. *PLoS ONE*, *14*(9), 1–13. https://doi.org/10.1371/journal.pone.0222466

Beaven, C. M., Kilduff, L. P., & Cook, C. J. (2018). Lower-limb passive heat maintenance combined with pre-cooling improves repeated sprint ability. *Frontiers in Physiology*, *9*, 1064. https://doi.org/10.3389/fphys.2018.01064

Beckham, G., Suchomel, T., & Mizuguchi, S. (2014). Force Plate Use in Performance Monitoring and Sport Science Testing. *New Studies in Athletics*, *3*, 25–37. https://www.researchgate.net/publication/269631495

Bedford, T. (1950). Environmental Warmth and Human Comfort. *British Journal of Applied Physics*, *1*(2), 33–38.

Behm, D. G., Button, D. C., Barbour, G., Butt, J. C., & Young, Warren. B. (2004). *Conflicting effects of fatigue and potentiation on voluntary force*. *18*(2), 365–372.

Bergh, U., & Ekblom, B. (1979). Influence of muscle temperature on maximal muscle strength and power output in human skeletal muscles. *Acta Physiologica Scandinavica*, *107*(1), 33–37. https://doi.org/10.1111/j.1748-1716.1979.tb06439.x

Bevan, H. R., Owen, N. J., Cunningham, D. J., Kingsley, M. I. C., & Kilduff, L. P. (2009). Complex Training in Professional Rugby Players: Influence of Recovery Time on Upper-Body Power Output. *The Journal of Strength and Conditioning Research*, *23*(6), 1780–1785. https://doi.org/10.1519/JSC.0b013e3181b3f269

Birzniece, V., Nelson, A. E., & Ho, K. K. Y. (2011). Growth hormone and physical performance. *Trends in Endocrinology & Metabolism*, *22*(5), 171–178. https://doi.org/10.1016/j.tem.2011.02.005

Blazevich, A. J., & Babault, N. (2019). Post-activation Potentiation Versus Post-activation Performance Enhancement in Humans: Historical Perspective, Underlying Mechanisms, and Current Issues. *Frontiers in Physiology*, *10*(November), 1–19. https://doi.org/10.3389/fphys.2019.01359

Bogdanis, G. C., Nevill, M. E., Boobis, L. H., & Lakomy, H. K. A. (1996). Contribution of phosphocreatine and aerobic metabolism to energy supply during repeated sprint exercise. *Journal of Applied Physiology*, *80*(3), 876–884. https://doi.org/10.1152/jappl.1996.80.3.876

Bogdanis, G. C., Tsoukos, A., Veligekas, P., Tsolakis, C., & Terzis, G. (2014). Effects of Muscle Action Type With Equal Impulse of Conditioning Activity on Postactivation Potentiation. *Journal of Strength & Conditioning Research*, *28*(9), 2521–2528.

Borg, G. A. V. (1982). Psychophysical bases of perceived exertion. *Medicine and Science in Sports and Exercise*, *14*(5), 377–381.

Brajkovic, D., Ducharme, M. B., Webb, P., Reardon, F. D., & Kenny, G. P. (2006). Insulation disks on the skin to estimate muscle temperature. *European Journal of Applied Physiology*, *97*(6), 761–765. https://doi.org/10.1007/s00421-005-0113-5

Brandt, R. A., & Pichowsky, M. A. (1995). Conservation of energy in competitive swimming. *Journal of Biomechanics*, *28*(8), 925–933.

Buchthal, F., Kaiser, E., & Knappeis, G. G. (1944). Elasticity, Viscosity and Plasticity in the Cross Striated Muscle Fibre. *Acta Physiologica*, *8*(1), 16–37.

Buckthorpe, M., Morris, J., & Folland, J. P. (2012). Validity of vertical jump measurement devices. *Journal of Sports Sciences*, *30*(1), 63–69. https://doi.org/10.1080/02640414.2011.624539

Button, K. S., Ioannidis, J. P. A., Mokrysz, C., Nosek, B. A., Flint, J., Robinson, E. S. J., & Munafò, M. R. (2013). Power failure: Why small sample size undermines the reliability of neuroscience. *Nature Reviews Neuroscience*, *14*(5), 365–376. https://doi.org/10.1038/nrn3475

Cain, D. F., & Davies, R. E. (1962). Breakdown of adenosine triphosphate during a single contraction of working muscle. *Biochemical and Biophysical Research Communications*, *8*(5), 361–366. https://sci-hub.tw/10.1002/iroh.19620470121

Calderbank, J. A., Comfort, P., & McMahon, J. J. (2020). Association of Jumping Ability and Maximum Strength With Dive Distance in Swimmers. *Human Kinetics Journal*, *16*(2), 296–303.

Carradori, S., Burkhardt, D., Sinistaj, S., Taylor, W. R., & Lorenzetti, S. (2015). Kinetic and Kinematic Analysis of the Leg Positioning in the Freestyle Track Start in Swimming. In F. Colloud, M. Domalain, & T. Monnet (Eds.), *33rd International Conference on Biomechanics in Sports* (pp. 808–811).

Carroll, T. J., Taylor, J. L., & Gandevia, S. C. (2017). Recovery of central and peripheral neuromuscular fatigue after exercise. *Journal of Applied Physiology*, *122*(5), 1068–1076. https://doi.org/10.1152/japplphysiol.00775.2016

Chiu, L. Z. F., Fry, A. C., Weiss, L. W., Schilling, B. K., Brown, L. E., & Smith, S. L. (2003). Postactivation Potentiation Response in Athletic and Recreationally Trained Individuals. *Journal of Strength and Conditioning Research*, *17*(4), 671–677. https://doi.org/10.1519/00124278-200311000-00008

Chtourou, H., Driss, T., Souissi, S., Gam, A., Chaouachi, A., & Souissi, N. (2010). The Effect of Strength Training at the Same Time of the Day on the Diurnal Fluctuations of Muscular Anaerobic Performances. *Strength And Conditioning*, *25*(9), 396–403. https://doi.org/10.1097/BRS.0b013e3182a7f449

Cicenia, A., Oster, C., & Mokha, M. (2019). Effects of Standardizing Kick Plate Position on Track Start Biomechanics in Elite Swimmers. *37th International Society of Biomechanics in Sport Conference*, 360–363. https://commons.nmu.edu/isbs/vol37/iss1/88

Clarkson, P. M., Byrnes, W. C., McCormick, K. M., Turcotte, L. P., & White, J. S. (1986). Muscle Soreness and Serum Creatine Kinase Activity Following Isometric, Eccentric and Concentric Exercise. *Medicine & Science in Sports & Exercise*, *7*(3), 152–155. https://doi.org/10.1249/00005768-198504000-00424

Clarkson, P. M., & Newham, D. J. (1995). Associations between muscle soreness, damage, and fatigue. *Advances in Experimental Medicine and Biology*, *384*, 457–469. https://doi.org/10.1007/978-1-4899-1016-5_35

Clarkson, Priscilla. M., & Sayers, S. P. (1999). Etiology of Exercise-Induced Muscle Damage. *Canadian Journal of Applied Physiology*, *24*(3), 234–248.

Comyns, T. M., Harrison, A. J., & Hennessy, L. K. (2010). Effect of squatting on sprinting performance and repeated exposure to complex training in male rugby players. *Journal of Strength and Conditioning Research*, *24*(3), 610–618. https://doi.org/10.1519/JSC.0b013e3181c7c3fc

Connaboy, C., Coleman, S., Moir, G., & Sanders, R. (2010). Measures of reliability in the kinematics of maximal undulatory underwater swimming. *Medicine and Science in Sports and Exercise*, *42*(4), 762–770. https://doi.org/10.1249/MSS.0b013e3181badc68

Cossor, J., & Mason, B. (2001). Swim Start performances at the Sydney 2000 Olympic Games. *Biomechanics Symposia*, 70–74.

Cossor, J., Slawson, S., Shillabeer, B., Conway, P., & West, A. (2011). Are land tests a good predictor of swim start performance? *Portuguese Journal of Sports Sciences*, *11*(2), 183–186. https://ojs.ub.uni-konstanz.de/cpa/article/view/4803

Craig, A. B., & Pendergast, D. R. (1979). Relationships of stroke rate, distance per stroke, and velocity in competitive swimming. *Medicine and Science in Sports and Exercise*, *11*(3), 278–283.

Cuenca-Fernández, F., Lopez-Contreras, G., & Arellano, R. (2015). Effect on Swimming Start Performance of Two Types of Activation Protocols: Lunge and YoYo Squat. *Journal of Strength and Conditioning Research*, *29*(3), 647–655.

Cuenca-Fernández, F., López-Contreras, G., Mourão, L., de Jesus, K., de Jesus, K., Zacca, R., Vilas-Boas, J. P., Fernandes, R. J., & Arellano, R. (2019). Eccentric flywheel post-activation potentiation influences swimming start performance kinetics. *Journal of Sports Sciences*, *37*(4), 443–451. https://doi.org/10.1080/02640414.2018.1505183

Currie, K. D., Coates, A. M., Slysz, J. T., Aubry, R. L., Whinton, A. K., Mountjoy, M. L., Millar, P. J., & Burr, J. F. (2018). Left Ventricular Structure and Function in Elite Swimmers and Runners. *Frontiers in Physiology*, *9*(November), 1–6. https://doi.org/10.3389/fphys.2018.01700

DeFreitas, J. M., Beck, T. W., Stock, M. S., Dillon, M. A., & Kasishke, P. R. (2004). Maximal strength and power, muscle mass, endurance and serum hormones in weightlifters and road cyclists. *Journal of Sports Sciences*, *22*(5), 465–478. https://doi.org/10.1080/02640410410001675342

DeFreitas, J. M., Beck, T. W., Stock, M. S., Dillon, M. A., & Kasishke, P. R. (2011). An examination of the time course of training-induced skeletal muscle hypertrophy. *European Journal of Applied Physiology*, *111*, 2785–2790. https://doi.org/10.1007/s00421-011-1905-4 de Jesus, K., de Jesus, K., Abraldes, J. A., Mourão, L., Borgonovo-Santos, M., Medeiros, A. I. A., Gonçalves, P., Chainok, P., Fernandes, R. J., Vaz, M. A. P., & Vilas-Boas, J. P. (2016). The effect of different foot and hand set-up positions on backstroke start performance. *Sports Biomechanics*, *15*(4), 481–496. https://doi.org/10.1080/14763141.2016.1182580

de Jesus, K., de Jesus, K., Figueiredo, P., Gonçalves, P., Pereira, S. M., Vilas-Boas, J. P., & Fernandes, R. J. (2013). Backstroke start kinematic and kinetic changes due to different feet positioning. *Journal of Sports Sciences*, *31*(15), 1665–1675. https://doi.org/10.1080/02640414.2013.794298

de Jesus, K., de Jesus, K., Figueiredo, P., Gonçalves, P., Pereira, S., Vilas-Boas, J. P., & Fernandes, R. J. (2011). Biomechanical analysis of backstroke swimming starts. *International Journal of Sports Medicine*, *32*(7), 546–551. https://doi.org/10.1055/s-0031-1273688

de Keijzer, K. L., Mcerlain-naylor, S. A., dello Iacono, A., & Beato, M. (2020). Effect of Volume on Eccentric Overload – Induced Postactivation Potentiation of Jumps. *International Journal of Sports Physiology and Performance*, *28,* 1–6. https://doi.org/10.1123/ijspp.2019-0411

dello Iacono, A., Padulo, J., & Seitz, L. D. (2018). Loaded hip thrust-based PAP protocol effects on acceleration and sprint performance of handball players. *Journal of Sports Sciences*, *36*(11), 1269–1276. https://doi.org/10.1080/02640414.2017.1374657

de Ruiter, C. J., & de Haan, A. (2000). Temperature effect on the force/velocity relationship of the fresh and fatigued human adductor pollicis muscle. *Pflugers Archiv European Journal of Physiology, 440*(1), 163–170. https://doi.org/10.1007/s004240051035

Desmedt, J. E., & Godaux, E. (1977). Ballistic contractions in man: characteristic recruitment pattern of single motor units of the tibialis anterior muscle. *The Journal of Physiology*, *264*(3), 673–693.

Dideriksen, J., Elias, L. A., Zambalde, E. P., Germer, C. M., Molinari, R. G., & Negro, F. (2022). Influence of central and peripheral motor unit properties on isometric muscle force entropy: A computer simulation study. *Journal of Biomechanics, 139*. https://doi.org/10.1016/j.jbiomech.2021.110866

Dobbin, N., Hunwicks, R., Highton, J., & Twist, C. (2017). Validity of a Jump Mat for assessing Countermovement Jump Performance in Elite Rugby Players. *International Journal of Sports Medicine, 38*(2), 99–104. https://doi.org/10.1055/s-0042-118313

Enoka, R. M., & Duchateau, J. (2008). Muscle fatigue: What, why and how it influences muscle function. *Journal of Physiology*, *586*(1), 11–23. https://doi.org/10.1113/jphysiol.2007.139477

Enoka, Roger. M., & Stuart, Douglas. G. (1992). Neurobiology of muscle fatigue. *Journal of Applied Physiology*, *72*(5), 1631–1648. https://doi.org/10.1152/jappl.1992.72.5.1631

Esformes, J. I., Keenan, M., Moody, J., & Bampouras, T. M. (2011). Effect of different types of conditioning contraction on upper body postactivation potentiation. *Journal of Strength and Conditioning Research*, *25*(1), 143–148.

Fairbank, M., Highton, J., & Twist, C. (2019). Passive Heat Maintenance After an Initial Warm-up Improves High-Intensity Activity During an Interchange Rugby League Movement Simulation Protocol. *Journal of Strength and Conditioning Research*, *Publish Ah*(00), 1–6. https://doi.org/10.1519/jsc.0000000000003061

Febbraio, M. A., Carey, M. F., Snow, R. J., Stathis, C. G., & Hargreaves, M. (1996). Influence of elevated muscle temperature on metabolism during intense, dynamic exercise. *American Journal of Physiology*, *271*(5 40-5). https://doi.org/10.1152/ajpregu.1996.271.5.r1251

Ferretti, G., Ishii, M., Moia, C., & Cerretelli, P. (1992). Effects of temperature on the maximal instantaneous muscle power of humans. *European Journal of Applied Physiology and Occupational Physiology*, *64*(2), 112–116. https://doi.org/10.1007/BF00717947

Field, A. (2013). *Discovering Statistics Using IBM SPSS Statistics* (M. Carmichael, Ed.; 4th Edition). Sage Publications Ltd.

FINA. (2017). *Part III FINA Swimming Rules*.

FINA. (2022a). *Competition Results*. https://www.fina.org/swimming/results?year=2021&month=6&disciplines=SW

FINA. (2022b). *Swimming Records*. https://www.fina.org/swimming/records?recordCode=WR&eventTypeId=&region=&countryId=&gender=M&pool=LCM

Flouris, A. D., Webb, P., & Kenny, G. P. (2015). Noninvasive assessment of muscle temperature during rest, exercise, and postexercise recovery in different environments. *Journal of Applied Physiology*, *118*(10), 1310–1320. https://doi.org/10.1152/japplphysiol.00932.2014

Folland, J. P., Wakamatsu, T., & Fimland, M. S. (2008). The influence of maximal isometric activity on twitch and H-reflex potentiation, and quadriceps femoris performance. *European Journal of Applied Physiology*, *104*(4), 739–748. https://doi.org/10.1007/s00421-008-0823-6

Folland, J. P., & Williams, A. G. (2007). The adaptations to strength training: Morphological and neurological contributions to increased strength. *Sports Medicine*, *37*(2), 145–168. https://doi.org/10.2165/00007256-200737020-00004

Fradkin, A. J., Zazryn, T. R., & Smoliga, J. M. (2010). Effects of Warming-up on Physical Performance: A Systematic Review with Meta-Analysis. *Journal of Strength and Conditioning Research*, *24*(1), 140–148.

Fukuda, T., Kawamoto, A., Arai, F., & Matsuura, H. (1994). Mechanism and swimming experiment of micro mobile robot in water. *Proceedings - IEEE International Conference on Robotics and Automation*, *pt 1*, 814–819. https://doi.org/10.1109/robot.1994.351388

Galbraith, A., & Willmott, A. (2018). Transition phase clothing strategies and their effect on body temperature and 100-m swimming performance. *European Journal of Sport Science*, *18*(2), 182–189. https://doi.org/10.1080/17461391.2017.1411528

Garcia-Hermoso, A., Escalante, Y., Arellano, R., Navarro, F., Domínguez, A. M., & Saavedra, J. M. (2013). Relationship between final performance and block times with the traditional and the new starting platforms with a back plate in international swimming championship 50-m and 100-m freestyle events. *Journal of Sports Science and Medicine*, *12*(4), 698–706.

Garcia-Ramos, A., Padial, P., de La Fuente, B., Arguelles-Cienfuegos, J., Bonitch-Gongora, J., & Feriche, B. (2015). Relationship Between Vertical Jump Height and Swimming Start Performance Before and After an Altitude Training Camp. *The Journal of Strength and Conditioning Research ·*, *30*(6), 1638–1645. https://doi.org/10.1519/JSC.0000000000001242

García-Ramos, A., Tomazin, K., Feriche, B., Strojnik, V., de La Fuente, B., Argüelles-Cienfuegos, J., Strumbelj, B., & Štirn, I. (2016). The relationship between the lower-body muscular profile and swimming start performance. *Journal of Human Kinetics*, *50*(1), 157–165. https://doi.org/10.1515/hukin-2015-0152

Gleeson, M. (1998). Temperature regulation during exercise. *International Journal of Sports Medicine*, *19*, 96–99. https://doi.org/10.1249/00005768-198315010-00006

Gołaś, A., Maszczyk, A., Zajac, A., Mikołajec, K., & Stastny, P. (2016). Optimizing post activation potentiation for explosive activities in competitive sports. *Journal of Human Kinetics*, *52*(1), 95–106. https://doi.org/10.1515/hukin-2015-0197

Gonjo, T., & Olstad, B. H. (2020). Start and turn performances of competitive swimmers in sprint butterfly swimming. *Journal of Sports Science and Medicine*, *19*(4), 727–734.

Gorassini, M., Yang, J. F., Siu, M., & Bennett, D. J. (2002). Intrinsic activation of human motoneurons: Possible contribution to motor unit excitation. *Journal of Neurophysiology*, *87*(4), 1850–1858. https://doi.org/10.1152/jn.00024.2001

Gourgoulis, V., Aggeloussis, N., Kasimatis, P., Mavromatis, G., & Garas, A. (2003). Effect of a Submaximal Half-Squats Warm-up Program on Vertical Jumping Ability. *Journal of Strength and Conditioning Research*, *17*(2), 342–344. https://doi.org/10.1519/00124278-200305000-00021

Gouvêa, A. L., Fernandes, I. A., César, E. P., Silva, W. A. B., & Gomes, P. S. C. (2013). The effects of rest intervals on jumping performance: A meta-analysis on post-activation potentiation studies. *Journal of Sports Sciences*, *31*(5), 459–467. https://doi.org/10.1080/02640414.2012.738924

Gray, S. R., Söderlund, K., & Ferguson, R. A. (2008). ATP and phosphocreatine utilization in single human muscle fibres during the development of maximal power output at elevated muscle temperatures. *Journal of Sports Sciences*, *26*(7), 701–707. https://doi.org/10.1080/02640410701744438

Grimby, L., & Hannerz, J. (1977). Firing rate and recruitment order of toe extensor motor units in different modes of voluntary contraction. *The Journal of Physiology*, *264*(3), 865–879. https://doi.org/10.1113/jphysiol.1977.sp011699

Grimby, L., Hannerz, J., Borg, J., & Hedman, B. (1981). Firing properties of single human motor units on maintained maximal voluntary effort. In *Human Muscle Fatigue: Physiological Mechanisms* (pp. 157–177). Ciba Foundation.

Gullich, A., & Sehmidtbleicher, D. (1996). MVC-induced short-term potentiation of explosive force. *New Studies in Athletics*, *11*(4), 67–81.

Guo, X., Li, Y., & Ling, H. (2017). LIME: Low-light image enhancement via illumination map estimation. *IEEE Transactions on Image Processing*, *26*(2), 982–993. https://doi.org/10.1109/TIP.2016.2639450

Hamada, T., Sale, D. G., & Macdougall, J. D. (2000). Postactivation potentiation in endurance-trained male athletes. *Medicine and Science in Sports and Exercise*, *32*(2), 403–411. https://doi.org/10.1097/00005768-200002000-00022

Hamada, T., Sale, D. G., MacDougall, J. D., & Tarnopolsky, M. A. (2000). Postactivation potentiation, fiber type, and twitch contraction time in human knee extensor muscles. *Journal of Applied Physiology*, *88*(6), 2131–2137. https://doi.org/10.1152/jappl.2000.88.6.2131

Hancock, A. P., Sparks, K. E., & Kullman, E. L. (2015). Postactivation Potentiation Enhances Swim Performance in Collegiate Swimmers. *Journal of Strength and Conditioning Research*, *29*(4), 912–917.

Hansen, S., Kvorning, T., Kjær, M., & Sjøgaard, G. (2001). The effect of short-term strength training on human skeletal muscle: The importance of physiologically elevated hormone levels. *Scandinavian Journal of Medicine and Science in Sports*, *11*(6), 347–354. https://doi.org/10.1034/j.1600-0838.2001.110606.x

Hardaker, N. J., Moss, A. D., Richards, J., Jarvis, S., Mcewan, I., & Selfe, J. (2007). Relationship between intramuscular temperature and skin surface temperature as measured by thermal imaging camera. *Thermology International*, *17*(2), 45–50.

Harper Smith, A. D., Crabtree, D. R., Bilzon, J. L. J., & Walsh, N. P. (2010). The validity of wireless iButtons and thermistors for human skin temperature measurement. *Physiological Measurement*, *31*, 95–114. https://doi.org/10.1088/0967-3334/31/1/007

Hedrick, A. (1992). Physiological Responses to Warm-Up. *National Strength and Conditioning Association Journal*, *14*(5), 25–27.

Henneman, E. (1957). Relation between size of neurons and their susceptibility to discharge. *Science*, *126*(3287), 1345–1347. https://doi.org/10.1126/science.126.3287.1345

Henneman, E. (1985). The size-principle: A deterministic output emerges from a set of probabilistic connections. *Journal of Experimental Biology*, *115*, 105–112.

Henschel, A. (1967). Obesity as an Occupational Hazard. *Canadian Journal of Public Health*, *58*(11), 491–493.

Hester, G. M., Pope, Z. K., Sellers, J. H., Thiele, R. M., & DeFreitas, J. M. (2017). Potentiation Effect of Ballistic and Heavy Exercise on Vertical Jump Performance. *Journal of Strength & Conditioning Research*, *31*(3), 660–666.

Hiller-Sturmhöfel, S., & Bartke, A. (1998). The endocrine system. *Alcohol Health and Research World*, *22*(3), 671–702. https://doi.org/10.1007/978-3-319-19207-9_25

Hill, A. V. (1922). The maximum work and mechanical efficiency of human muscles, and their most economical speed. *The Journal of Physiology*, *56*(1–2), 19–41. https://doi.org/10.1113/jphysiol.1922.sp001989

Hodgson, M., Docherty, D., & Robbins, D. (2005). Post-Activation Potentiation: Underlying Physiology and Implications for Motor Performance. *Sports Medicine*, *35*(7), 585–595.

Honda, K., Sinclair, P., Mason, B., & Pease, D. (2012). The Effect of Starting Position on Elite Swim Start Performance Using an Angled Kick Plate. *30 Th Annual Conference of Biomechanics in Sports-Melbourne*, *166*, 72–75.

Houston, M. E., Lingley, M. D., Stuart, D. S., & Grange, R. W. (1987). Myosin light chain phosphorylation in intact human muscle. *FEBS Letters*, *219*(2), 469–471. https://doi.org/10.1016/0014-5793(87)80274-0

Hughes, D. C., Ellefsen, S., & Baar, K. (2018). Adaptations to endurance and strength training. *Cold Spring Harbor Perspectives in Medicine*, *8*(6), 1–18. https://doi.org/10.1101/cshperspect.a029769

Ikeda, Y., Ichikawa, H., Nara, R., Baba, Y., & Shimoyama, Y. (2017). Does installation of the backstroke start device reduce 15-m start time in swimming? *Journal of Sports Sciences*, *35*(2), 189–195. https://doi.org/10.1080/02640414.2016.1161204

Itza-Ortiz, S. F., Rebello, S., & Zollman, D. (2004). Students’ models of Newton’s second law in mechanics and electromagnetism. *European Journal of Physics*, *25*(1), 81–89. https://doi.org/10.1088/0143-0807/25/1/011

James, C. A., Richardson, A. J., Watt, P. W., & Maxwell, N. S. (2014). Reliability and validity of skin temperature measurement by telemetry thermistors and a thermal camera during exercise in the heat. *Journal of Thermal Biology*, *45*, 141–149. https://doi.org/10.1016/j.jtherbio.2014.08.010

Jansson, E., Esbjornsson, M., Holm, I., & Jacobs, I. (1990). Increase in the proportion of fast-twitch muscle fibres by sprint training in males. *Acta Physiologica Scandinavica*, *140*(3), 359–363. https://doi.org/10.1111/j.1748-1716.1990.tb09010.x

Jaric, S. (2015). Force-velocity Relationship of Muscles Performing Multi-joint Maximum Performance Tasks. *International Journal of Sports Medicine*, 36(9), 699–704 https://doi.org/10.1055/s-0035-1547283

Jo, E., Judelson, D. A., Brown, L. E., Coburn, J. W., & Dabbs, N. C. (2010). Influence of Recovery Duration After a Potentiating Stimulus on Muscular Power in

Recreationally Trained Individuals. *Journal of Strength & Conditioning Research*, *24*(2), 343–347.

Kanehisa, H., Ikegawa, S., & Fukunaga, T. (1994). Comparison of muscle cross-sectional area and strength between untrained women and men. *European Journal of Applied Physiology and Occupational Physiology*, *68*, 148–154.

Kelley, J. (2014). *An evaluation of in-race time points measured using the Nemo race analysis software* (Issue October).

Keskinen, O. P., Keskinen, K. L., & Mero, A. A. (2007). Effect of pool length on blood lactate, heart rate, and velocity in swimming. *International Journal of Sports Medicine*, *28*(5), 407–413. https://doi.org/10.1055/s-2006-924505

Kibele, A., Biel, K., & Fischer, S. (2015). Swim Start Standpoints on the OSB11 Starting Block. In M. D. & T. M. Floren Colloud (Ed.), *33rd International Conference on Biomechanics in Sports* (pp. 1000–1003).

Kilduff, L. P., Bevan, H., Owen, N., Kingsley, M. I. C., Bunce, P., Bennett, M., & Cunningham, D. (2007). Optimal Loading for Peak Power Output During the Optimal Loading for Peak Power Output During the Hang Power Clean in Professional Rugby Players. *International Journal of Sports Physiology and Performance*, *2*, 260–269. https://doi.org/10.1123/ijspp.2.3.260

Kilduff, L. P., Bevan, H. R., Kingsley, M. I. C., Owen, N. J., Bennett, M. A., Bunce, P. J., Hore, A. M., Maw, J. R., & Cunningham, D. J. (2007). Postactivation potentiation in professional rugby players: Optimal recovery. *Journal of Strength and Conditioning Research*, *21*(4), 1134–1138. https://doi.org/10.1519/R-20996.1

Kilduff, L. P., Cunningham, D. J., Owen, N. J., West, D. J., Bracken, R. M., & Cook, C. J. (2011). Effect of Postactivation Potentiation on Swimming Starts in International Sprint Swimmers. *Journal of Strength and Conditioning Research*, *25*(9), 2418–2423.

Kilduff, L. P., West, D. J., Williams, N., & Cook, C. J. (2013). The influence of passive heat maintenance on lower body power output and repeated sprint performance in professional rugby league players. *Journal of Science and Medicine in Sport*, *16*(5), 482–486. https://doi.org/10.1016/j.jsams.2012.11.889

Kiuchi, H., Nakashima, M., Cheng, K. B., & Hubbard, M. (2010). Modeling fluid forces in the dive start of competitive swimming. *Journal of Biomechanical Science and Engineering*, *5*(4), 314–328. https://doi.org/10.1299/jbse.5.314

Klavora, P. (2000). Vertical-jump Tests: A Critical Review. *National Strength & Conditioning Association*, *22*(5), 70–75.

Krane, V. (1994). The Mental Readiness Form as a Measure of Competitive State Anxiety. *The Sport Psychologist*, *8*(2), 189–202. https://doi.org/10.1123/tsp.8.2.189

Kroesen, S. H., de Korte, J. Q., Hopman, M. T. E., Bongers, C. C. W. G., & Eijsvogels, T. M. H. (2022). Impact of thermal sensation on exercise performance in the heat: a Thermo Tokyo sub-study. *European Journal of Applied Physiology*, *122*(2), 437–446. https://doi.org/10.1007/s00421-021-04845-8

Lim, J. J. H., & Kong, P. W. (2013). Effects of Isometric and Dynamic Postactivation Potentiation Protocols on Maximal Sprint Performance. *The Journal of Strength and Conditioning Research*, *27*(10), 2730–2736.

Lorenz, D. (2011). Postactivation Potentiation: An Introduction. *The International Journal of Sports Physical Therapy*, *6*(3), 234–240. https://doi.org/10.1111/j.2042-3292.2011.00290.x

Lovegrove, B. G. (2009). Modification and miniaturization of Thermochron iButtons for surgical implantation into small animals. *Journal of Comparative Physiology B*, *179*(4), 451–458. https://doi.org/10.1007/s00360-008-0329-x

Lyttle, A., & Benjanuvatra, N. (2005). *Start Right-A Biomechanical Review of Dive Start Performance* (Vol. 15). http://coachesinfo.com/index.php?option=com_content&view=article&id=89:swimming-start-style&catid=49:swimming-coaching&Itemid=86

Lyttle, A., & Blanksby, B. (1988). *Techniques for Starts and Turns* (Vol. 44, Issue 0).

Lyttle, A. D., Blanksby, B. A., Elliott, B. C., & Lloyd, D. G. (2000). Net forces during tethered simulation of underwater streamlined gliding and kicking techniques of the freestyle turn. *Journal of Sports Sciences*, *18*(10), 801–807. https://doi.org/10.1080/026404100419856

Maglischo, E. W. (2003). *Swimming Fastest, the essential reference on technique, training and program design*. Human Kinetics.

Malcata, R. M., Hopkins, W. G., & Pearson, S. N. (2014). Tracking career performance of successful triathletes. *Medicine and Science in Sports and Exercise*, *46*(6), 1227–1234. https://doi.org/10.1249/MSS.0000000000000221

Manning, D. R., & Stull, J. T. (1982). Myosin light chain phosphorylation-dephosphorylation in mammalian skeletal muscle. *American Journal of Physiology - Cell Physiology*, *242*(3), 234–241.

Marieb, E. N. (1995). *Human Anatomy and Physiology* (Third). The Benjamin/Cummings Publishing Company, Inc.

Martin, T., Frisch, K., & Zwart, J. (2020). Systematic Errors in Video Analysis. *The Physics Teacher*, *58*(3), 195–197. https://doi.org/10.1119/1.5145415

Mason, B., & Cossor, J. (2000). *What can we learn from competition analysis at the 1999 Pan pacific swimming championships?* In International Symposium on Biomechanics in Sports Applied programme, Canberra, Australia, 75-82

Maughan, R. J., Watson, J. S., & Weir, J. (1983). Strength and cross-sectional area of human skeletal muscle. *Journal of Physiology*, *338*, 37–49.

McGowan, C. J., Pyne, D. B., Thompson, K. G., Raglin, J. S., Osborne, M., & Rattray, B. (2017). Elite sprint swimming performance is enhanced by completion of additional warm-up activities. *Journal of Sports Sciences*, *35*(15), 1493–1499. https://doi.org/10.1080/02640414.2016.1223329

McGowan, C. J., Pyne, D. B., Thompson, K. G., & Rattray, B. (2015). Warm-Up Strategies for Sport and Exercise: Mechanisms and Applications. *Sports Medicine*, *45*(11), 1523–1546. https://doi.org/10.1007/s40279-015-0376-x

McGowan, C. J., Thompson, K. G., Pyne, D. B., Raglin, J. S., & Rattray, B. (2016). 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*, *19*(4), 354–358. https://doi.org/10.1016/j.jsams.2015.04.012

Miller, J. A., Hay, J. G., & Wilson, B. D. (1984). Starting techniques of elite swimmers. *Journal of Sports Sciences*, 2(3), 213-223. http://dx.doi.org/10.1080/02640418408729718

Mohr, M., Krustrup, P., Nybo, L., Nielsen, J. J., & Bangsbo, J. (2004). Muscle temperature and sprint performance during soccer matches - Beneficial effect of re-warm-up at half-time. *Scandinavian Journal of Medicine and Science in Sports*, *14*(3), 156–162. https://doi.org/10.1111/j.1600-0838.2004.00349.x

Moir, G. L. (2008). Three different methods of calculating vertical jump height from force platform data in men and women. *Measurement in Physical Education and Exercise Science*, *12*(4), 207–218. https://doi.org/10.1080/10913670802349766

Monk, T. H., Buysse, D. J., Reynolds III, C. F., Berga, S., Jarrett, D. B., Begley, A. E., & Kupfer, D. J. (1997). Circadian rhythms in human performance and mood under constant conditions Cite this paper. *Journal of Sleep Research*, *6*, 9–18.

Mooney, R., Corley, G., Godfrey, A., Osborough, C., Quinlan, L. R., & ÓLaighin, G. (2015). Application of Video-Based Methods for Competitive Swimming Analysis: A Systematic Review. *Sports and Exercise Medicine - Open Journal*, *1*(5), 133–150. https://doi.org/10.17140/SEMOJ-1-121

Moore, R. L., & Stull, J. T. (1984). Myosin light chain phosphorylation in fast and slow skeletal muscles in situ. *American Journal of Physiology - Cell Physiology*, *247*(5), 462–471. https://doi.org/10.1152/ajpcell.1984.247.5.c462

Morais, J. E., Marinho, D. A., Arellano, R., & Barbosa, T. M. (2018). Start and turn performances of elite sprinters at the 2016 European Championships in swimming. *Sports Biomechanics*, *18*(1), 100–114. https://doi.org/10.1080/14763141.2018.1435713

Navandar, A., Veiga, S., Garcia, I., & Navarro, E. (2016). Analysis of Stroke, Coordinative and Temporal Parameters in Transition from Underwater to Surface Swimming. *34th International Conference on Biomechanics in Sports*, 23–26.

Neiva, H. P., Marques, M. C., Barbosa, T. M., Izquierdo, M., Viana, J. L., & Marinho, D. A. (2017). Effects of 10 min vs. 20 min passive rest after warm-up on 100 m freestyle time-trial performance: A randomized crossover study. *Journal of Science and Medicine in Sport*, *20*(1), 81–86. https://doi.org/10.1016/j.jsams.2016.04.012

Nguyen, C., Bradshaw, E. J., Pease, D., & Wilson, C. (2014). Is starting with the feet out of the water faster in backstroke swimming? *Sports Biomechanics*, *13*(2), 154–165. https://doi.org/10.1080/14763141.2014.885072

Nicolas, A., Gauthier, A., Bessot, N., Moussay, S., & Davenne, D. (2005). Time-of-day effects on myoelectric and mechanical properties of muscle during maximal and prolonged isokinetic exercise. *Chronobiology International*, *22*(6), 997–1011. https://doi.org/10.1080/07420520500397892

Noakes, T. D. (2001). *Lore of Running* (Fourth Edi). Human Kinetics.

Noffal, G. J., & Lynn, S. K. (2012). Biomechanics of Power in Sport. *Strength and Conditioning Journal*, *34*(6), 20–24. www.nsca-scj.com

O'Leary, D. D., Hope, K., & Sale, D. G. (1997). Posttetanic potentiation of human dorsiflexors. *Journal of Applied Physiology*, *83*(6), 2131–2138. https://doi.org/10.1152/jappl.1997.83.6.2131

Owen, N. J., Watkins, J., Kilduff, L. P., Bevan, H. R., & Bennett, M. A. (2014). Development of a criterion method to determine peak mechanical power output in a countermovement jump. *Journal of Strength and Conditioning Research*, *28*(6), 1552–1558. https://doi.org/10.1519/JSC.0000000000000311

Ozeki, K., Sakurai, S., Taguchi, M., & Takise, S. (2012). Kicking the Back Plate of the Starting Block Improves Start Phase Performance in Competitive Swimming. *30th Annual Conference of Biomechanics in Sport*, 373–376.

Palmieri, R. M., Ingersoll, C. D., & Hoffman, M. A. (2004). The Hoffmann reflex: Methodologic considerations and applications for use in sports medicine and athletic training research. *Journal of Athletic Training*, *39*(3), 268–277.

Perez-Gomez, J., Rodriguez, G. V., Ara, I., Olmedillas, H., Chavarren, J., González-Henriquez, J. J., Dorado, C., & Calbet, J. A. L. (2008). Role of muscle mass on sprint performance: Gender differences? *European Journal of Applied Physiology*, *102*(6), 685–694. https://doi.org/10.1007/s00421-007-0648-8

Picerno, P., Camomilla, V., & Capranica, L. (2011). Countermovement jump performance assessment using a wearable 3D inertial measurement unit. *Journal of Sports Sciences*, *29*(2), 139–146. https://doi.org/10.1080/02640414.2010.523089

Powers, S. K., & Howley, E. T. (2012). *Exercise Physiology* (Eighth). McGraw-Hill.

Price, M. J., & Campbell, I. G. (1997). Thermoregulatory responses of paraplegic and able-bodied athletes at rest and during prolonged upper body exercise and passive recovery. *European Journal of Applied Physiology and Occupational Physiology*, *76*(6), 552–560. https://doi.org/10.1007/s004210050289

Qaisar, R., Bhaskaran, S., & van Remmen, H. (2016). Muscle fiber type diversification during exercise and regeneration. *Free Radical Biology and Medicine*, *98*, 56–67. https://doi.org/10.1016/j.freeradbiomed.2016.03.025

Rago, V., Brito, J., Figueiredo, P., Carvalho, T., Fernandes, T., Fonseca, P., & Rebelo, A. (2018). Countermovement jump analysis using different portable devices: Implications for field testing. *Sports*, *6*(91). https://doi.org/10.3390/sports6030091

Ranatunga, K. W. (1984). The force-velocity relation of rat fast- and slow-twitch muscles examined at different temperatures. *The Journal of Physiology*, *351*(1), 517–529. https://doi.org/10.1113/jphysiol.1984.sp015260

Rantalainen, T., Gastin, P. B., Spangler, R., & Wundersitz, D. (2018). Concurrent validity and reliability of torso-worn inertial measurement unit for jump power and height estimation. *Journal of Sports Sciences*, *36*(17), 1937–1942. https://doi.org/10.1080/02640414.2018.1426974

Rassier, D. E., & MacIntosh, B. R. (2000). Coexistence of potentiation and fatigue in skeletal muscle. *Brazilian Journal of Medical and Biological Research*, *33*(5), 499–508. https://doi.org/10.1590/S0100-879X2000000500003

Requena, B., Sáez-Sáez de Villarreal, E., Gapeyeva, H., Ereline, J., García, I., & Pääsuke, M. (2011). Relationship Between Postactivation Potentiation of Knee Extensor Muscles, Sprinting and Vertical Jumping Performance in Professional Soccer Players. *Journal of Strength & Conditioning Research*, *25*(2), 367–373. http://journals.lww.com/nsca-jscr/Abstract/2007/02000/The_Effect_of_Static,Ballistic,_and_Proprioceptive.40.aspx%5Cnhttp://www.ncbi.nlm.nih.gov/pubmed/20940642$%5C$nhttp://www.researchgate.net/publication/47403924%7B_%7DValidity%7B_%7Dand%7B_%7DReliabilit

Ring, E. F. J., & Ammer, K. (2012). Infrared thermal imaging in medicine. *Physiological Measurement*, *33*, R33–R46. https://doi.org/10.1088/0967-3334/33/3/R33

Rodriguez, F. A., & Mader, A. (2010). Energy Systems in Swimming. In L. Seifert, Chollet D, & Mujika I (Eds.), *World Book of Swimming: From Science to Performance*. Nova Science Publishers, Inc.

Ross, A., Leveritt, M., & Riek, S. (2001). Neural influences on sprint running training adaptations and acute responses. *Sports Medicine*, *31*(6), 409–425. https://doi.org/10.2165/00007256-200131060-00002

Ruschel, C., Araujo, L., Pereira, S. M., & Roesler, H. (2007). Kinematical Analysis of the Swimming Start: Block , Flight and Underwater Phases. *XXV ISBS Symposium*, 385–388.

Russell, A. P., Feilchenfeldt, J., Schreiber, S., Praz, M., Crettenand, A., Gobelet, C., Meier, C. A., Bell, D. R., Kralli, A., Giacobino, J., & Deriaz, O. (2003). Endurance Training in Humans Leads to Fiber Type-Specific Increases in Levels of Peroxisome Proliferator-Activated Receptor-γ Coactivator-1 and Peroxisome Proliferator-Activated Receptor-α in Skeletal Muscle. *Diabetes*, *52*(12), 2874–2881.

Safran, M. R., Seaber, A. v., & Garrett, W. E. (1989). Warm-Up and Muscular Injury Prevention An Update. *Sports Medicine*, *8*(4), 239–249. https://doi.org/10.2165/00007256-198908040-00004

Sale, D. (2002). Postactivation potentiation: Role in Human Performance. *Exercise and Sport Science Reviews*, *30*(3), 138–143. https://doi.org/10.1136/bjsm.2002.003392

Sale, D. (2004). Postactivation potentiation: Role in performance. *British Journal of Sports Medicine*, *38*(7), 386–387. https://doi.org/10.1136/bjsm.2002.003392

Sammoud, S., Negra, Y., Chaabene, H., Bouguezzi, R., Moran, J., & Granacher, U. (2019). Effects of Plyometric Jump Training on Jumping and Swimming Performances in Prepubertal Male Swimmers. *Journal of Sports Science and Medicine*, *18*, 805–811. http://www.jssm.org

Santavy, I. (1986). Newton's First Law. *European Journal of Physics*, *7*, 132–133.

Sargeant, A. J. (1987). Effect of muscle temperature on leg extension force and short-term power output in humans. *European Journal of Applied Physiology and Occupational Physiology*, *56*(6), 693–698. https://doi.org/10.1007/BF00424812

Sarramian, V. G., Turner, A. N., & Greenhalgh, A. K. (2015). Effect of Postactivation Potentiation on Fifty-Meter Freestyle in National Swimmers. *Journal of Strength and Conditioning Research*, *29*(4), 1003–1009.

Seifert, L., Vantorre, J., & Didier, C. (2007). Biomechanical analysis of the breaststroke start. *International Journal of Sports Medicine*, *28*, 1–7. https://doi.org/10.1055/s-2007-965005

Seitz, L. B., de Villarreal, E., & Haff, G. G. (2014). The Temporal Profile of Postactivation Potentiation Is Related to Strength Level. *Journal of Strength & Conditioning Research*, *28*(3), 706–715.

Seitz, L. B., Mina, M. A., & Haff, G. G. (2017). A sled push stimulus potentiates subsequent 20-m sprint performance. *Journal of Science and Medicine in Sport*, *20*(8), 781–785. https://doi.org/10.1016/j.jsams.2016.12.074

Shaffer, F., Combatalade, D., & Peper, E. (2016). A Guide to Cleaner Skin Temperature Recordings and More Versatile Use of Your Thermistor. *Biofeedback*, *44*(3), 168–176. https://doi.org/10.5298/1081-5937-44.3.06

Shellock, F. G. (1983). Physiological benefits of warm-up. *The Physician and Sportsmedicine*, *11*(10), 134–139. https://doi.org/10.1080/00913847.1983.11708664

Sinistaj, S., Burhardt, D., Carradori, S., Taylor, W. R., & Lorenzetti, S. (2015). Kinetic and kinematic analysis of the backstroke start. *33 International Conference of Biomechanics in Sports*, 808–811.

Slawson, S. (2010). *A Novel Monitoring System For The Training Of Elite Swimmers*. https://dspace.lboro.ac.uk/2134/6292

Slawson, S., Conway, P. P., Cossor, J., Chakravorti, N., & West, A. A. (2013). The categorisation of swimming start performance with reference to force generation on the main block and footrest components of the Omega OSB11 start blocks. *Journal of Sports Sciences*, *31*(5), 468–478. https://doi.org/10.1080/02640414.2012.736631

Slawson, S. E., Conway, P. P., Cossor, J., Chakravorti, N., Le-Sage, T., & West, A. A. (2011). The effect of start block configuration and swimmer kinematics on starting performance in elite swimmers using the Omega OSB11 block. *Procedia Engineering*, *13*, 141–147. https://doi.org/10.1016/j.proeng.2011.05.064

Smith, J. C., & Fry, A. C. (2007). Effects of a ten-second maximum voluntary contraction on regulatory myosin light-chain phosphorylation and dynamic performance measures. *Journal of Strength and Conditioning Research*, *21*(1), 73–76. https://doi.org/10.1519/00124278-200702000-00014

Souissi, N., Gauthier, A., Sesboüé, B., Larue, J., & Davenne, D. (2004). Circadian Rhythms in Two Types of Anaerobic Cycle Leg Exercise: Force-Velocity and 30-s Wingate Tests. *International Journal of Sports Medicine*, *25*(1), 14–19. https://doi.org/10.1055/s-2003-45226

Sousa, E., Vardasca, R., Teixeira, S., Seixas, A., Mendes, J., & Costa-Ferreira, A. (2017). A review on the application of medical infrared thermal imaging in hands. *Infrared Physics and Technology*, *85*, 315–323. https://doi.org/10.1016/j.infrared.2017.07.020

Stephens, J., Bostjancic, M., & Koskulitz, T. (2019). A Study on Parallax Error in Video Analysis. *The Physics Teacher*, *57*(3), 193–195. https://doi.org/10.1119/1.5092485

Stienen, G. J. M., Kiers, J. L., Bottinelli, R., & Reggiani, C. (1996). Myofibrillar ATPase activity in skinned human skeletal muscle fibres: Fibre type and temperature dependence. *Journal of Physiology*, *493*(2), 299–307. https://doi.org/10.1113/jphysiol.1996.sp021384

Sygulla, K. S., & Fountaine, C. J. (2014). Acute Post-Activation Potentiation Effects in NCAA Division II Female Athletes. *International Journal of Exercise Science*, *7*(3), 212–219. http://www.ncbi.nlm.nih.gov/pubmed/27182405%0Ahttp://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=PMC4831861

Takagi, H., & Sanders, R. (2000). Hydrodynamics makes a splash. *Physics World*, *13*(9), 39–43. https://doi.org/10.1088/2058-7058/13/9/30

Takeda, T., Itoi, O., Takagi, H., & Tsubakimoto, S. (2014). Kinematic analysis of the backstroke start: Differences between backstroke specialists and non-specialists. *Journal of Sports Sciences*, *32*(7), 635–641. https://doi.org/10.1080/02640414.2013.845678

Takeda, T., Takagi, H., & Tsubakimoto, S. (2012). Effect of inclination and position of new swimming starting block's back plate on track-start performance. *Sports Biomechanics*, *11*(3), 370–381. https://doi.org/10.1080/14763141.2011.637122

Thapa, R. K., Kumar, A., Kumar, G., & Narvariya, P. (2020). A combination of ballistic exercises with slow and fast stretch-shortening cycle induces post-activation performance enhancement. *Trends in Sport Sciences, 27*(4), 203–211. https://doi.org/10.23829/TSS.2020.27.4-3

Thng, S., Pearson, S., Rathbone, E., & Keogh, J. W. L. (2020). The prediction of swim start performance based on squat jump force-time characteristics. *PeerJ, 8*, e9208. https://doi.org/10.7717/peerj.9208

Tillin, N. A., & Bishop, D. (2009). Factors modulating post-activation potentiation and its effect on performance of subsequent explosive activities. *Sports Medicine*, *39*(2), 147–166. https://doi.org/10.2165/00007256-200939020-00004

Toft Nielsen, E., Jørgensen, P. B., Mechlenburg, I., & Sørensen, H. (2019). Validation of an inertial measurement unit to determine countermovement jump height. *Asia-Pacific Journal of Sports Medicine, Arthroscopy, Rehabilitation and Technology*, *16*, 8–13. https://doi.org/10.1016/j.asmart.2018.09.002

Tor, E., Pease, D., & Ball, K. (2015a). Do Swimmers Always Perform Better Using their Preferred Technique? In F. Colloud, M. Domalain, & T. Monnet (Eds.), *33rd International Conference on Biomechanics in Sports* (pp. 1263–1266).

Tor, E., Pease, D., & Ball, K. A. (2014). Characteristics of an elite swimming start Swimming Competition Analysis View project Swim Start Biomechanics View project. *Conference: Biomechanics and Medicine in Swimming*. https://doi.org/10.13140/2.1.2350.2087

Tor, E., Pease, D. L., & Ball, K. A. (2015b). How does drag affect the underwater phase of a swimming start? *Journal of Applied Biomechanics*, *31*(1), 8–12. https://doi.org/10.1123/JAB.2014-0081

Tor, E., Pease, D. L., & Ball, K. A. (2015c). Key parameters of the swimming start and their relationship to start performance. *Journal of Sports Sciences*, *33*(13), 1313–1321. https://doi.org/10.1080/02640414.2014.990486

Tor, E., Pease, D. L., & Ball, K. A. (2015d). Comparing three underwater trajectories of the swimming start. *Journal of Science and Medicine in Sport*, *18*(6), 725–729. https://doi.org/10.1016/j.jsams.2014.10.005

Toussaint, H. M., & Beek, P. J. (1992). Biomechanics of competitive front crawl swimming. *Sports Medicine*, *13*(1), 8–24.

Turner, A. N., Comfort, P., McMahon, J., Bishop, C., Chavda, S., Read, P., Mundy, P., & Lake, J. (2020). Developing Powerful Athletes, Part 1: Mechanical Underpinnings. *Strength and Conditioning Journal*, *42*(3), 30–39. www.nsca-scj.com

Vandervoot, A. A., & McComas, A. J. (1983). A Comparison of the Contractile Properties of the Human Gastrocnemius and Soleus Muscles. *European Journal of Applied Physiology and Occupational Physiology*, *51*, 435–440.

van Marken Lichtenbelt, W. D., Daanen, H. A. M., Wouters, L., Fronczek, R., Raymann, R. J. E. M., Severens, N. M. W., & Van Someren, E. J. W. (2006). Evaluation of wireless determination of skin temperature using iButtons. *Physiology and Behavior*, *88*, 489–497. https://doi.org/10.1016/j.physbeh.2006.04.026

Vantorre, J., Chollet, D., & Seifert, L. (2014). Biomechanical Analysis of the Swim-Start: A Review. *Journal of Sports Science and Medicine*, 13, 223–231.

Vantorre, J., Seifert, L., Fernandes, R. J., Vilas-Boas, J. P., & Chollet, D. (2010). Biomechanical Influence of Start Technique Preference for Elite Track Starters in Front Crawl. *The Open Sports Sciences Journal*, *3*, 137–139. https://doi.org/10.2174/1875399x01003010137

Veiga, S., Cala, A., Mallo, J., & Navarro, E. (2013). A new procedure for race analysis in swimming based on individual distance measurements. *Journal of Sports Science*, *31*(2), 159–165. https://doi.org/10.1080/02640414.2012.723130

Vingren, J. L., Kraemer, W. J., Ratamess, N. A., Anderson, J. M., Volek, J. S., & Maresh, C. M. (2010). Testosterone Physiology in Resistance Exercise and Training. *Sports Medicine*, *40*(12), 1037–1053. https://doi.org/10.2165/11536910-000000000-00000

von Loebbecke, A., Mittal, R., Fish, F., & Mark, R. (2009). Propulsive efficiency of the underwater dolphin kick in humans. *Journal of Biomechanical Engineering*, *131*(5), 1–4. https://doi.org/10.1115/1.3116150

Wakeling, J. M., Uehli, K., & Rozitis, A. I. (2006). Muscle fibre recruitment can respond to the mechanics of the muscle contraction. *Journal of the Royal Society Interface*, *3*(9), 533–544. https://doi.org/10.1098/rsif.2006.0113

Weber, K. R., Brown, L. E., Coburn, J. W., & Zinder, S. M. (2008). Acute effects of heavy-load squats on consecutive squat jump performance. *Journal of Strength and Conditioning Research*, *22*(3), 726–730. https://doi.org/10.1519/JSC.0b013e3181660899

Welcher, R. L., Hinrichs, R. N., & George, T. R. (2008). Front- or rear-weighted track start or grab start: Which is the best for female swimmers? *Sports Biomechanics*, *7*(1), 100–113. https://doi.org/10.1080/14763140701683247

West, D. J., Cook, C. J., Beaven, M. C., & Kilduff, L. P. (2009). The Influence of the Time of Day on Core Temperature and Lower Body Power Output in Elite Rugby Union Sevens Players. *Journal of Strength and Conditioning Research / National Strength & Conditioning Association*, *16*(4), 1042–1049. https://doi.org/10.1519/R-21636.1

West, D. J., Dietzig, B. M., Bracken, R. M., Cunningham, D. J., Crewther, B. T., Cook, C. J., & Kilduff, L. P. (2013). Influence of post-warm-up recovery time on swim performance in international swimmers. *Journal of Science and Medicine in Sport*, *16*(2), 172–176. https://doi.org/10.1016/j.jsams.2012.06.002

West, D. J., Owen, N. J., Cunningham, D. J., Cook, C. J., & Kilduff, L. P. (2011). Strength and Power Predictors of Swimming Starts in International Sprint Swimmers. *The Journal of Strength and Conditioning Research*, *25*(4), 950–955. https://doi.org/10.1519/JSC.0b013e3181c8656f

West, D. J., Russell, M., Bracken, R. M., Cook, C. J., Giroud, T., & Kilduff, L. P. (2016). Post-warmup strategies to maintain body temperature and physical performance in professional rugby union players. *Journal of Sports Sciences*, *34*(2), 110–115. https://doi.org/10.1080/02640414.2015.1040825

Wilcox, J., Larson, R., Brochu, K. M., & Faigenbaum, A. D. (2006). Acute explosive-force movements enhance bench-press performance in athletic men. *International Journal of Sports Physiology and Performance*, *1*(3), 261–269. https://doi.org/10.1123/ijspp.1.3.261

Wilkins, E. L., & Havenith, G. (2017). External heating garments used post-warm-up improve upper body power and elite sprint swimming performance. *Journal of Sports Engineering and Technology*, *231*(2), 91–101. https://doi.org/10.1177/1754337116650322

Williams, A. M., & Hodges, N. J. (2005). Practice, instruction and skill acquisition in soccer: Challenging tradition. *Journal of Sports Sciences*, *23*(6), 637–650. https://doi.org/10.1080/02640410400021328

Williams, N. (2012). *The effect of passive heat maintenance on elite swimming performance*. Swansea University.

Wilson, J. M., Duncan, N. M., Marin, P. J., Brown, L. E., Loenneke, J. P., Wilson, S. M. C., Jo, E., Lowery, R. P., & Ugrinowitsch, C. (2013). Meta-Analysis of Postactivation Potentiation and Power: Effects of Conditioning Activity, Volume, Gender, Rest Periods, and Training Status. *Journal of Strength & Conditioning Research*, *27*(3), 854–859.

Xenofondos, A., Bassa, E., Vrabas, I. S., Kotzamanidis, C., & Paikas, D. A. (2017). Muscle Twitch Torque During Two Different in Volume Isometric Exercise Protocols Fatigue Effects on Postactivation Potentiation. *Journal of Strength & Conditioning Research*, *32*(2), 578–586.

Xenofondos, A., Laparidis, K., Kyranoudis, A., Galazoulas, C. H., Bassa, E., & Kotzamanidis, C. (2010). Post-activation potentiation: factors affecting it and the effect on performance. *Journal of Physical Education and Sport*, *28*(3), 32–38.

Yamakawa, K. K., Shimojo, H., Takagi, H., Tsubakimoto, S., & Sengoku, Y. (2017). Effect of increased kick frequency on propelling efficiency and muscular co-activation during underwater dolphin kick. *Human Movement Science*, *54*(August 2016), 276–286. https://doi.org/10.1016/j.humov.2017.06.002

Young, Warren. B., Jenner, A., & Griffiths, K. (1998). Acute enhancement of power performance from heavy load squats. *Journal of Strength & Conditioning Research*, *12*(2), 82–84.

Zatsiorsky, V. M. (1997). On Muscle and Joint Viscosity. *Motor Control*, *1*(4), 299–309. https://doi.org/10.1123/mcj.1.4.299

Zochowski, T., Johnson, E., & Sleivert, G. G. (2007). Effects of varying post-warm-up recovery time on 200-m time-trial swim performance. *International Journal of Sports Physiology and Performance*, *2*(2), 201–211. https://doi.org/10.1123/ijspp.2.2.201