Muscle Fiber Typology is Associated with Determinants of Performance in Elite-Level Swimmers

By

Adam J. Mallett

BSc (Hons.) MScRes

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School of Allied Health
Griffith University
Gold Coast Campus
Queensland, Australia

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Declaration of Originality

This thesis is submitted to Griffith University in fulfilment of requirements for a Doctor of Philosophy

“This work has not previously been submitted for a degree or diploma in any university. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made in the thesis itself.”

........................................................................................................... 9th October 2020

Adam James Mallett .................................. Date

Candidate
Preface

Where to start?! What to say?! A preface will normally say it has been a journey, a rollercoaster, a challenge, but I’m not sure that there are actually words that can describe what a PhD does! Emotions are felt, and can’t easily be put into words, which is probably why writing this section is the hardest of them all! Having hung up the togs competitively in 2016, I had the pleasure of experiencing ‘normal life’ for all of 6 months, before embarking on life’s’ next challenge… a PhD.

The world of swimming has been a consistency like no other in my life, from 4 years old I have been indoctrinated with water. Throughout my childhood going to the pool and watching David Attenborough’s shows on the underwater world developed a passion that has only grown stronger and stronger over the years. Accompany this with an inquisitive mind, my life was only heading in one direction!

At 16 years old I was offered the opportunity to move to the other side of the world to pursue my swimming career; pound for pound the Australian’s are the world’s greatest swimming nation, who better to compete against day in day out, it was a no brainer! 10 years later the togs were hung, and 4 days later I was back on pool deck coaching and had accepted an offer to research swimming as well! I was going to get the full 360 view of the swimming world, in the water, on the deck and in the data. What really defines swimming performance? Surely I could help!

This thesis is written in the loving memory of Grandad - always a support and never to be forgotten.
Investigative Studies

Study 1 (Chapter 2):

‘The age, height, and body mass of Olympic swimmers: A 50-year review and update.’

This review article that explores peer-reviewed literature on the age, height and body mass of Olympic and world-class swimmers, and also adds original data on these determinants with data from the 1968, 1992, and 2016 Olympic Games.

Study 2 (Chapter 3):

‘Muscle fiber typology and its association with start and turn performance in elite swimmers.’

Study 2 investigates the association between muscle fiber typology and determinants of racing performance in world-class and elite swimmers. This study employs a non-invasive protocol for the determination of muscle fiber typology and specifically determines the association of this physical characteristic with the start and turn performance of elite swimmers during competition.

Study 3 (Chapter 4):

‘The influence of muscle fiber typology on the pacing strategy of 200-m freestyle swimmers.’

The third study utilises the same non-invasive protocol to determine muscle fiber typology in world-class and elite swimmers, and then explores its relationship with the pacing strategies used by world-class and elite 200-m freestyle swimmers.
Study 4 (Chapter 5):

‘Adaptations to concentrated volume overload training in elite swimmers: Does muscle fiber typology play a role?’

Whilst studies two and three explored the influence muscle fiber typology had on the determinants of racing performance, study four investigated the performance responses to training overload, and related these responses to muscle fiber typology in order to determine if this physical characteristic is a moderating factor.
Acknowledgements

There are too many people to thank for the incredible support and opportunities throughout the last three and a half years, but hopefully everyone is covered.

To Clare, Phil and Wim, thank you for allowing me to become a part of such a worldwide and innovative project, it has opened my eyes to see how these kind of collaborations are necessary for research to become as effective as possible at the grass-roots level. Phil, your patience with improving my writing is sincerely appreciated.

Katie, Lachie, Simon, Emily, Lisa, Gyan, Allan, Jeff, Brie, your willingness to lend a hand at any time, or get your ear chewed off when it was one of those days will never be forgotten, the return offer is always there should you ever need it.

TSS you have been the centre of my Australian adventure, this PhD opportunity would not have occurred without you; I thank everyone for becoming such an influential and supportive part of my life over the last 13 years.

Liam, David, Ben, Danny, Janice, thank you, your open ears, moral support and continual presence has gotten me through this, I will be forever grateful, you are considered family.

Tom, your guidance and mentorship throughout the last 4 years has been more important than I initially realised. Your outside the box thinking, in such a thorough and pure fashion is refreshing. I am truly grateful and only hope that we can collaborate more in the future.

Chris, I don’t really know what to say, thank you doesn’t seem enough. Your willingness to go above and beyond, at any time, has only helped me to realise that
anything is possible if you truly believe and are willing to work hard. I cannot thank you enough.

Mum, Dad and Ash, you’ve allowed me to be free. You let me off on an adventure to the other side of the world when I was just 16, little did any of us know that I would not return. I am forever thankful that you support me every step of the way, and have always allowed me to follow my dreams.
Summary

The determinants of sporting performance are important when attempting to identify and influence world-class and elite sporting results. This is highly relevant in swimming, as the complexities the aquatic environment creates for swimmers could mean that the determining characteristics could be of greater influence to their overall performance. However, the physiological determinants of world-class and elite swimming performance are underexplored in scientific research because of the complexity the water creates. For example, a protocol to measure gas exchange during swimming has not been developed with the level of accuracy, which can be obtained from a running on a treadmill or cycling on an ergometer. Consequently, research in swimming has primarily focused on the determinants that can be measured or monitored on land, opposed to in the water. In light of the restrictions or undeveloped methodology in swimming, the aim of this thesis was to explore a potential physical characteristic that could be deterministic of swimming performance – muscle fiber typology.

In study 1, peer-reviewed literature that described the age, height and body mass of Olympic level swimmers was reviewed to better understand whether these characteristics were deterministic to performance at the highest level of swimming competition, and whether these are still valuable to assess. In addition to this collation of literature, this study also assembled original data on the age, height and body mass of freestyle swimmers at the 1968, 1992 and 2016 Olympic Games. Data from all 4 swimming strokes was also collected from the 2016 Olympic Games in order to describe the current state of these characteristics in world-class swimmers. This assemblage of data highlighted that both female and male FR swimmers were taller at the 1992 (175.0 ± 6.1 cm and 189.0 ± 6.7 cm) Olympic Games compared
to FR swimmers at the 1968 (168.2 ± 4.1 cm and 180.9 ± 5.8 cm) Olympic Games and there was no further significant changes in height from 1992 to 2016 (173.2 ± 6.5 cm and 189.0 ± 6.3 cm). Body mass followed the same trend with both females and males increasing from 1968 to 1992 (58.8 ± 0.8 kg to 63.6 ± 0.9 kg; 76.0 ± 0.8 kg to 80.5 ± 0.9 kg respectively) and then also plateauing from 1992 to 2016 (2016: 64.6 ± 0.7 kg and 80.5 ± 0.8 kg). However, the age of female and males differed; female swimmers continually increased in age from 1968 to 1992 to 2016 (16.7 ± 2.1, 19.7 ± 2.4 to 22.7 yr) whereas the male swimmers’ age followed a similar trend and plateau to height and body mass (20.1 ± 2.4, 21.8 ± 2.9 to 22.6 ± 2.8 yr). The plateau in age (males only), height and body mass, suggested that these characteristics may be exhausted in their ability to be deterministic of swimming performance at the world-class and elite level. Indeed, these characteristics could not differentiate between truly world-class swimmers and their elite counterparts. Therefore, it was concluded that new or alternative physical determinants of performance warranted exploration in order to provide new avenues for swimming coaches and applied sports scientists to progress the training and talent identification process of elite swimmers.

With new determinants of swimming performance needing to be explored, and a novel non-invasive method of determining muscle fiber typology recently developed, the consequent studies directed their focus on the influence muscle fiber typology has on the key performance determinants. The non-invasive estimation of muscle fiber typology is determined from the measurement of muscle carnosine which is a stable intramuscular metabolite that is two-fold higher in concentration in type II muscle fibers. Study two and three specifically investigated the influence muscle fiber typology has on race specific determinants of performance. Study 2
recruited 46 world-class swimmers, determined their muscle fiber typology using the non-invasive protocol and investigated the influence muscle fiber typology had on the start and turn segments of career best competitive performance. The results suggested that muscle fiber typology was not found to be influential in start time, turn time or turn out time when swimmers competing in all strokes and events were collectively analysed. However, when the start, turn and turn out time were found to be significantly faster in 100-m events compared to events greater than 200-m. It was then discovered that those swimmers who possessed a greater estimated proportion of type II muscle fibers had a quicker start time to 15 m (p = 0.02), whereas turn time and turn out time were not found to be significantly influenced by muscle fiber typology (p = 0.12 and 0.12 respectively). From a practical perspective this was highlighted in the 100-m freestyle, whereby swimmers with a greater estimated proportion of type II muscle fibers were 0.25 s (CI 90%, 0.17 s) faster to 15 m.

Study 3 investigated how the pacing strategy of 200-m freestyle swimmers was influenced by muscle fiber typology. After the recruitment of 25 world-class 200-m freestyle swimmers, they too had their muscle fiber typology estimated with the non-invasive methodology, and it was determined that swimmers with divergent muscle fiber typology did pace the 200-m freestyle differently. Swimmers with greater estimated proportions of type II muscle fibers spent a significantly larger percentage of overall race time on the third lap compared to those swimmers with greater estimated proportions of type I fibers (p = 0.02). It was highlight that this difference could be because of the energetic demands of this lap may be preferential for swimmers with greater proportions of type I muscle fibers given that this lap has the greatest contribution from aerobic energy metabolism. Interestingly, the
overall performance times did not differ when swimmers with greater estimated proportions of type II fibers were compared to those with greater proportions of type I fibers. In contrast, there were substantial difference in the relative percentage of time spent on each lap. It was concluded that muscle fiber typology is influential in the pacing strategy of swimmers competing in the 200-m freestyle event, and consequently the relationship between pacing strategy of other events should be explored in relation to muscle fiber typology.

Study 3 highlighted that the marked differences in pacing strategy could be due to the physiological characteristics of different muscle fibers. Therefore, it seemed warranted to explore how different physiological and performance determinants of overall swimming performance are influenced by training volume and whether the muscle fiber typology is a moderating factor in the responses to training volume. Since physiological tests in swimming are under established, the final study implemented a number of swimming performance tests to determine their relationship with muscle fiber typology. Study 4 recruited 10 elite swimmers for a 7 wk training intervention study that increased the training volume by ~ 30% for 3 wk. The key finding from this study was that 200-m time trial performance was significantly impaired following the period of increased volume training (p < 0.01), and the change in time trial performance from pre- to post high volume training was positively associated with muscle fiber typology (r = 0.697, p =0.025). That is, swimmers with a greater estimated proportion of type II muscle fibers had larger decrements in performance.

The findings of this thesis demonstrate that the muscle fiber typology of world-class and elite swimmers is deterministic of swimming performance. It was initially
found that previously researched determinants of performance (i.e., age, height and body mass) had started to plateau and may be less relevant for predicting performance, and therefore the exploration of a new determinant of performance is warranted. In light of this, it was found that the novel non-invasive technique to determine muscle fiber typology with the use of magnetic resonance spectroscopy is user friendly in the perception of world-class swimmers and coaches and therefore can be used to study such populations. The muscle fiber typology of swimmers influences determinants of race performance, including the start performance of swimmers in 100-m events and the pacing strategy of swimmers competing in the 200-m freestyle event. The results not only highlight the direct impact muscle fiber typology has on race performance, but also the necessity to individualise racing and training performance in relation to a swimmers muscle fiber typology. Muscle fiber typology has been deemed a moderating factor in how swimmers respond to training overload, with swimmers of greater proportions of type II muscle fiber having greater decrements in performance following high volume training, when compared to those swimmers who possess greater estimated proportions of type I fibers. Collectively, the findings from this group of studies show that muscle fiber typology is influential in the racing and performance determinants of swimming. This research is multi-faceted in that it adds to the knowledge of muscle fiber typology; it’s interaction with swimming performance, and also offers suggestions for how this research can be further explored in the swimming world. Furthermore, this body of work has determined that the non-invasive measurement of muscle fiber typology is embraced by world-class coaches and swimmers.
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Chapter 1: Review of the Literature
1.1 Introduction

Maximizing performance at the highest level of competitive sport is an extremely complex process. It is the finely tuned collation of physical, physiological, psychological and technical factors that enables athletes to maximize their performance and compete with the world’s best athletes in a given sport. This is no different for swimming performance at the highest level. In fact, the aquatic environment creates greater complexities compared to those sports that are performed on land. For example, the low mechanical efficiency caused by the high resistive forces in water and the fact that swimmers are more isolated from their opponents compared to other racing events may mean that particular characteristics have a greater influence on performance. Despite this premise, it remains unclear which factors systematically discern between world-class swimmers and their elite counterparts. The complex swimming environment no doubt contributes to this, whereas research in other sports such as running, cycling and rowing allow for reliable and accurate measures of physical and physiological determinants through laboratory-based assessments. However, it is impossible to recreate swimming specific movements in a controlled laboratory setting due to the adverse aquatic environment, meaning the scientific research unpinning swimming performance is somewhat lacking compared to land-based sport. Therefore, assessments of swimming performance have primarily focused on swimming tests in the pool and/or indirect measurements of physical performance out of the pool.

Whilst it is important to be able to identify and measure the determinants of swimming performance, in order to improve training protocols and identify talent, unless the studied sample is of a world-class calibre the results may not be reflective of the determinants of world-class performance. Despite the necessity to use world-
class populations, research incorporating this calibre of swimmer is scarce due to their availability to partake in research projects, and the disruptions which are caused to training schedules. In light of this, if physical characteristics can be determined efficiently and non-invasively, this body of research in relation to swimming performance can develop dramatically with technological advancements.

Improving performance and identifying talent is the goal of all sports, swimming is no different in this respect. However, the determinants of performance, and consequently identifying talent are somewhat underexplored in the literature. An example which highlights the diversity in both talent and performance, is at the 2016 Olympic Games. There was a 3-way tie for the silver medal in the men’s 100-m butterfly and when all 3 of the competitors stood on the 2nd place rostrum, they all stood taller than the swimmer who was stood on the middle of the dais collecting the gold medal. The greater height of the 2nd place finishers was not advantageous over the gold medal winner. Whilst height is only one example of a physical characteristic that appeared to vary dramatically across the top 4 finishing swimmers in an Olympic final, it is possible that there are other characteristics that are deterministic for performance which helped the gold medal winner to 1st position. Whether that be a trait or characteristic that is deterministic for swimming performance or the ability to adapt favorably to training, the identification of such a characteristic is extremely important to performance.

One factor that may underpin different characteristics of swimming performance, as well as explain some degree of the variability in the responses to training is the variability in the ratio of type I (slow-twitch) and type II (fast-twitch) muscle fibers.
Type I muscle fibers produce force relatively slowly\textsuperscript{1} but have superior fatigue resistance compared to type II fibers.\textsuperscript{2,3} Type II fibers can produce more power,\textsuperscript{1} but are thought to have greater fatigability than type I fibers.\textsuperscript{4} It is conceivable that variation in the proportion of these fibers that an athlete has, may dictate how this athlete executes a race, responds to training from an acute recovery time course perspective, as well as the long-term chronic adaptations to a given training block. In addition, muscle fiber typology may underpin performance in different aspects of swimming competition (i.e., starts and turns, pacing strategy and/or stroke rate). As such, variation in muscle fiber typology might be important for specializing in different swimming events and in individualizing training and recovery cycles. The focus of this thesis is to explore muscle fiber typology and its relationship with swimming performance.

1.1.1 Competitive Swimming

Swimming is one of the mainstay sports at the Olympic level of competition, and as with any competitive environment, the identification, optimization and scientific understanding of factors underpinning performance is critical to achieving the best possible result. Swimming is a sport that is divided into different styles (known as strokes), Freestyle (FR), Backstroke (BK), Butterfly (FL) and Breaststroke (BR), each requiring a different and specific technique to enable locomotion through water. In a swimming competition, competitors compete in races against others of the same gender, swimming with the same stroke and over the same distance. Each stroke can be swum over a variety of distances: 50 m, 100 m, and 200 m, whilst FR is also contested over a greater variety of distances, including 400 m, 800 m and 1500 m; and since 2008 an open water event (10,000 m) has also been included at the Olympic Games. Additionally, there are also two events in which the four
strokes are swum collectively to form an individual medley (IM), i.e. 200 m and 400 m IM. A quarter of the total distance is swum with each stroke in the sequential order of FL, BK, BR and FR. The complete range of strokes and distances offers fourteen different individual events per gender at an Olympic level, and seventeen at a World Championship level of competition (50-m BK, BR, and Fly are not included at the Olympic Games). This diversity in events creates many complexities when attempting to compare, analyse and understand the world-class swimming population from a scientific perspective, due to the necessity to have extremely large population sizes. Ultimately, each swimmers’ potential to complete an event in a quickest possible time is dependent on their ability to produce propulsive forces and reduce the amount of drag force though the technical specialities and requirements. However, the physical characteristics unpinning the optimisation of these propulsion-generating motions are currently under-researched.

1.1.2 Australian Swimming History

Swimming is Australia’s most successful sport at the Summer Olympic Games, whereby swimmers having won 58 of Australia’s 143 total Olympic Gold medals. The 58 Gold medals won in swimming is the second highest tally in the world, behind only the United States of America which have won 217. Australia sent 34 swimmers to the most recent Olympic Games, which were held in 2016 in Rio de Janeiro, Brazil, and they won 10 medals (3 Gold, 4 Silver, and 3 Bronze), finishing 2nd behind the United States of America in the medal table. Notably, this placed Australia ahead of more populous countries such as Great Britain, China, Russia and Japan. With Australia seeking to close the gap to the United States of America, and maintain its swimming prowess over other countries, it is imperative that coaches, sports scientists and researchers continually look for ways to enhance
swimming performance and identify talent at a young age. The opportunities for doing this have developed considerably in the 21st century with advancements in technology and sport science support, which in turn, have helped to increase the knowledge and understanding of swimming to a level far beyond that which existed in the mid- to late 20th century. If Australia is to maintain its status as a top swimming nation, then the utilisation of these technological advancements is crucial for identifying and maximising performance in world-class swimmers.

1.1.3 Defining World-Class and Elite Swimmers

Whilst sports scientists, researchers and coaches have always been intrigued with measuring the physical characteristics of world-class athletes to explain, in part, how they are superior to their competitor counterparts and the general population; there has been limited conclusive research in this area with regards to the world-class swimming populations. This is partially due to their tight training schedules, necessity to allow adequate recovery time and competition programs. In addition to the accessibility to athletes, the terminology used to describe such populations within sports science literature does not administer itself well for researchers to be easily able to identify studies involving such athletes. For example, since 2019, the term ‘elite athlete’ was used in the description of research populations which consisted of: i. Boston marathon runners (no race times presented),

5 ii. “Physical performance defined by the maximum VO2 or muscle strength (rated as excellent),”

6 and, iii. Athletes participating in international competition.7 The large variation in descriptors of elite athletes makes it hard to draw comparisons between studies that use high calibre performers, and highlights the necessity to have collective descriptors. Specifically in swimming, the definition of these high calibre performers has been described as: i. ‘Best’ (top-12 placing) versus ‘Rest’ (outside
top-12 placings) swimmers at the 1991 World Championships, and ii. ‘finalist’ (participation in the ‘final’ race) versus ‘non-finalist’ (participation in heat and semi-final races) swimmer at the 1976 Olympic Games. Study 1 (chapter 2) explores this definition further and presents a new method of describing such swimmers. If research is to continue to help maximise the performance of athletes, more clarity in the terminology of world-class and elite athletes is required so that comparisons in physical and physiological characteristics between athletes of different standards can be made.

1.1.4 Differentiating between World-Class and Elite Swimmers

It is probable that there is a wide range of physiological, physical and technique factors that are important for competitive swimming performance. Previous research identified that the sum of skinfolds and speed at the end of a 200 m step test were the best predictors of swimming performance in females, while stroke rate at a blood lactate concentration of 4 mmol·l⁻¹ and peak blood lactate concentration for male swimmers. While this study was able to demonstrate the relationship between changes in fitness test and measures of body composition and changes in competition performance in elite swimmers over several seasons, surprisingly few studies have compared these characteristics between truly world-class swimmers and their elite counterparts. One of the major reasons for this is the accessibility of truly world-class swimmers and effort and resources required to obtain such measurements. Other characteristics that have been measured more readily include the age, body mass and height, as well as other anthropometric measures, of Olympic swimmers. Despite the simplicity of these measures, they may provide insight and differentiation between world-class and elite swimmers.
1.1.5 Height and Body Mass

Two characteristics of swimming performance which are often used to describe world-class and elite population are the height and body mass. These two measurements are two of the most documented characteristics of swimmers over the past 50 years. However, there is limited research discussing the differences between swimmers competing in different events and strokes, and discussing the changes of these characteristics over time. Investigative study 1 (chapter 2) is a review article that explores how these characteristics have changed among Olympic swimmers across a 50 yr period, alongside their age. The results of this chapter highlight that these characteristics have plateaued and that the necessity to explore other physical characteristics which may be determining performance at the world-class level. One of these characteristics is the muscle fiber typology (MFT) which is the area of focus for the research in this thesis.

1.1.6 Muscle Fiber Typology

The MFT of human skeletal muscle is the degree to which the muscle is made up of type I and type II fibers, simplistically referred to as slow-twitch and fast-twitch, respectively. Type II fibers can further be sub-divided into type IIa and IIx sub-categories. These different muscle fiber types show great variation in both mechanical and physiological characteristics, which in turn define the contractile and metabolic performance of the muscle (Table 1). The maximal shortening velocity of type II muscle fibers is substantially greater than that of type I muscle fibers, contributing to the superior maximal power output these fibers can produce. Furthermore, type II fibers are characterized by a greater ATPase activity, greater creatine phosphate and glycogen content and shorter excitation times when compared to type I fibers. These characteristics are thought to be important for
movements that require a high level of muscular power output and rate of force development (e.g., jumping, throwing and sprinting).14

Historically, MFT has been determined through the use of the invasive muscle biopsy methodology and histochemical staining. This process was developed in the 1960s15 and has allowed both sport science and medicine to gain deeper understandings of the metabolic processes and biological make-up of exercising muscles. The Bergstrom needle employed for biopsies consists of two cylinders, the outer cylinder 3-5 mm in diameter with a window at the tip. As the needle penetrates the muscle, the surrounding muscle enters into the window. Pushing the smaller sharp inner needle through the outer, the segment of muscle that entered the window is cut from the muscle and stays within the inner needle until later extraction. Up to 80 mg of muscle tissue can be extracted with each penetration and typically a local anesthetic is administered around the insertion point, to nullify any pain. Once the muscle sample is extracted, chemical determination of the MFT can be completed. There are three typical methodologies, which include:

1. *Myosin ATPase Histochemical staining*. The hydrolysis rates for type II muscle fibers is 2 to 3 times faster than type I. The difference in hydrolysis rates is not directly determined by histochemical staining; however the intensity of the staining is determined by the differences in pH sensitivity of the muscle fiber.16

2. *Myosin heavy chain (MHC) isoform identification*. Different ATPase-based fibers relate to different MHC isoforms.17 These MHC isoforms are identified by immunohistochemical analysis using antimyosin antibodies.18
Each MHC having its own reaction to specific antibodies allows for the identification of type I and type II muscle fibers.

3. *Biochemical identification of metabolic enzymes.* The enzymes targeted for biochemical analysis reflect metabolic pathways that are associated with aerobic (oxidative) or anaerobic (glycolytic) metabolism. This methodology of classification determines three types of fibers as; type I oxidative, type II oxidative, and type II glycolytic, which are then correlated with type I, type IIa and type IIx fibers respectively.

Whilst the muscle biopsy method is classified as the “gold standard” in the determination of MFT, the invasive nature of this process has led to limited studies on world-class and elite athletes. In recent years, the risk of infection following the use of this method has been diminished through the improvement in medical procedures, but when world-class athletes are trying to optimize their performance through minimizing the risk of injury, illness and infection, the invasive nature of such a procedure is far from desirable for them. Other negatives of the muscle biopsy procedure include muscular damage caused by the extraction of the sample, whereby the training and competition interruptions following the procedure and the large costs of employing medical professionals and analysing the samples make this technique redundant in elite sport. An additional major disadvantage is the low test-retest reliability which may result from alterations in the depth of the muscle biopsy, the yield of fibers that are obtained and/or other sources of technical error. A valid and reliable non-invasive technique to estimate MFT would circumvent many of these limitations and allow increased application of the
learnings from classical muscle biopsy studies to talent identification and training prescription for world-class athletes.

**Table 1: Muscle fiber characteristics**

<table>
<thead>
<tr>
<th>Fiber Type</th>
<th>Type I fibers</th>
<th>Type IIa fibers</th>
<th>Type IIx fibers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contraction speed</td>
<td>Slow (90 - 140 ms)</td>
<td>Fast (50 – 100 ms)</td>
<td>Fast (50 – 100 ms)</td>
</tr>
<tr>
<td>Size of motor neuron</td>
<td>Small</td>
<td>Large</td>
<td>Large</td>
</tr>
<tr>
<td>Resistance to fatigue</td>
<td>High</td>
<td>Intermediate</td>
<td>Low</td>
</tr>
<tr>
<td>Force Production</td>
<td>Low</td>
<td>Intermediate</td>
<td>High</td>
</tr>
<tr>
<td>Number of Mitochondria</td>
<td>High</td>
<td>Intermediate</td>
<td>Low</td>
</tr>
<tr>
<td>Capillary density</td>
<td>High</td>
<td>Intermediate/Low</td>
<td>Low</td>
</tr>
<tr>
<td>Oxidative capacity</td>
<td>High</td>
<td>Intermediate/Low</td>
<td>Low</td>
</tr>
<tr>
<td>Glycolytic capacity</td>
<td>Low</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>ATPase levels</td>
<td>Low</td>
<td>Intermediate/High</td>
<td>High</td>
</tr>
<tr>
<td>Predominant use</td>
<td>Endurance activities</td>
<td>Intermediate activities (~2min)</td>
<td>Explosive activities</td>
</tr>
</tbody>
</table>
1.1.7 Muscle Fiber Typology of Elite Swimmers

The range in the proportion of type I and type II muscle fibers is relatively small in studies investigating swimmers compared to compared to track and field athletes competing across different disciplines (i.e., sprint and endurance events).\textsuperscript{25-27} For example, sprint, middle-distance and distance runners were found to have 26.0, 47.0 – 55.0 and 70.0 – 75.0% type I muscle fibers respectively.\textsuperscript{28} Whereas Gollnick et al.\textsuperscript{28} reported that the deltoid muscle of swimmers contained 74.3% ± 5.7 type I fibers, while Houston et al.\textsuperscript{29} reported a value of 57.8% type I fibers in the gastrocnemius muscle and 62.6% in the deltoid muscle of swimmers from the Waterloo swimming club (training status not provided). Costill et al.\textsuperscript{30} studied collegiate swimmers and reported 67.6% of muscle fibers to be type I in the deltoid, while Trappe et al.\textsuperscript{31} reported that 64.5% ± 6.7 type I fibers in the deltoid muscle of highly trained collegiate swimmers. Table 2 further details the published research on MFT of swimmers. Cumulatively the results from these studies suggest that swimmers have a relatively high proportion of type I fibers; however, these studies did not provide sufficient data to identify the training status of the swimmers, nor did they describe whether the swimmers were sprint or endurance orientated.\textsuperscript{28-31} The study of Gerard et al.\textsuperscript{32} was the only one to explore this distinction by attempting to identify whether there were distinguishable differences in the MFT of sprint and endurance swimmers. In this study, it was reported that male endurance swimmers had a significantly greater percentage of type I fibers in the vastus lateralis compared to middle distance and sprint swimmers (endurance: 60.4% type I fibers; middle distance: 43.8% type I fibers; sprint: 47.8% type I fibers); however there was no significant differences between the latter groups. Furthermore, there was no significant differences in the MFT of long-, middle- or sprint distance female swimmers. The reported values present far less contrast
compared to the polarity of sprint and endurance runners, whereby track sprinters have a very low proportion of type I fibers (26.0%) compared to middle distance runners (51.9%) and endurance runners (69.4%).

Whilst previous literature has provided an insight into the MFT of trained swimmers, and typically suggests that swimmers have more homogeneity in their MFT compared to sprint and endurance track and field athletes. The lack of world-class calibre swimmers in these studies has prevented definitive conclusions regarding the importance of MFT as a determinant of swimming performance.28-31 This is in part due to the lack of differentiation between a sprint and endurance swimmer is previous studies, while the influence MFT has on swimming performance and training has not been explored. While classical studies have provided some information on the MFT of swimmers, contemporary information is sparse given the invasive nature of the muscle biopsy procedure. As such, non-invasive technology would be preferential in the evaluation of MFT in world-class and elite sporting populations. More recently, such a technique has been developed with the use of proton magnetic resonance spectroscopy (1H-MRS).27
<table>
<thead>
<tr>
<th>Author</th>
<th>Title</th>
<th>Population</th>
<th>Muscle</th>
<th>% (± SD) Type I Fibers</th>
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<tr>
<td></td>
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<td>1972.28</td>
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<td>Vastus Lateralis</td>
<td>57.7 ± 9.3</td>
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<td>Deltoid, Latissimus Dorsi, Rectus Femoris</td>
<td>~72, ~64, ~62</td>
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<td>1978.33</td>
<td>in man</td>
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<td>Muscle Biopsy Research: Application of Fiber Composition to Swimming</td>
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<td>Deltoid</td>
<td>30-68</td>
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<td>Houston et al.,</td>
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<td>Deltoid</td>
<td>62.6 ± 4.8 and 62.6 ± 7.9</td>
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<td>1981.29</td>
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<td>Gastrocnemius</td>
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<td>MD 43.8 ± 2.5</td>
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<td>Fitts et al.,</td>
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<td>1991.37</td>
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<td>SD 65.5 ± 8.9</td>
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<td>Trappe et al.,</td>
<td>Effect of swim taper on whole muscle and single muscle fiber contractile</td>
<td>Male n=6</td>
<td>Deltoid</td>
<td>64.5 ± 6.7</td>
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<td>2000.31</td>
<td>properties</td>
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1.2 Magnetic Resonance Spectroscopy

Nuclear magnetic resonance (NMR) spectroscopy is a non-invasive method for identifying intramuscular metabolites and determining their biophysical characteristics. The main use of NMR in clinical settings is to non-invasively, detail magnetic resonance images (MRI) throughout the body. Typically, NMR is known as MRS to avoid erroneous associations with nuclear medicine, radioactive materials and ionising radiation.\textsuperscript{38} MRS technology is sensitive enough to detect concentrations of metabolites that are less than 10 mM, and have high flexibility within and between cells. MR spectra determine many metabolites within the human body by using a variety of nuclei, hydrogen ($^1$H), phosphorus ($^{31}$P), fluorine ($^{19}$F), carbon ($^{13}$C), sodium ($^{23}$Na). However, in biomedicine $^1$H-MRS is typically used due to the higher sensitivity of the $^1$H nucleus, the almost 100% availability of this isotope and the abundance of this nucleus within metabolites.\textsuperscript{38} It is the $^1$H nuclei in water and fats that is used in the acquisition of MR images, which means the $^1$H-MRS can be performed with relative ease using existing MR imaging systems with radio-frequency (RF) coils. Typically, the use of $^1$H-MRS is in the quantification of metabolites with small concentrations, (i.e., carnosine and creatine), however molecules of larger concentrations can also be assessed (i.e., intra and extra-cellular lipids). MR systems with higher magnetic field strengths are desirable for the quantification of the metabolic spectra; magnetic field strengths of greater than 1.5 Tesla (T) help to improve signal-to-noise ratios meaning that it is possible to build a spectra from even very small metabolites present in low concentrations. Whilst in recent years MR systems have developed to have different magnetic field strengths (i.e., 7 to 14 T), these systems are typically not used in scientific research, due to the extreme costs, technical challenges and current concerns about the biological effects on humans.
1.2.1 Magnetic Resonance Spectroscopy Methodology

The $^1$H-MRS examination starts with the attainment of anatomical MR images of the tissue or location of interest. These images are used as a guide to select the desired volume of tissue from which the spectrum is to be acquired (figure 1). Each metabolite within the body has a different resonance frequency. The concentration of metabolites is determined from the positioning of the electrons within the molecular formation: electrons held closer to the nuclei shield the reflective ability of the molecule and consequently resonate at a higher frequency. A sequence of radio frequency pulses are emitted from the RF coils into the localised tissue using a single voxel point-resolved spectroscopy sequence (PRESS). The radio frequency is emitted in a series of pulses, firstly from a 90-degree angle to the tissue and then from two 180-degree angles along each of the spatial directions, this allows for the resonance of the molecules to be received and generate a signal in

![Figure 1: Top: 3-dimensional voxel positioning using MRI. Below: Proton spectra, for the resonance of carnosine C2-H and C4-H imidazole protons at ~7 and ~8 parts/million (ppm).](image)
the form of an echo spin. Each radio frequency pulse aligns all metabolites within the voxel so they are all spinning in the same uniform direction. When the radio frequency is paused between pulses, the different relaxation times (time to resume normal spinning motion) of different metabolites are measured. The difference in relaxation times allow for the identification of the different metabolites within the spectrum and the determination of their concentrations.

1.2.2 Magnetic Resonance Spectroscopy in Sport

During the last two decades there have been rapid advancements in MR technology. It is now possible to non-invasively detect changes in important intramuscular metabolites through the use of MRS. Previously, such changes in intramuscular metabolites were only able to be identified though invasive muscle biopsies, which have numerous drawbacks when working with world-class and elite athletes.41

MRS offers a non-invasive methodology that can directly quantify the concentration of substrates and metabolites within muscles (i.e., glycogen, creatine phosphate, glucose-6-phosphate, lactate and carnosine) with good repeatability, time efficiency and somewhat better precision.42-45 There are drawbacks in that the required equipment is expensive and requires advanced knowledge and speciality. However, recent research has demonstrated that the non-invasive quantification of various muscle metabolites is reliable and valid.27,46 The application of the non-invasive quantification of muscle metabolites in a sporting context include:

i) Monitoring the effectiveness of different carbohydrate loading protocols, through the assessment of muscle and liver glycogen
concentrations before and after carbohydrate ingestion. This information can be ascertained through the use of $^{13}$C-NMR.\textsuperscript{47,48}

ii) Optimisation of the efficiency of training schedules in relation to fuelling and overtraining. This can determined through the assessment of the depletion and regeneration of muscle and liver glycogen concentration before and after training competition.\textsuperscript{49,50}

iii) Assessing substrate repletion after training and competition through the quantification of muscle glycogen depletion and intramuscular lipids.

iv) Estimating the MFT of athletes through the quantification of intra-muscular concentrations of carnosine.\textsuperscript{27,51}

The benefits to using this technology in sport are that athletic performance can be maximised with this non-invasive assessment. It could reduce the risk of overtraining through continuous non-invasive assessment of metabolite concentrations, plus it could identify performance determining physical characteristics in world-class athlete cohorts. Recent research has used this technology...
technology to non-invasively estimate the MFT in world-class and elite sporting populations, through the quantification of intra-muscular carnosine concentration,\textsuperscript{27,51,52} which is where this thesis directs its emphasis.

\subsection*{1.2.3 The role of Carnosine in Muscle Fiber Typology determination}

Carnosine is synthesized from L-histidine and β-alanine in a reaction catalysed by carnosine synthase, and is abundant in human skeletal muscles (~ 5 mM in wet weight or ~20 mmol/kg in dry weight).\textsuperscript{53} Carnosine has multiple functions within the muscle including, a proton buffering,\textsuperscript{54,55} calcium regulation,\textsuperscript{56-58} antioxidant activity,\textsuperscript{59} antiaging,\textsuperscript{60} inhibition of protein glycosylation,\textsuperscript{61} wound healing,\textsuperscript{62} and inhibition of protein-protein cross-linking.\textsuperscript{61} Increased quantities of carnosine have been shown to improve athletic performance through improved muscular contractions resulting from several physiological mechanisms, (i.e. increasing the non-bicarbonate muscle buffering capacity,\textsuperscript{63,64} increasing of the sensitivity of calcium release channels,\textsuperscript{56} and providing protection against reactive oxygen species\textsuperscript{65,66}). Importantly, the concentration of carnosine has been determined to be two-fold higher in type II muscle fibers compared to type I,\textsuperscript{67-69} a distribution that favours the primary role of carnosine as a buffering agent of H$^+$ ions (figure 3). Carnosine is a relatively stable in human skeletal muscle (~10\% variation over a 3 month period),\textsuperscript{46} with only long-term vegetarianism,\textsuperscript{70} and high doses of beta-alanine supplementation for a prolonged period shown to change the muscle carnosine content.\textsuperscript{71} However, more recently it has been reported that carnosine concentrations remain stable following a 3 – 6 month change to a vegetarian diet,\textsuperscript{72} leaving the effects of vegetarianism on carnosine concentration up for debate. Furthermore, studies investigating the influence of short to medium term training interventions (4 - 12 wk) on carnosine concentrations and found that levels were
As such, given that muscle carnosine can be measured non-invasively, its concentration is markedly different between muscle fiber types and is stable in response to most changes in diet and in response to training, it seems to be a good candidate to provide a marker of MFT estimation. Previous studies\textsuperscript{27,51} have demonstrated that the measurement of carnosine can differentiate between athletes who specialise in sprint or power sports, and those competing in intermediate or long-distance events (figure 4 and 5). This is thought to be due to the athletes competing in shorter, explosive events requiring a high proportion of type II muscle fibers compared to athletes competing in middle- or long-distance events where a greater proportion of type I muscle fiber is advantageous.\textsuperscript{26,28} Further to these findings, Bex et al.,\textsuperscript{51} found the muscle carnosine concentrations to more strongly associated with the movement frequency of a sporting activity than with the duration of the activity.

\textbf{Figure 3:} Carnosine contents of type I (•) and type II (○) muscle fibers of the vastus lateralis of four subjects. (From Harris et al., 1998).
Figure 4: Carnosine content of gastrocnemius muscle in track-and-field and triathletes compared to an untrained male control population (from Baguet et al., 2011).

Figure 5: $^1$H-MRS determination of muscle fiber typology, athletes of each sport were divided into Sprint, Intermediate and Endurance groups. Positive Z-score infers a larger proportion of type II muscle fibers (from Bex et al., 2017).
1.3 Determinants of Swimming Performance

The determining factors of world-class and elite swimming performance are diverse, but as previously discussed, are in part, the combination of a swimmer’s physical characteristics (i.e., height, body mass) and physiological characteristics (i.e., aerobic power, anaerobic power and capacity and strength), as well as technical skills. Furthermore, swimming performance can be categorized by three important race segments; that is, the start, the turn and the free-swimming segment which is categorized by a swimmer’s pacing strategy. It is highly probably that these race segments are underpinned by variability in a swimmer’s physical, physiological and technical skill set therefore all of these characteristics will be integrated into the following section.

Swimming performance is complex, but a race can be broken down into individual determinants, such as the start and turn performance, the free-swimming segments and pacing strategy; all of which require their own specific attributes. Whilst physical characteristics such as height and MFT are genetically influenced, other possible determinants of performance such as body mass and composition, aerobic power and anaerobic power and strength are trainable. Indeed, swimmers may have a diverse profile and while the majority of this diversity may be due to training characteristics and subsequent training adaptations, MFT may be one inherent characteristic that is not influenced by training, but could be deterministic and underpin performance across a range of characteristics underpinning swimming performance.

One of the most simple methods to assess and evaluate a swimming race performance is to take the split times at specific distances throughout the duration
of the event. Typically, the segments of a race are broken into three distinct areas, the start, the turn and free-swimming. Research teams have evaluated these segments of the race at a variety of international competitions; Olympics, World Championships, and European Championships, and this has provided useful feedback to coaches and sports science practitioners working with world-class and elite swimmers. This data has allowed derivation and evaluation of each swimmer’s individual race profile, allowing coaches and sports science practitioners to identify specific area for attention within the training environment. However, there is no research on the physical characteristics that are deterministic of these segments of performance. Similarly, while there have been no studies aimed at evaluating possible relationships between the pacing strategy used by swimmers in racing and specific physical characteristics that swimmers possess. Importantly, MFT is largely dependent on genetic predisposition and is not thought to change substantially in response to training. As such, there is a complex interplay between how much training induced adaptations and genetic predisposition contributes to swimming performance and how training and racing strategies could be individualized for each swimmer. Therefore, the influence that MFT may have on all of these determinants of performance warrants further exploration. The following section of this review explores these determinants of swimming performance, and where appropriate, briefly discusses the influence MFT could have on these parameters.

1.3.1 Swim Start
The swimming start is an action that requires a completely different movement pattern within a swimming event; to date there has been more research in this area of swimming performance as this movement takes place on land, and is
consequently easier to study and monitor, compared to the locomotion and rotation actions that take place in the water. The combination of the start and turn segments of a swimming race can equate to up to 30% of the overall race distance, and contribute to over 25% of the race time (i.e. ~20% of the race time in 50 m events, and ~28% in 1500 m events). Given that international swimming events can be won or lost by margins of 0.01 s, the research into the underpinning physical determinants of performance is limited.

The starting performance across a wide variety of sports has been highlighted as a key component in success. The starting segment of a swimming event is typically described by the time it takes the swimmer to complete the first 15-m from the starting signal. The start time contributes to around ~12% of the overall performance time in 100-m events, ~7% in 200-m events, ~2.5% in 400-m events, and ~1% in 800/1500-m events, which highlights its importance particularly for races over shorter distances. In a recent systematic review, of eight cross-sectional studies it was found that the start time in swimming was highly related to the performance of a number of land-based exercises, and it was deemed that; vertical squat jump height (SJ) and counter-movement jump height (CMJ) were more indicative of start performance than were measures of maximal strength. Body weight exercises were more highly correlated to start performance compared to weighted exercises, and squat jump height was more predictive of start performance compared to other kinetic or kinematic measures of SJ and CMJ. High correlations (r = 0.7 – 0.9) were also found between start time to 5-m and 15-m and loaded SJ across 4 loads. In combination, the results of these studies suggest that the explosiveness of the lower limbs is a major determinant of swim start performance. While this information is important, it should be noted that lower limb
power is a trainable characteristic and swim start performance is highly technical. As such, gaining a better understanding as to the non-modifiable characteristics that underpin swim start performance is fundamental for our understanding of elite swim performance and designing talent identification protocols.

Whilst the ability to produce force and power are deemed essential to the swimming start through their effect on jump height, the underpinning optimal physical characteristics have not been directly investigated. Higher vertical CMJ and SJ height has previously been correlated with the proportion of type II muscle fibers in elite weightlifters.\textsuperscript{93} However, ‘in-vivo’ research of this type has not been conducted within the swimming population especially in relation to the start performance, which is thought to be characterised by lower body explosiveness. Previous research from West et al.,\textsuperscript{92} suggested that strategies that may result in the hypertrophy of type II muscle fibers may be important in improving the start time of swimmers, but to date no peer-reviewed research has explored this. In light of the available findings, it seems reasonable to suggest that a swimmer who has a greater proportion of type II muscle fibers could have more natural explosive characteristics and consequently better performance when it comes to the swim start. This relationship warrants investigation given that finishing position in swimming races can be decided by small fractions of a second.

1.3.2 Swimming Turn Performance

Swimming is a cyclical locomotive sport and it is unlike other sports of this nature (i.e., cycling, running and rowing), as the underwater environment in a fixed distance pool (i.e. 25 or 50-m), creates a limiting distance before the swimmer has
to change from a loco-motional (swimming) to rotational (the turn) action in order to complete the event.

These movement patterns in swimming could necessitate different physical characteristics for each part of the event. For example, the rotational movement at the turn could require maximal muscle power for elite performance, compared to the locomotion between the turns, which may require a more fatigue resistant characteristics to maximise movement efficiency. The turn phase in swimming has two technique types, the tumble; used in FR and BK events, and the tuck; used in FL and BR events. The tumble turn is characterised as the foot making contact with the wall at the end of each lap, with this occurring after a forward somersault on the approach to the wall. The tuck turn has two wall contact periods. The first is a hand touch, and the second is the foot contact. Understanding as to the influence the turn has on swimming performance has predominantly come from post-race analysis. The turn phase in 100-m and 200-m events has been proven to have moderate to strong magnitudes of correlations with overall race performance, and therefore this element of swimming race performance is important to understand from an ‘in-vivo’ perspective, in order for it to be optimised. Several researchers have tried to identify the key biomechanical parameters that define the performance of a turn, with the investigated parameters including turn start distance, pivot time, peak force, impulse, push-off velocity, breakout distance, and speed at stroke resumption. However, only small to moderate amounts of variance could be attributed to each of these individual parameters and consequently it was suggested that an ‘holistic’ approach to improving the performance of the turn should be implemented. Due to the marked differences in turn performance between
different calibres of swimmers, the findings from these studies may not always be applicable to world-class and elite populations. 

Jumping parameters have been suggested to have little association with the turning performance of swimmers, leading to a conclusion that either such exercises lack specificity or that ‘the importance of leg power in the tumble turn velocity is overstated.’ Another study found that elite swimmers had superior force and power output in jumping performance, compared to junior elite swimmers, and also had superior turn performance. However, the authors went on to suggest that this relationship was likely to be associated with the number of years spent undertaking prescribed resistance training rather than to an underlying physiological or physical characteristic. Further research, was deemed necessary to determine the ability of measures obtained during strength training exercises to predict turn performance. Other research has been of dubious relevance world-class and elite turn performance as samples were sub-elite, and in some cases pre-pubescent, which brings in to question the impact of physical development and maturity on the outcome measures. Research on the underpinning physical characteristics that influence turn performance are unknown, and therefore MFT and its effect on turn performance warrants further exploration.

1.3.3 Pacing Strategy in Swimming Performance
Research investigating the pacing strategies adopted by athletes has grown considerably over the past decade, with the majority of studies investigating pacing in endurance sports such as running, cycling and triathlon. The likely reason for the plethora of research in these sports is the relative ease with which pacing can be manipulated in both laboratory and field conditions. Pacing research in swimming
is comparatively limited, probably because of the relative difficulty of externally controlling swimming pace and obtaining physiological measurements in the aquatic environment. Even so, the lack of research into swimming pacing is surprising since pacing is likely to be “more critical” in swimming than other sports due to the low mechanical efficiency of the technique and the highly resistive properties of water compared to land. This is highlighted by the fact that only 6-18% of energy generated is converted to mechanical work, which is low compared to cycling at 18-24%. Due to the differences in efficiency it has been suggested that optimal pacing strategies necessary in swimming could be unique to the sport, and that strategies developed for land-based sports may be limited in their applicability to swimming performance. In addition, within swimming competition the separation of competitors by the lane lines helps to limit the influence of other competitors in the race, when compared to other sports such as athletics and cycling. Typically, the pacing profiles of elite swimmers in competition are identified by plotting split times, mean lap velocity or the percentage of overall time spent on each lap (figure 6 and 7). The necessary data can be readily accessed from online sources, which enables researchers to analyse larger population sizes, and can provide a descriptive analysis of the pacing profiles adopted by swimmers in competition. Whilst these profiles can be easily constructed, it remains unclear as to whether the pacing strategy used by the swimmers could be individualised in order to maximise performance. There have been a wide range of pacing strategies used in swimming; the variation is largely dependent on both the race distance and stroke (figure 6 and 7). The most prevalent pacing profiles used in swimming are negative, all-out, positive, even, parabolic, and J-shaped (figure 6). In all events, the velocity on the first lap is the fastest, due to the rapid acceleration gained from a dive start. The faster first lap occurs to
a lesser extent in backstroke given that the swimmers start in the water which reduces the time advantage afforded to starts performed on the blocks.  

The key to successful swimming performance, with regards to employing the most effective pacing strategy has been described as the ability to maintain the highest possible average velocity over the entirety of the race.  Whilst swimmers in sprint events exhibit a positive/all-out pacing profile, swimmers in endurance events have been documented to apply a negative or parabolic profile. Researchers have examined the reproducibility of pacing profiles within individuals and have found there to be low variability between heats and finals, despite in some cases the overall time being substantially different. Pacing profiles have also been suggested to remain stable between competitions. It would naïve for both coaches

Figure 6: Schematic diagram illustrating examples of various pacing profiles commonly observed in swimming across a range of competitive events. (from McGibbon et al., 2018).
and sports scientists to generalise an optimal pacing profile to an event, as there are often inter-individual differences within the same event, and even race. An example of this is the pacing strategy used in the men’s 100m Freestyle Olympic final in 2016. The gold medallist, Kyle Chalmers of Australia was the overall winner of the event, was 7th at the half-way point, 0.92 s behind the leader, yet ended up winning the race by 0.22 s. He employed an even/parabolic pacing strategy in his 100-m freestyle races which goes against the norm in 100-m freestyle swimming, whereby the other seven competitors in that final employed a positive or all out pacing profile. The reason for this variation in strategy is unknown, but one reason for this could be that Kyle’s physical and/or physiological characteristics meant that his optimal pacing strategy was different from that of the other swimmers. Whilst the hypothesis is unproven, there is the possibility that the variation in pacing strategy

![Figure 7: Pacing profiles across different swimming events (reproduced with permission from Thompson, 2014 (From McGibbon et al., 2018).]
used by very high calibre of swimmers is at least partly dependent on marked differences in their individual physical and physiological characteristics.\textsuperscript{119,120} Further research into the unpinning influences of the pacing strategy that maximises performance in swimming is necessary in order to allow coaches and sports scientists to optimise an individual’s pacing strategy. The differences in physiological and mechanical characteristics of different muscle fiber types, and therefore MFT, could be an underlying determinant of divergent pacing strategies in swimming performance, and this warrants further exploration.

1.3.4 Critical Speed and Supra-CS Distance Capacity Performance

While the measurement of physiological characteristics limited by aerobic metabolism are no doubt important in swimming, the challenges of the aquatic environment make it difficult to quantify precise measurements. For example, while different methods have been used to quantify the oxygen uptake of swimmers,\textsuperscript{121,122} and estimate the maximal oxygen uptake, these measurements are difficult to undertake in practice. As such, alternative swimming tests have been developed that may estimate other physiological characteristics that may be important for performance.\textsuperscript{123,124} According to Toussaint and Hollander,\textsuperscript{125} swimming performance is described as the result of the transformation of metabolic power into mechanical power with a given energetic efficiency. In swimming, environmental and technological constraints have meant that the ability to measure critical power (CP) and supra-critical power work capacity (W’) are not attainable or able to be accurately measured. Typically, these measures are calculated from a series of maximal effort time trials that have a set power output or speed from which a maximal metabolic steady state can be determined from time trials lasting between 2 – 15 min. However, due to the restrictive nature of the aquatic environment,
swimming researchers have used critical speed (CS); the highest speed that can be maintained while preserving a metabolic steady state. In addition, different methodologies also allow for the measurement of a parameter referred to as the supra-CS distance capacity (D’), which is the total distance that can be swum above CS, to replace measures of CP and W’. These measurements are synonymous with CP and W’ that are typically measured in cycling. The methodology typically used to derive CS and D’ is the time trial method, which is cumbersome and can take many days to complete. A more time friendly method to assess CS and D’ in swimming has been developed, derived from the 3-min all-out cycling ergometer test developed by Vanhatalo et al.\textsuperscript{126} which assessed CP and W’. Tsai and Thomas,\textsuperscript{127} undertook a protocol which incorporated a single session 3-min all-out swim effort, from which 25 m split times were recorded and used to calculate CS and D’. The results of this 3 min methodology were shown to be comparable to the time trial method in assessing the CS and D’ of swimmers, however reliability measures were not reported. Nonetheless, a promising reliable and valid methodology of assessing CS and D’ has arisen in recent literature, through the use of a modified 3-min all-out test.\textsuperscript{123,124} The test utilizes a protocol whereby swimmers completed 12 x 25 m maximal efforts separated by 5 s of passive rest, in order to irradicate the variability of turn technique and technique depreciation. Average velocity per lap is equated from the time, from which D’ can be calculated from the integration of speed-time model using the following equation:

\[
D' = ((t_1 \times S_1) - (CS \times t_1)) \\
+ \left( \left( \int_{t_1}^{t_{12}} ae^{bt} + c \right) - CS \right)
\]
where \( t_1 \) = total time (s) and the end of 25 #1, \( t_{12} \) = total time (s) at the end of 25 #12, CS = critical speed (m.s\(^{-1}\)), \( a, b \) and \( c \) are weighting factors. CS is derived from the slowest 2 of the last 4, 25-m efforts. This protects against an end spurt pacing mistake, while also replicating the \( \sim 30 \) s time period typically employed in cycling protocols to estimate CP.\(^{123,126}\) The coefficient of variation for \( D' \) and CS was 5.7 and 1.2\% respectively. Further to the reliability measures, the construct validity was evidenced by there being no significant change in velocity after effort number 8. Furthermore, construct validity was also illustrated through the comparison of a sprint freestyler (100m), and an endurance freestyler (400m), whereby the sprint swimmer had a greater peak velocity (1.86 vs 1.81 m s\(^{-1}\)) and larger \( D' \) (24.4 vs 10.7 m) but slower CS (1.41 vs 1.61 m s\(^{-1}\)). Mitchell et al.\(^{123}\) continued to state that ‘endurance athletes generally have a slower peak velocity, a faster decay (lower \( D' \)) and a faster CS,’ which suggests that CS and \( D' \) measures determined through this methodology could differentiate between elite swimmers specializing in sprint and endurance events. Nonetheless, it should be mentioned that the CS derived from the modified 3-min all-out test has not been experimentally validated, whereby markers of metabolism (i.e., VO\(_2\), blood lactate concentration, heart rate etc) have not been measured in swimmers who swim slightly above, at or below this speed to ensure that it represents a metabolic steady state. The authors of this methodology of assessing CS and \( D' \) found that the drop off \% from peak velocity to CS was substantially larger in 100 m specialists compared to swimmers who had a preference towards 200 m events. Interestingly, it was proposed by Mitchell et al.,\(^{124}\) that the fatigue index, and difference between peak speed and CS may be associated with the variation in MFT between swimmers. This theory was rationalized by the influence that MFT has on fatigue index\(^{52,128}\) whereby subjects with a greater percentage of type II muscle fiber fatiguing more rapidly than those
with greater proportions of type I muscle fibers. Whilst these relationships have not been determined for CS, it would be reasonable to suggest that the swimmers possessing a greater percentage of type II fibers would have a slower CS based on studies in cycling.129,130

1.3.5 Strength

Traditional resistance training is employed to improve competitive performance of athletes many sports, and swimming is no different. For example, low-volume, high velocity resistance-training has resulted in improved swimming performance.106,131-133 Specifically, resistance training studies,106,131,132 have found improvements in sprint swimming performance (22.9- and 50-m performance), through the employment of such modalities. Furthermore, Aspenes et al.,133 reported that a high velocity resistance-training program, significantly improved 400-m swimming performance. These findings highlight the importance of dry-land resistance training to swimming performance. In addition, Strass,106 found that it was the improvements in maximal explosive force production, as opposed to maximal force production, that were most highly influential in improving swimming performance. The authors went on to suggest that this could be due to various neuromuscular adaptations including, motor unit recruitment, synchronization, co-contraction, rate coding, intra- and inter-neuromuscular coordination and reduced neural inhibition. Each of the aforementioned studies used high velocities during the concentric phases of the exercises. This methodology of resistance training has been linked to greater neuromuscular adaptations and the preferential recruitment of type II muscle fibers.134-136 Given that high velocity resistance training has been shown to be beneficial for swimming performance, measuring the velocity of prominent
upper and body movements in the gym may be an effective way to monitor the training progress of swimmers.

Whilst dry-land force and velocity improvements have been associated with swimming performance improvements, the influence of force production on swimming performance has long been discussed,\textsuperscript{137} and it has been reported that the force exerted in water is a major factor for success.\textsuperscript{138,139} In theory, the maximum force produced on a tether corresponds to the propelling force that a swimmer can produce to overcome water resistance at maximum swimming velocity.\textsuperscript{140,141} Both maximum force\textsuperscript{142} and average force\textsuperscript{143} have been shown to be strong determinants of swimming performance, but few studies have assessed these measurements longitudinally in response to changes in training load.

\textbf{1.3.6 Determinants of Swimming Performance Summary}

As highlighted above there are many determinants of swimming performance, from specific race segments to the physiological and physical characteristics of the swimmer. It’s the effective combination of these characteristics that helps to maximize swimming performance overall. MFT is one characteristics that may underpin each of these determinants of swimming performance, but this remains to be comprehensively investigated.

The majority of research investigating how MFT related to swimming performance has involved studies that have characterized the MFT of swimmers of varying and unknown standards,\textsuperscript{28-31,33,35-37} and very few have applied experiment designs to determine the influence that MFT may have on swimming performance. On previous study reported that there may be fiber-type specific differences in how
fibers respond to overload training in swimmers but more research is required, particularly in elite swimmers.

### 1.3.7 Training Programs of Elite Swimmers

Training programs of athletes are multi-faceted but can be broadly characterized by the intensity, duration, and frequency of training.\(^{37,144-147}\) It is the effective combination of these training variables that promotes adaptations in the physiology of athletes and subsequently, improvements in exercise performance. The integration of training intensity and training volume (the product of the session duration and the relative exercise intensity) within the overall training program is highly dependent on the discipline-specific competition, which dictates the physiological requirements of the event. In regards to swimming competition, events typically last between 22 s and 15 mins (50-m – 1500-m) which imposes a wide variation in the relative importance of aerobic and anaerobic metabolism throughout the range of events.\(^{148}\) Typically, the training volume of elite swimmers is extremely high, even for short distance swimmers (50- to 400-m swimmers), particularly when considering the relatively brief duration of these competitive events (22 s to 4.5 min event duration).\(^{149}\) While training intensity and frequency are important training variables, a polarized debate around the training volume of swimmers necessary to maximize performance continues to evolve. As such, the final experimental chapter of this thesis will focus on manipulating the training volume of elite swimmers and will aim to determine whether MFT is a moderating factor on the individual responses to training.
1.3.8 Swimming Training and Volume

Applied sport scientists, swimming coaches, and researchers have become engaged in a substantial debate concerning the necessary training volume for elite swimmers. Some argue that high volumes are essential for swimmers to gain a better ‘feel’ for the water, whilst others argue that time spent at less than race velocity is irrelevant. Neither view has been conclusively investigated in swimming research. The debate regarding the training volume of elite swimmers, in particular, for sprint swimmers is continual. Some argue that high volumes can be translated to improved biomechanics of body/head position, control, connection and proprioception from a skill acquisition perspective. Others would argue that the large training volumes of swimmers, is not warranted.

It has been described that highly developed aerobic and anaerobic capabilities are required for peak swimming performance, and it has been reported that in a group of elite swimmers that ~ 90% of the weekly training volume was completed at an intensity which accumulated a blood lactate concentration of less than 4mmol.L$^{-1}$. Other studies have similarly found that swimmers have high training volumes, where there is a “medium” intensity achieved, which does not necessarily align with the energetic demands of swimming races, especially those that last for less than 2.5 minute.

To date, the most frequently studied interventions in swimming are related to the manipulation of training volume. Following a period of high-volume training (HVTr), Faude et al., observed no difference in 100- or 400-m freestyle time trial (TT) performance following a period of either normal training (NormTr) or high-volume training (HVTr) lasting 4 w (81.2 vs 167.8 km.4wk). Houston et
al. observed no significant improvements in performance of 22.9- 91.4- and 457-m freestyle TT following either a period of normal training (NormTr) or HVTr,\textsuperscript{29} lasting 6.5 w (HVTr group performed 1350 m per training session more than NormTr. Similarly Costill et al., found that 45.7- and 182.9-m performance did not significantly improve with a period of 6 w HVTr compared to NormTr (9435 m.d\textsuperscript{1} versus 4950 m.d\textsuperscript{1}).\textsuperscript{37} In addition historical research by Fitts et al., found that a 10 d period of overload training (8970 ± 161 vs 4266 ± 264 m) did not affect swim performance, but did however, reduce the diameter and maximal shortening velocity of type II muscle fibers.\textsuperscript{36} The relationship between HVTr interventions and the MFT of swimmers has not been studied in relation to specific swimming performance determinants. Whilst studies from Costill et al.\textsuperscript{37} and Fitts et al.\textsuperscript{36} assessed changes in the characteristics of different muscle fiber types, how these changes may relate to specific swimming performance, or how the MFT of a swimmer influences the responses to HVTr has not been explored.

In summary of these studies, it could be purported that HVTr may not be beneficial to improve swimming performance, however these studies did not consider the physiological diversity of the swimmers studied, whereby variation in MFT may be important. However, it should be noted that McKinnon et al., found weekly volume increases of 30 - 40% from NormTr over a period of 4 wk, led to diverse responses between swimmers, with 33% of swimmers developing symptoms of over-reaching.\textsuperscript{155} Whilst this highlights that there is variability in responses to HVTr, it does highlight the necessity to determine which characteristics are influencing these different responses to HVTr.
A recent study on middle-distance runners revealed that the variability in performance responses following a period of HVTr and subsequent taper were associated with the variation in MFT, determined through the $^1$H-MRS technique.\textsuperscript{156} Runners with a higher estimated proportions of type I muscle fibers were able to better maintain performance in response to HVTr, and subsequently achieved a superior performance super-compensation. Conversely, runners with a greater estimated proportion of type II muscle fibers could not tolerate the increase in training volume and achieved inferior performance supercompensation. MFT was not assessed by McKinnon et al.,\textsuperscript{155} but if the findings of Bellinger et al.,\textsuperscript{156} hold true for swimmers then MFT may also be a modulating factor in the performance responses to HVTr in swimming. Exploration of this possibility could help to resolve arguments concerning the training volume required in swimming, and greatly assist individualisation of training programs for swimmers.

1.4 Conclusion

The research discussed in this review, highlights that there is an obvious need to explore how the physical characteristics of world-class and elite swimmers may affect performance. In light of the technological advancements and the novel ability to determine MFT with the use of non-invasive $^1$H-MRS technology, this thesis will explore some of the ways in which MFT might influence the determinants of swimming performance in world-class and elite swimming populations. Specifically, the review of relevant published literature has shown that the determinants of swimming performance are underexplored; therefore, research into the underpinning characteristics is warranted. Parameters such as the start and turn have been identified as substantial contributors to overall swimming race performance, yet their underpinning physical characteristics are unknown. Pacing
strategies have been found to differ both between events and competitors within events, yet the reason for these differences are unknown. Whilst it is known that periods of overload training may be necessary in order to induce physiological adaptations, it is unknown if the inter-individual variation in the responses to these overload periods can be explained by a variation in MFT. Therefore, this thesis aims to use a non-invasive technique to determine MFT in elite and world-class swimmers and understand whether this trait influences the determinants of swimming performance.
1.5 Thesis Aims

Given the identified gaps in current knowledge, the overall aim of the research reported in this thesis was to use $^1$H-MRS to determine the MFT of world-class and elite swimmers, and to determine if this characteristic is influential on the determinants of swimming performance.

More specifically,

1. Chapter 2 aims to critically evaluate peer-reviewed literature describing the age, height and body mass of Olympic Level swimmers, throughout the past 50 years, and then make a new comparison of the age, height and body mass of freestyle swimmers competing at the 1968, 1992 and 2016 Olympic Games.

2. Chapter 3 aims to use $^1$H-MRS to determine the influence that muscle fiber typology has on the start and turn times of elite and world-class swimmers.

3. Chapter 4 aims to investigate whether the pacing strategy implemented by swimmers in the 200-m freestyle event is associated with the variability in MFT.

4. Chapter 5 aims were
   a. To examine the individual changes in time-trial (TT) performance before, and after HVTr and a subsequent taper in elite swimmers
   b. Identify if MFT is a moderating factor for changes in TT performance in response to alterations in training volume.
   c. Determine if changes in 200-m TT performance in response to alterations in training volume are associated with changes in various measures relating to swimming performance
d. Determine if MFT is a moderating factor on the variability in the responses to various measures relating to swimming performance in response to alterations in training volume.
Chapter 2: Investigative

Study 1
2.0 Declaration of co-authorship within Thesis Chapter 2

This chapter includes a co-authored paper:


In the case of Chapter 1, the nature and extent of my contribution to the work was the following:

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<thead>
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<tr>
<td>Data collection</td>
<td>70%</td>
</tr>
<tr>
<td>Analysis and interpretation</td>
<td>50%</td>
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Candidate Signed: ____________________________  Date: 25/8/20

Adam Mallett

Co-authorship declaration:

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<td>Dr Phillip Bellinger</td>
<td></td>
<td>8th October 2020</td>
</tr>
<tr>
<td>Prof. Wim Derave</td>
<td></td>
<td>8th October 2020</td>
</tr>
<tr>
<td>Dr Mark Osborne</td>
<td></td>
<td>8th October 2020</td>
</tr>
<tr>
<td>Supervisor - A/Prof. Clare Minahan</td>
<td></td>
<td>8th October 2020</td>
</tr>
</tbody>
</table>
2.1 Title: The age, height, and body mass of Olympic swimmers: A 50-year review and update

1,2 Adam Mallett, 1,3 Phillip Bellinger, 4 Wim Derave, 5 Mark Osborne, 1 Clare Minahan

1 Griffith Sports Science, Griffith University, Gold Coast, Australia;
2 Queensland Academy of Sport, Nathan, Australia;
3 Menzies Health Institute Queensland, Griffith University, Gold Coast, Australia;
4 Department of Movement and Sports Sciences, Ghent University, Belgium;
5 Swimming Australia Limited, Melbourne, Australia

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Conflict of interest: All authors declare that they have no conflicts of interest

Word Count: 6131 (Excl, tables, figures, references)
2.2 Abstract

A difficulty in identifying the optimal age, height, and body mass of swimmers is the heterogeneity of the athletes examined (i.e., gender, calibre), the variability in race distance and stroke, and the influence of time. Nonetheless, age, height, and body mass remains the most readily available data of all athlete characteristics, supporting their contribution to the prediction of performance. This review presents the findings of previous studies over the last 50 years and offers new insights by examining data from swimmers competing at the 1968, 1992, and 2016 Olympic Games. Our data investigates gender differences in age, before exploring gender-specific variations in the age, height, and body mass across year, distance, stroke, and calibre. We show that there are differences in swimmers competing at the 2016 compared to the 1968 and 1992 Olympic Games. Today the age of world-class swimmers is independent of gender, race distance and stroke, as well as calibre. Swimmers competing in freestyle are taller and heavier than in butterfly, while height remains associated with performance in some, but not all events in female swimmers. In 2016 the average age, height and body mass of world-class swimmers is 22.7±3.6 and 23.2±23.3 years, 175.1±6.6 cm and 188.3±6.0 cm and 63.8±6.8 and 81.3±7.3kg for females and males respectively. These findings provide coaches with a new perspective on the optimal age, height, and body mass of world-class female and male swimmers.

Key words: Physique; Sports performance; Talent identification; Elite swimmers; World-class
2.3 Introduction

Disparity in the physical characteristics of athletes compared with the general population has been well documented.\textsuperscript{157,158} Indeed, substantial variability in the height, body mass, and body composition of athletes within some sports can also be easily identified.\textsuperscript{159,160} Nonetheless, the ability to distinguish ‘World-class’ (e.g., top-10 finisher, finalists, or ‘best’) from ‘elite-level’ (e.g., finished outside the top-10, non-finalists, ‘rest’, or participant) within a single event at elite-level competitions (i.e., Olympic Games or World Championships) using physical characteristics maybe more difficult. Therefore, whether age and/or physical characteristics can be used as a predictor of World-class athletic performance remains questionable,\textsuperscript{9,161} when training age, and level of competitive experience also have a large role in determining performance.

There has been considerable interest in the age and physical characteristics of swimmers competing at the Olympic Games or World Championships over many decades (see Table 1). Early studies examining only amateur athletes include those by Cureton,\textsuperscript{162} de Garay et al.,\textsuperscript{163} and Novak et al.\textsuperscript{164,165} During the 1980’s and 90’s, Olympic athletes were more frequently supported by their governments to train and complete as well as attracting increasing amounts of private funding; the physical characteristics of these athletes are described in the studies by Khosla,\textsuperscript{9} Chengalur and Brown,\textsuperscript{166} and Carter and Ackland.\textsuperscript{8} To identify a possible historical trend, Mazzilli,\textsuperscript{167} recently compared the height of sprint-distance freestyle (FR) medalists at the Olympic Games and World Championships between 1908 and 2016. Collectively the findings of these studies suggest that male swimmers are faster, taller, and heavier than female swimmers,\textsuperscript{162-165} the age, height, and body mass of all swimmers has increased over the last 50-100 yr.\textsuperscript{8,162-165,167} and that World-class
swimmers may be taller than elite-level swimmers. However, many of these studies are limited to a single gender, year of competition, stroke, and/or distance, and few make the distinction between World-class swimmers and those simply participating at the elite-level, for the purpose of this review, we classify World-class swimmers as those who achieve a top-10 time at a major championship event, and elite-level as those who achieve a time ranked from 11-20. Later sections highlight discrepancies in the terminology of these terms within the literature. No more eloquent is the comprehensive ‘Kinanthropometry in Aquatic Sports (KASP)’ study of swimmers competing at the 1991 World Championships (Perth, Australia) by Carter and Ackland. Data presented in the KASP study include age and physical characteristics (42 body size dimensions) of swimmers based on gender, stroke, distance, and calibre (i.e., World-class vs. elite level). Despite the comprehensive analyses of swimmers’ physical characteristics, these authors summarize that, “…aside from differences in stature and body mass, there was little distinction in body composition.” In the present review, we too consider gender, event distance, stroke, and calibre of the swimmer at the 2016 Rio Olympic Games to better understand if age and/or height and body mass could be used as predictors of World-class performance today. The aim of this study was two-fold, i) to evaluate previously published literature on the age, height and body mass of World-class swimmers and then, ii) to make a comparison of the age, height and body mass, among FR swimmers competing at the 1968 Mexico City (Mexico): the first Olympics to have the complete arrangement of ‘modern’ freestyle events (100, 200, 400 for male and female, and 800 and 1500 for female and male respectively): 1992 Barcelona (Spain): the mid-point between 1968 and 2016; and 2016 Rio (Brazil): Olympic Games, the most recent Olympic competition. Data was collected from freely available online resources, to provide insight into how changes to the
age, height and body mass of World-class and elite-level swimmers over the past 50 years might have contributed, in part, to the concomitant improvements observed in swimming performances (see Table 2a).
<table>
<thead>
<tr>
<th>Year and Competition</th>
<th>Author</th>
<th>Main Findings</th>
</tr>
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</table>
| 1968 Olympic Games   | Hebbelnick et al. 1975 | Height (cm); Females 164.4±7.1, Males 179.3±6.2  
|                      |        | Body Mass (kg); Females 59.9±9.1, Males 72.1±6.8  
|                      |        | *No specified calibre* |
| 1976 Olympic Games   | Khosla. 1984 | Female swimmers competing in 100-m finals were significantly taller than female swimmers who did not qualify for finals (168.6±6.1 vs 172.1±4.3cm) |
|                      |        | 21.42±3.15, 19.94±2.23 and 20.35±3.48 years.  
|                      |        | Female Gold medal winners’ average age (100-, 400- and 800-m Freestyle)  
|                      |        | 19.40±2.90, 17.5±1.91, and 16.0±1.41 years. |
| 1988 Olympic Games   | Chengahu and Brown. 1992 | “Body size is an important determinant of success in...” 100-m events  
|                      |        | “Males are superior to females in 100-m swimming performance, due primarily to their greater stature, age and longer stroke lengths.”  
|                      |        | *Kennedy et al. 1990.*  |
| 1991 World Championships | Carter and Ackland (Eds.). 1994 | “In distinguishing between Best (top-12 performers) and Rest (placed 13th to last), a general pattern emerges in favor of older taller athletes with longer limb, hand and foot lengths. Age could also be a factor because of associated physiological and structural maturity, but emotional and psychological maturity are likely to be important factor.”  
|                      |        | “Successful freestyle swimmers are characterized by... greater stature.”  
|                      |        | “Male freestyle swimmers, in comparison to their female counterparts, are older, are taller...”  
|                      |        | “As the race distance increases from 50 to 200 m, the age of the swimmer decreases.”  
| 1992 Olympic Games   | Arellano et al. 1994 | “… the age of the finalists increased in both the World Championships and the Olympic Games… and performance of the finalists improved. Thus older swimmers can achieve the finals in World Championships and Olympic Games and they can improve their performance” |
| 1992-2013 Olympic Games & World Championships | König et al. 2014 | “…the age of the finalists increased in both the World Championships and the Olympic Games… and performance of the finalists improved. Thus older swimmers can achieve the finals in World Championships and Olympic Games and they can improve their performance” |
| 1898-2014 Olympic Games | Elmreshawy et al. 2015 | “we found that the age of Olympic medal winners increased significantly and consistently in all six events evaluated in women...”  
<p>| 1908-2016 Olympic Games &amp; World Championships | Mazzilli. 2019 | “…the present study confirm and expand the observations of other authors about the increase in body height of elite swimmers in the last half-century and reinforce the notion that this trait is an important predictor of swimming performance.” |</p>
<table>
<thead>
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2.4 Background

*Competitive Swimming and the Olympic Games*

Although swimming as a human activity has been documented for over four-thousand years, competitive swimming only became prominent in the 1830’s. This is in stark contrast to competitive running and wrestling with evidence of competition dating back to 1000 BCE. Moreover, the front crawl was first used in competition as recently as 1899 by champion Australian swimmer Richmond Cavill while butterfly (FL) was not recognized as an independent stroke until 1952. Thus, competitive swimming can be regarded as a relatively new human endeavour for which the optimal physical characteristics are yet to be clearly defined.

Fifty countries participated in swimming events at the 1968 Mexico City Olympic Games with women and men competing in twelve individual events. Spain hosted the 1992 Olympic Games and added the 50-m FR event to the program making thirteen individual swimming events for female and male athletes from ninety-two countries. Today, one-hundred seventy-four nations participate in swimming events at the Olympic Games. At the 2016 Rio Olympics, women and men competed in fourteen individual events each, including the four established strokes: FR, backstroke (BK), breaststroke (BR), and FL as well as the individual medley (IM) comprising all four strokes. The women’s and men’s programs were almost identical, as they contained the same number of events, with only one difference: the FR distance of 800 m for women and 1,500 m for men.
Defining ‘elite-level’ and ‘World-class’ swimmers

The term ‘elite’, when used in reference to athletes, is often poorly defined in the sports-science literature; or defined with enough ambiguity that it is difficult to compare data between studies. On examination of the top-10 results of a Google Scholar search (Since 2019) using the term ‘elite athletes’ (excluding youth or young elite athletes), elite athletes were defined as: 1. Boston Marathon runners (no race times presented),^5 2. “Physical performance defined by the maximum VO\textsubscript{2} or muscle strength (rated as excellent),”^6 3. Athletes participating in international competition (none stated),^7 4. World and Olympic Championship medallists,^174 5. Athletes training for the Winter Olympics Games,^175 6. National-team athletes competing at international competition (none stated),^176 7. National Premier League players,^177 8. National-team level or ‘equivalent,’^178 9. Competed at a World Championships or Olympic Games,^179 10. Undefined.^180 Indeed, it is difficult to find a clear definition of ‘World-class’ in any field; the most common being, “ranked among the world's best.”

Previous literature that has directly compared the physical characteristics of World-class and elite-level swimmers have made the following distinctions: i. ‘Best’ (top-12 placing) versus ‘Rest’ (outside top-12 placings) swimmers at the 1991 World Championships,^8 and ii. ‘Finalist’ (participation in the ‘final’ race) versus ‘non-finalist’ (participation in heat and semi-final races) swimmer at the 1976 Olympic Games.^9 The present review classifies ‘World-class’ swimmers with a top-10 race time in a single event at the Olympic Games. We compare the age, height, and body mass of the swimmers who posted these top-10 race times, with the age, height, and body mass of the swimmers who posted times ranked 11-20\textsuperscript{th} (elite-level swimmers) in the same event. Importantly, the top-10 race times in each event may
have been achieved at any stage of the competition, e.g. a heat, semi-final, B final or the final event, to ensure that the best performances at the competition were included. It is also important to note, that the World-class group in the present review may not always represent the world’s top-10 ranked swimmers in each event as: i. A world top-10 swimmer may not have competed at the Olympic Games due to injury/illness or due to the ‘two-athlete per country per event’ rule, or simply ii. A poor performance on the day. The next best ten race times were used as the elite-level group in order to: i. Eliminate unqualified ‘Universality’ (i.e., wild-card) swimmers being included in the analysis, ii. Compare even groups across year of collection, event distance and stroke, iii. Reduce the variability in the relative performance times, particularly in the 1968 Olympic Games where race times differed by up to 18% (Source: http://www.fina.org) compared to the 2016 Olympic Games where race times differed by only 8%. Table 2b shows the race time ranges of FR events expressed relative (%) to the fastest time of World-class (i.e., 1-10 race times) and elite-level (i.e., 11-20 race times) swimmers at the 1968, 1992, and 2016 Olympic Games. Restricting the observations to the top-20 race times further controls the level of athlete to within 8% of the fastest time across the Olympic years allowing for fairer comparisons to be made.
Table 2b. Race times expressed relative (%) to the fastest time of World-class and elite-level freestyle swimmers at the 1968, 1992, and 2016 Olympic Games.

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<td>World-class</td>
<td>1968</td>
<td>100.0 - 103.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1992</td>
<td>100.0 - 102.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2016</td>
<td>100.0 - 102.3</td>
</tr>
<tr>
<td></td>
<td>Elite-level</td>
<td>1968</td>
<td>104.0 - 105.8</td>
</tr>
<tr>
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<td>1992</td>
<td>102.8 - 105.2</td>
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<td>2016</td>
<td>102.3 - 103.7</td>
</tr>
<tr>
<td>Men</td>
<td>World-class</td>
<td>1968</td>
<td>100.0 - 104.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1992</td>
<td>100.0 - 102.3</td>
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<td></td>
<td></td>
<td>2016</td>
<td>100.0 - 101.5</td>
</tr>
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<td></td>
<td>Elite-level</td>
<td>1968</td>
<td>104.6 - 106.5</td>
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<tr>
<td></td>
<td></td>
<td>1992</td>
<td>102.5 - 103.6</td>
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<tr>
<td></td>
<td></td>
<td>2016</td>
<td>101.5 - 102.3</td>
</tr>
</tbody>
</table>

NB: World-class = top-10 race times; Elite-level = 11-20th race times. Relative race time ranges were calculated using the following equations: World-class – Lower limit = Race time 1st ranked / Race time 1st ranked *100, Upper limit = Race time 10th ranked / Race time 1st ranked *100; Elite-level – Lower limit = Race time 11th ranked / Race time 1st ranked *100, Upper limit = Race time 20th ranked / Race time 1st ranked *100. Source: http://www.fina.org.
Importance of age, height, and body mass on swimming performance

Table 1 presents an overview of previous studies that have reported the age and physical characteristics of swimmers at an elite-level competition (i.e., Olympic Games or World Championships). Excluding age, height, and body mass, no other variable is consistent across two or more studies making it difficult to compare results. Therefore, the present review builds on previous literature by focusing on these three characteristics that have been presented in the scientific literature across several decades and are reported consistently over 50 years.

It is widely recognized that athletes of a similar chronological age (number of years elapsed since birth) can differ by several years in their level of biological maturation i.e., reproductive, skeletal, and developmental age, as well as their training age. Nonetheless, it is reasonable to suggest that an athlete with the benefit of five additional years is more likely to have completed adolescence, reached peak bone mass, and have more favourable anthropometric and physical characteristics in comparison with younger athletes. Furthermore, older athletes are likely to be advanced in their cognitive development (e.g., decision-making) as well as their mental and emotional thinking (e.g., motivation, self-efficacy, and self-esteem). Finally, it is more likely that an athlete with a higher chronological age has performed more specialized training and competition in one sport. Therefore, while chronological age cannot independently predict swimming performance, it is likely to be associated with strong determinants of performance.

The advantages of tall stature to swimming performance can be explained in terms of the laws of physics. Geladas et al., describes the advantage of tall swimmers as being able to better ‘glide’ through the water, while Saucedra et al., and others, associate a swimmer’s height with a larger arm span that results in
a longer stroke length and subsequently improved swimming economy. Furthermore, height and arm span have been associated with a greater capacity to produce propulsive forces during swimming. Therefore, it is plausible that taller swimmers might feature in final races more frequently than their shorter stature counterparts might.

Whereas age and height are predetermined, the body mass of an athlete is not only influenced by genetic predisposition and height, but by environmental factors such as diet and training. A greater body mass in elite-level athletes is often associated with a higher proportion of muscle mass as the demands of many sports require athletes to possess a large muscle mass while maintaining a low percentage of body fat in order to maximize relative force production and movement economy. Previous research has highlighted that the ability to produce power in land-based sport tests is relative to lean body mass. While measurement of the lean body mass values of World-class swimmers would no doubt provide further valuable information, the measurements are not readily available in the majority of studies or online sources. Therefore, it is less clear if body composition is critically important for successful performance in swimming. Although it has been suggested that excessive body fat may hinder performance by increasing drag force in the water, a higher level of body fat has been previously suggested as advantageous during swimming due to higher buoyancy effect. The higher drag coefficient associated with fat mass should also be extended to muscle whereby swimmers with a greater muscle mass would have to overcome the deleterious effects of excessive drag (i.e., decreased economy) with superior force generation. Regardless of the advantages and disadvantages, the body mass of elite-level Australian swimmers is formally recorded approximately eight times per year, suggesting that body mass
remains a fundamental determinant of maturation and training adaptation. It should be noted that the force a swimmer is able to apply to the water, is done so with a propelling efficiency,\textsuperscript{198} which is highly dependent on the swimmers’ body mass. Whether or not body mass can distinguish between elite-level and World-class swimmers in events of varying stroke and distance remains unknown.

### 2.5 Materials and methods

**Research questions**

The age, height, and body mass of swimmers may be influenced by a number of contextual factors such as gender, the year of data collection (e.g., 60’s vs. 90’s), the swimming stroke (e.g., BR vs. BK), the event distance/duration (e.g., 100-m vs. 800-m), and the calibre of the swimmer (e.g., finalist and non-finalist). Our analyses in the context of these factors may provide further clarity on the current optimal age, height, and body mass of elite-level and World-class swimmers. The present study reviews and interprets previous literature providing the reader with a summary regarding what is currently known about the age and physical characteristics of elite-level swimmers. In addition, we explored new data collected from FINA archival sources (Source: http://www.fina.org/athletes) to compare the changes in age, height, and body mass among swimmers competing at the 1968 Mexico City (Mexico), 1992 Barcelona (Spain), and 2016 Rio (Brazil) Olympic Games, in order to identify changes and differences over the past 50 years. All observations (published or new) are restricted to events strokes of the FR, BK, BR, and FL and distances of between 50-m to 1500-m, thus excluding all open-water races and individual medley events. This study meets the ethical standards set out in the Ethical Standards in Sport and Exercise Science Research document.\textsuperscript{199} The present review aims to answer the following research questions:
Does age, height, and body mass vary according to competition year, and if so, is this dependent on the gender and calibre of the swimmer, as well as the race distance? To answer this research question, we used data from swimmers competing in the following categories:

1968, 1992, and 2016 Olympic Games
Female and male swimmers
Top 1-10 (World-class) and 11-20 (elite level) race times
FR 100-, 200-, 400-, 800-, and 1500-m events

What is the mean age, height, and body mass of current swimmers in the context of gender, race distance and stroke, as well as the calibre of the swimmer? To answer this research question, we used data from swimmers competing in the following events:

2016 Olympic Games
Female and male swimmers
Top 1-10 (World-class) and 11-20 (elite level) race times
FL, BK, BR, FR 100- and 200-m events

Statistical analyses

Data presented are mean ± standard deviation (SD). We performed a linear mixed model (LMM) to determine the effect of competition year, gender, calibre of swimmer, and race distance on the age, height, and body mass of swimmers. Where
there was an interaction or main effect involving gender, we interpreted the pairwise comparisons with Bonferroni adjustments. However, in order to reduce the complexity of the interpretation, LMM analyses were also performed independently for female and male swimmers to examine the effect of competition year, calibre of swimmer, and race distance on the age, height, and body mass of swimmers. Where a significant interaction or main effect of the factors (year, calibre, distance) was observed, pairwise comparisons with Bonferroni adjustments were performed. Also, a LMM was used to describe and compare the current (2016 Olympic Games) age values of 100- and 200-m swimmers according to gender, race distance and stroke, and calibre of swimmer. For height and body mass, separate LMM’s were used for both female and male data. Where a significant interaction or main effect was observed, pairwise comparisons with Bonferroni adjustments were performed to identify differences between pairs of experimental groups. Significance was accepted at $p \leq 0.05$.

2.6 Findings and results

Summary of findings in previous literature

Age

Konig et al.,$^{172}$ presents the most comprehensive investigation regarding the ages of swimmers examining all races held in both the World Championships (1994–2013) and the Olympic Games (1992–2012). These authors found that over a 20-year period from 1992 to 2013, the age of World-class swimmers (i.e., finalists) has generally increased.

Female and male swimmers competing at the 1991 World Championships were 19.5 and 21.3 yr, respectively,$^8$ which is similar to the mean ages reported by Schulz
and Curnow\textsuperscript{161} for Olympic gold-medal female and male FR swimmers between 1896-1936 (18.0 and 21.1 yr) and between 1948-1980 (17.9 and 19.9 yr). The trend in the aforementioned studies indicating female swimmers to be younger when compared with male swimmers is supported by the mean ages reported for female (19.1 yr) and male (21.3 yr) swimmers competing at the 1988 Seoul Olympic Games.\textsuperscript{171} Furthermore, in Barcelona (1992 Olympic Games), female 50-, 100-, and 200-m FR swimmers were typically 8-9\% younger compared with male swimmers.\textsuperscript{96}

Female 100-m (all-strokes) finalists (18.0 yr) were reported as being of similar age to non-finalists (17.3 yr) at the 1976 Olympics.\textsuperscript{9} Nonetheless, the age effect on swimming performance (i.e., calibre), has been reported by a number of previous authors suggesting that older swimmers are more successful than younger swimmers.\textsuperscript{8,171} Carter and Ackland,\textsuperscript{8} reported that the ‘best’ (i.e., top-12 placings) male swimmers (across distance and stroke) at the 1991 World Championships were significantly older compared with the ‘rest’ (remaining participants), whereas distinction among swimmer calibre based on age was not observed in the female cohort, regardless of the event distance or stroke.

Schulz and Curlow\textsuperscript{161} report advancing age as event distance in FR swimming decreases from the 800/1500-m FR (16.0 and 19.4 yr) to the 100-m FR (20.3 and 20.8 yr) in women and men, respectively. This trend is not replicated in the findings of Carter and Ackland,\textsuperscript{8} who report female distance (22.8 yr) swimmers to be older than sprint and middle-distance (19.3 yr) swimmers. Nonetheless, the same disparity between event distance was not observed for male swimmers (21.8 and 21.3 yr, respectively).\textsuperscript{8} Arellano et al.,\textsuperscript{96} reported that the average age of swimmers
was lower as race distance increased from 50-, to 100- and 200-m FR supporting the findings of Schulz and Curlow.\textsuperscript{161} Indeed, the race-distance effect on age is clear in the study by Konig et al.,\textsuperscript{172} who report both female and male 50- and 100-m FR finalists to be older than their distance swimming (i.e., 400-1500 m) counterparts. This is true for both female and male FR finalists at the 1992, 2000, and 2012 Olympic Games.

Although the evidence is scant, FR swimmers may be older compared with swimmers favoring other strokes. Konig et al.,\textsuperscript{172} reports FR 50- and 100-m swimmers (20.7, 24.8, 24.8 yr) to be older than swimmers of the BR (20.1, 19.8, 22.5 yr), BK (19.0, 21.5, 21.6 yr), and FL (20.7, 23.4, 22.4 yr) for the 1992, 2000, and 2012 Olympics, respectively. Nonetheless, female and male FR swimmers at the 1988 Seoul Olympic Games were not different in age compared with swimmers participating in other strokes.\textsuperscript{171} Carter and Ackland,\textsuperscript{8} do not report a stroke effect on age for swimmers competing at the 1991 World Championships; given the complexity and completeness of the study, it might be assumed that age was not different among strokes for female and male swimmers.
Figure 1: The age (top), height (middle), and body mass (bottom) of female (dark grey) and male (light grey) swimmers competing at the 1968 Mexico, 1992 Barcelona, and 2016 Rio Olympic Games. Statistical significance is indicated in the text.

**Height**

There is no doubt that elite-level swimmers have increased in height over time. At the 1968 Olympic Games, female and male swimmers were on average 163.8 and 178.8 cm, and were then measured at a height of 170.9 and 183.3 cm at the 1988
Seoul Olympic Games,\textsuperscript{171} and at 171.5 and 183.8 cm at the 1991 World Championships,\textsuperscript{8} respectively. Mazzilli,\textsuperscript{167} provides a comprehensive analyses of the height of 50- and 100-m FR medalists at the Olympic Games and World Championships from 1908-2016 reporting a large increase in the height of female and male swimmers from the early- (1908-1968: 170.7 ±1.8 and 183.5±0.9 cm) to the late- (1972-2016: 177.0±0.6 and 193±0.5 cm) 20\textsuperscript{th} century. Perhaps the most interesting observations regarding height is the appreciable differences in height between swimmers of varying calibre as well as among those competing in varying strokes and distances.

In general, Carter and Ackland,\textsuperscript{8} reported that the ‘best’ (top-12) female and male swimmers performing at the 1991 World Championships to be taller than the ‘rest’ (remainder of population of swimmers at the World-Championships), while Khosla \textsuperscript{9} reported that the height of female finalists (172.1 cm) at the 1982 Olympics were taller than those swimmers who didn’t qualify for finals (168.6 cm). The notion that the calibre of swimmer is associated with height is supported by the findings of Kennedy et al.,\textsuperscript{171} who examined female and male Olympic swimmers in the 100-m events. These authors reported a significant relationship between height and race time and suggest that taller swimmers are more successful. Even more compelling, are the results of Arellano et al.,\textsuperscript{96} who concluded that across all events the factor of height accounted for 25-56\% of the variability in race time. Nonetheless, Arellano et al.,\textsuperscript{96} provides no support for an effect of race distance, reporting 50-100, and 200-m FR swimmers competing at the 1992 Olympic Games were of a similar height.

At the 1968 Olympic Games, height did not distinguish female swimmers competing in events of varying stroke,\textsuperscript{170} whereas male FR swimmers were reported to be taller than BR swimmers. Although no statistically significant effect of stroke
on height was reported for swimmers performing at the 1988 Olympic Games, Kennedy et al., reported taller female and male swimmers for FR and BK when compared with FL and BR. This is in agreement with the findings of Carter and Ackland, who reported that FR events featured taller swimmers when compared with other strokes.

**Body mass**

It is reasonable to suspect that the body mass of World-class and elite-level swimmers has increased over time due to the strong positive relationship between height and body mass \((r=0.79-0.85; \text{Arellano et al., 1994})\). Surprisingly, not all studies examining Olympic and World Championship swimmers report body mass despite performing comprehensive analyses on age, and height. This is possible since age and height are stable and can be recalled by swimmers, and reported by FINA, with a high-level of accuracy. Nonetheless, body mass is more variable; thus, if body mass is not directly measured by the research group, it is unclear exactly when body mass was recorded and by what method (i.e., recall or measurement). In addition, the strong relationship between height and body mass may render body mass a redundant variable in regression-type analyses that use anthropometric variables to predict swimming performance.

Arellano et al., published ‘self-reported’ values for the body mass of female and male 50- (61.6±7.1 and 76.6±10.8 kg), 100- (61.8±7.2 and 76.8±10.1 kg), and 200-m (61.9±7.1 and 76.8±8.2 kg) FR swimmers performing at the 1992 Barcelona Olympic Games. Aside from the obvious gender differences, no other effect (distance, race time) on body mass was reported. The values for body mass reported by Arellano et al., are like those reported for male (74.2±7.1 kg), but not female
(53.4±9.9 kg) FR swimmers at the 1968 Mexico Olympic Games. Carter and Ackland,\textsuperscript{200} tabled the mean ± SD as well as the minimum and maximum values for body mass of female and male swimmers by stroke and distance. The lightest male swimmer at the 1991 World Championships (excluding open-water and individual-medley swimmers), reported in the KASP study,\textsuperscript{8} was a 50-/100-m BK swimmer weighing 60.4 kg. The heaviest was a middle-distance (200- and 400-m) FR swimmer weighing 95.8 kg. Despite the large variability in the body mass of male swimmers observed, there was no statistically significant effect of race stroke or distance on body mass\textsuperscript{8} with mean values for FR (78.9±7.3 kg), BR (76.6±6.5 kg), BK (78.8±8.1 kg) and FL (79.2±5.3 kg) swimmers of all distances being similar. A female 200-m BR swimmer was the lightest of all swimmers (46.6 kg) and almost 30 kg lighter than the heaviest female swimmer (200/400-m FR; 75.1 kg). Indeed, all 200-m (57.5±6.5 kg) female BR swimmers (but not 50-/100-m; 64.0±5.3 kg) tended to be lighter than both 50-/100-m (65.0±5.8 kg) and 200-/400-m (64.6±6.3 kg) female FR swimmers (p<0.05). There were no other significant differences in body mass between other race strokes and distances in female swimmers.\textsuperscript{8}

Remarkably, body mass did not distinguish the ‘best’ female swimmers from the ‘rest’ in any race stroke or distance, whereas male swimmers finishing in the top-12 placings (i.e., ‘best’) in the 200-/400-m FR and 50-/100-m BR events were heavier compared with swimmers placing outside the top-12 (i.e., ‘rest’) in the same event. Nonetheless, it is interesting to note, that for all strokes and distances in both female and male events, the mean body mass of the ‘rest’ swimmers was lower than the mean body mass of the ‘best’ swimmers in every instance.
2.7 Analysis of findings from new data

Age

Data from the 1968 (Mexico City, Mexico), 1992 (Barcelona, Spain), and 2016 (Rio, Brazil) Olympics indicate that there has been an overall increase in the age of FR (FR) swimmers of about 10% for each 24-year period (Figure 1). In 1968, female FR swimmers were younger than male FR swimmers (p<0.001; 16.7±2.1 and 20.1±2.4 yr, respectively) and despite a ~15% increase in age, female FR swimmers remained significantly younger compared with male FR swimmers in 1992 (p<0.001; 19.7±2.4 and 21.8±2.9 yr, respectively). The age of male FR swimmers varied by just ~4% from 1992 to 2016, whereas the age of female FR swimmers again rose by ~16%, resulting in little difference in the age of female (22.7±3.8 yr) and male (22.6±2.8 yr) FR swimmers at the Rio Olympics (p=0.864). When a LMM was run separately for female data, there were no interactions among the fixed factors (year, distance, and calibre), and year (F=85.234, p<0.001) was the only factor distinguishing the age of FR swimmers. Indeed, the age of female FR swimmers increased from 1968 to 1992 (p<0.001) and from 1992 to 2016 (p<0.001). Similarly, in male FR swimmers, there were no interactions among the fixed factors. However, both year (F=18.696, p<0.001) and distance (F=4.912, p<0.001), but not calibre, influenced age (Figure 1). As implied earlier, male FR swimmers were younger in 1968 compared with 1992 (p<0.001), and their age did not change from 1992 to 2016 (p=0.153). Regardless of Olympic Games year, male 100-m (p=0.019, p=0.718) and 200-m (p=0.004, p=0.250) FR swimmers were older than 1500-, but not 400-m FR swimmers, respectively.

Using data from the 2016 Rio Olympics, age was not dependent on any interaction or main effect of gender, race distance or stroke, or calibre of swimmer.
Height

Height was analyzed using separate LMM’s for female and male FR swimmers. Year was the only distinguishing factor regarding the height of female FR swimmers (F=39.244, p < 0.001). Female FR swimmers at the 1992 (175.0±6.1 cm) Olympic Games were taller than FR swimmers in 1968 (168.2±4.1 cm; p<0.001), but there was no further change in height from 1992 to 2016 (173.2±6.5 cm) in female FR swimmers (p=0.544). In male FR swimmers, there was no interaction among the three fixed factors (year, distance, and calibre) regarding height. However, year (F=44.299, p<0.001), distance (F=7.843, p<0.001) and calibre (F=8.512, p=0.004) had a main effect on the height of male FR swimmers. Male FR swimmers did not differ in height between the 1992 (189.0±6.7 cm) and 2016 (189.0±6.3 cm) Olympic Games (p>0.999), whereas male FR swimmers were shorter in 1968 (180.9±5.8 cm) compared with both 1992 (p<0.001) and 2016 (p<0.001).

There is an appreciable trend for increasing height in male FR swimmers as the race distance shortens. Significant differences in height were observed between race distances at least two levels away. For example, 100-m (188.6±7.4 cm) FR swimmers were taller than 400- (184.8±6.5 cm; p=0.019) and 1500-m (183.4±7.3 cm; p<0.001) FR swimmers, but not 200-m (187.4±6.9 cm; p>0.999) FR swimmers. Also, 200-m FR swimmers were taller than 1500-m (p=0.003) FR swimmers but not 400-m (p=0.166) FR swimmers, and there was no difference in height between 400- and 1500-m FR swimmers (p>0.999). Finally, male FR swimmers ranked 1-10 (187.4±0.6 cm) were taller (p=0.004) than those ranked 11-20 (185.0±0.6 cm).
There were no interaction effects on height among the fixed factors (stroke, distance, calibre) for either female or male swimmers performing at the 2016 Rio Olympic Games. However, main effects of stroke ($F=4.625$, $p=0.004$) and calibre ($F=7.913$, $p=0.006$) were apparent for female swimmers, whereas stroke ($F=3.645$, $p=0.014$) was the only factor imposing an effect on height in male 2016 Olympic swimmers. In both female (176.7±1.0 vs. 172.3±1.1 cm; $p=0.020$) and male (191.0±1.0 vs. 186.7±1.0 cm; $p=0.012$) 2016 Olympic swimmers, FR swimmers were taller than FL swimmers, respectively. This was the only distinction among strokes in male swimmers, whereas female BK (BK) swimmers (177.0±1.2 cm) were also taller than FL swimmers ($p=0.023$) (Table 3).

Regardless of whether a male swimmer, competing at the Rio Olympic Games, was classified at the elite-level (i.e., race ranking 11-20; 188.5±0.7 cm) or as World-class (i.e., race ranking 1-10; 188.1±0.7 cm), their height was similar ($p=0.729$). This contrasts with World-class (176.4±0.7 cm) female swimmers who in 2016 were taller than their elite-level counterparts (173.4±0.8 cm, $p=0.006$) (Table 2c).
### Table 2c. Age, height, and body mass of World-class and elite-level freestyle swimmers at the 1968, 1992, and 2016 Olympic Games.

<table>
<thead>
<tr>
<th>Year</th>
<th>Gender</th>
<th>Calibre</th>
<th>Age</th>
<th>Height</th>
<th>Body Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>1968</td>
<td>World-class</td>
<td>18.3±1.8</td>
<td>168.7±5.4</td>
<td>61.7±3.4</td>
<td>17.5±2.4</td>
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<tr>
<td>1992</td>
<td>World-class</td>
<td>20.5±2.9</td>
<td>176.3±5.7</td>
<td>66.3±4.8</td>
<td>20.0±3.4</td>
</tr>
<tr>
<td>2016</td>
<td>World-class</td>
<td>22.0±3.3</td>
<td>179.7±4.0</td>
<td>67.4±7.2</td>
<td>22.3±3.4</td>
</tr>
<tr>
<td>1968</td>
<td>Elite-level</td>
<td>17.8±1.8</td>
<td>169.2±3.0</td>
<td>61.6±7.0</td>
<td>16.0±1.5</td>
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<tr>
<td>1992</td>
<td>Elite-level</td>
<td>19.6±2.8</td>
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<tr>
<td>2016</td>
<td>Elite-level</td>
<td>22.8±4.7</td>
<td>174.6±3.0</td>
<td>64.2±7.5</td>
<td>22.3±4.4</td>
</tr>
</tbody>
</table>

**NB:** World-class = top-10 race times; Elite-level = 11-20th race times. A = age (yr), H = height (cm), BM = body mass (kg).
Body mass

As expected, body mass followed a similar pattern to height whereby year was the only distinguishing factor regarding the body mass of female FR swimmers (F=15.435, p<0.001). Female FR swimmers at the 1968 (58.8±0.8 kg) Olympic Games were lighter than FR swimmers in 1992 (63.6±0.9 kg; p<0.001), and there was no further change in body mass from 1992 to 2016 (64.6±0.7 kg) in female FR swimmers (p>0.999). Nonetheless, while there was no interaction among the three fixed factors, year (F=11.203, p<0.001), distance (F=10.532, p<0.001) and calibre (F=6.840, p=0.010) all had independent main effects on the body mass of male FR swimmers. Male FR swimmers were lighter in 1968 (76.0±0.8 kg) compared with both 1992 (p<0.001) and 2016 (p<0.001), but their body mass did not differ between the 1992 (80.5±0.9 kg) and 2016 (80.5±0.8 kg) Olympic Games (p>0.999). Distance was also associated with the body mass of male FR swimmers with 100-m (82.3±0.9 kg) FR swimmers reporting to be heavier compared with 400-m (77.7±1.0 kg) and 1500-m (75.5±0.9 kg), but not 200-m (80.5±0.9 kg) FR swimmers. Like height, significant differences in body mass were observed between race distances at least two levels away and across all years and race distances, FR swimmers ranked 1-10 (80.2±0.6 kg) were heavier (p=0.010) than FR swimmers ranked 11-10 (77.8±0.7 kg).

Only stroke (F=2.779, p=0.044) in female, and distance in male (F=5.068, p=0.026) swimmers had a significant effect on body mass in swimmers ranked 1-20 competing in their respective event at the 2016 Rio Olympic Games. Female FR swimmers (64.8±1.1 kg) were heavier compared with FL swimmers (60.5±1.2 kg; p=0.050) and male 100-m swimmers (82.7±0.8 kg) were heavier than 200-m swimmers (79.9±0.9 kg; p=0.026). There were no other significant differences in
body mass among race stroke and distance for female and male swimmers, respectively (table 3).
Table 3. Mean performance times, age, height, and body mass of World-class and elite-level swimmers at the 2016 Olympic Games.

<table>
<thead>
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<th>STROKE</th>
<th>GENDER</th>
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<td>T</td>
<td>A</td>
<td>H</td>
<td>BM</td>
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<tr>
<td>Freestyle</td>
<td>Women</td>
<td>World-class</td>
<td>00:53.1±00:00:4</td>
<td>22.0±3.3</td>
<td>179.7±4.6</td>
<td>67.4±7.2</td>
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<tr>
<td></td>
<td></td>
<td>Elite-level</td>
<td>00:54.3±00:00:2</td>
<td>22.8±4.7</td>
<td>174.6±5.4</td>
<td>64.2±7.5</td>
</tr>
<tr>
<td></td>
<td>Men</td>
<td>World-class</td>
<td>00:48.0±00:00:2</td>
<td>22.2±3.2</td>
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<td>24.3±3.4</td>
<td>188.7±5.5</td>
<td>84.9±4.4</td>
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<td></td>
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<tr>
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<td>21.7±4.5</td>
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<td></td>
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<td>22.8±2.9</td>
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NB: World-class = top-10 race times; Elite-level = 11-20th race times. T = race time (mm:ss.00); A = age (yr), H = height (cm), BM = body mass (kg).
2.8 Summary

World-class swimmers in the 2010’s

We briefly explored why it may be advantageous for swimmers to be older, taller, and heavier (see section 2c). Furthermore, differences in the physiological, biomechanical, and psychological demands required for success in different swimming events are likely contributors to the variability in the age and physical characteristics observed. For example, varying event distances (and therefore durations) among events might dictate, in part, the physical characteristics of athletes either as a result of the demands of the sport, or by way of natural selection. Given the reliance on lower-body muscle power and anaerobic energy production in shorter (e.g., 100 m) compared to longer (e.g., 800 m) swimming events it might be reasonable to suggest that athletes competing in sprint-swimming events possess a larger muscle mass compared to athletes in distance events. However, these questions remain: i. Why are FR swimmers older than they were in 1968, and why are female FR swimmers older now than in 1992? ii. Are the increases in height and body mass observed in FR swimmers over 50 yr commensurate with changes in height and body mass of the general population, or are they over and above any population-related increase? If so, why? iii. Have we reached the optimal age, height, and body mass ranges for peak swimming performance?

It is plausible that the age of swimmers has increased from 1968 to the present day due to financial, sociological, and political influences. For both men and women, growing governmental and private investment in sport has provided athletes with the opportunity to continue training and competing in their sport without the pressure to retire early and work. Furthermore, increasing financial investment in
sport has contributed to the improvement in illness/injury prevention and rehabilitation strategies that afford athletes the ability to continue training and competing, after a once career-ending experience. The remaining age difference between female and male Olympic FR swimmers observed in the 1990’s might be explained by the persisting influence of women-specific social expectations such as ‘family commitment (i.e., marriage and children)’ or early government sport-scholarship programs that seemed to exclude women despite their ‘podium potential’ and previous achievements (e.g., Although women in Australia were the greatest source of Olympic medals, the Australian athletic union nominated no women athletes for Olympic track and field scholarships in 1977). Nonetheless, the landscape has changed, due in part, to legislation such as ‘Title IX’ (USA, 1972) and the ‘Commonwealth Sex Discrimination Act’ (Australia, 1984). With a shift in social expectations and financial support, it has become more feasible for women to continue swimming competitively beyond their teenage years.

Recognizing that there has been a significant increase in the human height over the last 100 years, Mazzilli stated that changes in the height of the general population may explain some of the observed increase in the height of elite-level swimmers. Furthermore, given the pace of growth in height has not been uniform among countries, it is possible that the increased number of swimmers with varied ancestral origin competing at the Olympic Games may have also contributed to the increase in the height of Olympic swimmers. Nonetheless, given the increasing awareness of the relationship observed between height and swimming performance, it is likely that both natural selection and talent identification have contributed to the increased height of swimmers over and above what is observed in the general population. All things being equal, an increase in
height results in a concomitant increase in body mass. Therefore, there is no surprise that swimmers’ body mass has followed the same pattern as their height; that is, both the height and body mass of World-class and elite-level swimmers increased from the 1968 to the 1992 Olympic Games with no further increase from 1992 to 2016 Olympic Games. However, training and nutritional interventions that support skeletal muscle growth such as resistance exercise training and high-protein diets may also contribute to an increase in body mass independent of height. Without measurements of body composition, it is difficult to know if changes in the body mass of swimmers over time are a result of increases in lean mass alone.

Interestingly the findings of the present study suggest that in order of size, FR are the largest with FL swimmers being the smallest, with BK and BR swimmers residing in the middle of this spectrum. Whilst conclusive evidence as to why this ordering may occur is not available, it could be postulated that swimmers typically start learning to swim FR before the other strokes, with FL the last stroke for young swimmers to develop. Therefore is could be hypothesized that the longer time spent developing the strength and technical attributes in freestyle provides the taller swimmers greater lengths of time to become strong and coordinated enough to become competitive at the world level.

What remains to be seen are any further changes in the age, height, and body mass of World-class and elite-level swimmers. Given that age has now plateaued in female swimmers, and at the same level as men, it could be suggested that the optimal age for swimmers has been reached. Further support for this notion is the observation that there is no age difference between World-class and elite-level swimmers. However, it is unknown exactly why, in 2016, swimmers retire. If the
future brings greater financial support, improved illness and injury prevention strategies, and longer-term training interventions, it is possible that the average age of World-class swimmers will change. Nonetheless, with the benefit of previously published data, as well as newly analyzed historical and recent data, we have summarized in a snapshot, the age and physical characteristics of World-class swimmers as at 2016:

Female World-class swimmers are:
22.7±3.6 yr; independent of race distance, stroke, calibre, but older than in the 1990’s
175.1±6.6 cm; but FR taller than FL and taller than elite-level swimmers
63.8±6.8 kg; but FR heavier than FL and heavier than elite-level swimmers

Male World-class swimmers are:
23.2±3.3 yr, independent of race distance and stroke, and calibre
188.3±6.0 cm; but FR taller than FL, and sprinters taller than distance
81.3±7.3 kg; but FR heavier than FL

Considerations and conclusions

Before formulating generalized conclusions, it should be recognized that several weaknesses exist in the data of the present study. Firstly, some of the data represented in previously published research and all the newly presented data is based on self-recall. The age, height, and body mass of swimmers in the new data analyzed in the present study was extracted from FINA. Thus, the exact values at the time of the race were not determined. Although age and height self-recall could
be considered reliable due to the stable nature of these measurements, body mass might attract greater error due to the within- and between-day fluctuations associated with body mass as well as the errors associated with measurement variability. Therefore, it is likely that there is some error in the present data. Consequently, we assumed that the deviations from the very exact values for body mass compensated one another by normal distribution. It should also be noted that there are frequent anomalies and individual differences in the characteristics of World-class swimmers that do not necessarily conform to the mean values provided here. For example, in 2008 a female swimmer won a silver medal aged 41 yr, while in 2012 two female swimmers won gold at 15 yr, which suggests that the experience required to reach an international medal, may not be as definitive as some physical characteristics.

Throughout this 50 year period there have been many changes in the rule and regulations within swimming competition which may influence the changes seen in the characteristics and age of swimmers. These include: i) the use of technical racing suits, which created greater buoyancy for the swimmers. ii) the number of competitors per nation has decreased which means that nations with a greater height and mass within their population would not skew the central tendency of the swimmers at a major championships. iii) the inclusion of international doping controls, now means that in 1992, and 2016 the data should be rid of athletes who have unnatural influences on their physical characteristics.

It should be noted that the outcomes from each of these studies are based on one specific event; and contextual factors of the event location may suit the characteristics of a given swimmer For example, contextual factors such as the
altitude or temperature and humidity during the competition may be more advantageous for a given swimmer that is more adapted to these conditions.

The data collated for this present study was manually extracted from online sources; however, there are recent methodologies which use machine learning techniques, such as Wisdom of Crowd Classifier (WoCC), to determine trends and predict swimming performance. A recent study used such techniques to analyze the age trends in junior swimming from over 4,000,000 races. If height, body mass, and other anthropometric measures could be collected in World-class swimmers, then the use of machine learning techniques could be extremely useful in talent identification and the classification of World-class swimmers.

The age, height, and body mass of swimmers has been consistently reported over time, providing some valuable information about the optimal characteristics of World-class swimmers. However, as technological advances in sports science and medicine create new opportunities to collect data on World-class and elite-level athletes, an opportunity to produce more precise models to predict performance potential may arise.
Chapter 3: Investigative

Study 2
3.0 Declaration of co-authorship Thesis Chapter 3

This chapter includes a co-authored paper:


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

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<th>Nature of Contribution</th>
<th>Extent of Contribution (%)</th>
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<tr>
<td>Study design</td>
<td>60%</td>
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<tr>
<td>Data collection</td>
<td>80%</td>
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<tr>
<td>Analysis and interpretation</td>
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Candidate Signed:  
Adam Mallett  
Date: 25/8/20

Co-authorship declaration:

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<td></td>
<td>8th October 2020</td>
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<tr>
<td>Prof Wim Derave</td>
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<td>8th October 2020</td>
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<tr>
<td>A/Prof Clare Minahan Supervisor</td>
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3.1 Title: Muscle fiber typology and its association with start and turn performance in elite swimmers.

Submission Type: Original investigation

Authors: Adam Mallett¹, ², Phillip Bellinger¹, ², Wim Derave³, Eline Lievens³, Ben Kennedy⁴, Hal Rice⁴, Clare Minahan¹

Affiliations:
¹Griffith Sports Science, Griffith University, Gold Coast, Queensland, Australia.
²Queensland Academy of Sport, Nathan, Queensland, Australia
³Department of Movement and Sports Sciences, Ghent University, Ghent, Belgium
⁴Qscan Radiology, Australia

Corresponding Author:
Adam Mallett
School of Allied Health Sciences, Griffith University, Queensland, Australia, 4222.
Phone: +61 (0) 456782313
Email: adam.mallett@griffithuni.edu.au
ORCID: 0000-0002-7507-4464

Running Head: Swim Start and Muscle Fiber Type

Abstract word count: 250

Text-only word count: 3504

Number of tables: 3

Number of figures: 1
3.2 Abstract

**Purpose:** To determine the association between estimated muscle fiber typology and the start and turn phases of elite swimmers during competition. **Methods:** International and national competition racing performance was analyzed from twenty-one female (FINA points 894±39: 104.5±1.8%WR) and twenty-five male (FINA points 885±54: 104.8±2.1%WR) elite swimmers. The start, turn and turn out time were determined from each of the swimmers’ career best performance time (FINA points 889±48: 104.7±2.0%WR). Muscle carnosine concentration was quantified by proton magnetic resonance spectroscopy in the gastrocnemius and soleus and was expressed as a carnosine aggregate Z-score relative to an age and gender matched non-athlete control group to estimate muscle fiber typology. Linear mixed models were employed to determine the association between muscle fiber typology and the start and turn times. **Results:** While there was no significant influence of carnosine aggregate Z-score on the start and turn time when all strokes and distance events were entered into the model; swimmers with a higher carnosine aggregate Z-score (i.e., faster muscle typology) had a significantly faster start time in 100-m events compared to swimmers with a lower carnosine aggregate Z-score ($P=0.02$, $F=5.825$). The start and turn time were significantly faster in male compared to female swimmers, in the 100-m events compared to other distances and between the four different swimming strokes ($P<0.001$). **Conclusion:** This study suggests that start times in sprint events, are partly determined (and limited) by muscle fiber typology, which is highly relevant when ~12% of the overall performance time is determined from the start time.

**Keywords:** Carnosine, swim start, swim turn, World-class swimmers, muscle fiber composition
3.3 Introduction

In order to analyze competitive swimming performances, races can be segmented into different phases: i) swim time: the total time taken to swim the entire distance of the race, ii) splits: The time taken to swim each 50-m lap of the race, iii) start time (StT): the time taken to complete the first 15-m, iv) turn time (TnT): the total time taken to complete the last 5-m (approach) and first 7.5- to 15-m (departure) of consecutive laps, v) turn out time (ToT): the time taken from the initial touch on the wall within the turn phase, to the 7.5- to 15-m point on the subsequent lap; vi) free swim time: the swim time during the free swimming segments of the race.

Analyzing swimming races in this way indicates that successful performance relies heavily on the StT and TnT, as the combination of these segments can equate to greater than 25% of the overall performance time (i.e., ~20% in 50-m events, or ~28% in a 1500-m events). Given that swimming events at the Olympic Games and World Championships can be won or lost by margins of 0.01 s, understanding the determinants of StT and TnT is warranted.

It is well established that several biological systems must be optimized for superior athletic performance and that the measurement of physiological, biomechanical, and psychological characteristics can be used to understand the limiting factors of performance. However, most previous studies that demonstrate strong associations between swimming performance and physical attributes examine characteristics that change with maturation, training, and/or other factors. For example, elite swimmers demonstrate higher maximum muscle strength of the shoulder muscles compared to recreational swimmers, which may be a result of training, while the enhanced ‘mental toughness’ evident in elite swimmers has also been found to change with training. Therefore, research that examines
genetically determined physical characteristics may offer promising explanations of aspects of performance that cannot be solely explained by training.\textsuperscript{214} One key physical characteristic that is principally genetically determined is skeletal muscle fiber typology.\textsuperscript{25,218} Indeed, muscle fiber typology seems to be resistant to changes in response to prolonged training and detraining; given that young talented, active elite and retired ex-elite athletes competing in sprint and endurance disciplines have polarized muscle fiber typology.\textsuperscript{28,219}

The muscle fiber typology of human skeletal muscle is the degree to which the muscle is made up of type I and type II fibers, often referred to as slow-twitch and fast-twitch, respectively. Type I and type II fibers show great variation in their respective mechanical and physiological characteristics, which in turn dictates the performance characteristics of the muscle.\textsuperscript{11,12} The maximal shortening velocity of type II muscle fibers is substantially greater than type I muscle fibers, contributing to the superior maximal power output of these fibers.\textsuperscript{4} Furthermore, type II fibers are characterized by a greater ATPase activity, creatine phosphate and glycogen content and shorter excitation times when compared to type I fibers.\textsuperscript{11,12} As such, these characteristics are thought to be important for activities that are limited by maximal muscular power output and rate of force development (e.g. jumping, and sprinting).\textsuperscript{14} Therefore, it could be suggested that muscle fiber typology may be important for swimming performance parameters that require a high level of muscular power output, such as the StT, TnT and ToT. For example, the ability to rapidly produce force and power in lower body limbs, has been shown to influence the StT in swimming.\textsuperscript{92,220,221}
A previous study has developed a non-invasive methodology to estimate the muscle fiber typology, based on the proton magnetic resonance spectroscopy (\(^1\)H-MRS) derived measurement of intra-muscular carnosine\(^{219}\). Carnosine is a stable, dipeptide that has a two-fold higher concentration in type II fibers\(^{73,222}\) and is associated with the muscle biopsy determined percentage area occupied by type II fibers (\(P < 0.01\) and \(r = 0.71\))\(^{219}\). Bex et al.,\(^{223}\) demonstrated the construct validity of this technique by confirming that explosive sprint athletes had the highest carnosine Z-scores, endurance athletes had the lowest, while middle-distance athletes were typically situated within these extreme disciplines. The present study aimed to use this non-invasive technique to assess the influence that muscle fiber typology has on the start and turn times of elite and world-class swimmers. It is hypothesized that swimmers with higher carnosine Z-score values would have a faster StT, TnT, and ToT.

3.4 Methodology

Subjects

Twenty-one female and twenty-five male elite swimmers volunteered to participate in the present study. The characteristics of the swimmers are presented in table 1. All swimmers had been ranked in the world top-100 in their best swimming event (highest FINA points scoring event), within four years of the \(^1\)HMRS measurement in the present study. No swimmer was vegan or vegetarian or had consumed β-alanine supplementation in the 3 months prior to the study, in order to restrict unnatural influences to muscle carnosine concentration. Previous research has shown decreases in carnosine concentrations to be “very low or even non-existent” from adulthood to eldely,\(^{224}\) and relatively stable over a period of 3-months.\(^{46}\) The
study was approved by the Griffith University Human Ethics Committee and subjects gave their written informed consent to participate.

Research Design

An observational research design was employed for the present study. Subjects attended a radiology clinic on one occasion to have their muscle fiber typology estimated using $^1$H-MRS to measure the carnosine content of the gastrocnemius and soleus. The subject’s career best race performances were analyzed and linear mixed models were employed to determine the association between muscle fiber typology and start and turn times.

Muscle Fiber Typology

Muscle carnosine content was measured by $^1$H-MRS in the soleus and gastrocnemius medialis muscle of each subject’s right limb in order to estimate muscle fiber type composition. $^1$H-MRS measurements were performed on a 3-T whole body MRI scanner (Philips Medical Systems Best, The Netherlands). Subjects were lying in a supine position, while their lower leg was fixed in a spherical knee-coil. All the spectra were acquired using single voxel point-resolved spectroscopy (PRESS) with the following parameters; repetition time (TR) of 2000 ms, echo time (TE) of ~40 ms, number of excitations was 128 (carnosine) and 16 (water), spectral bandwidth was 2048 Hz, and a total acquisition time of 4 min 16 s (carnosine) and 32 s (water). The voxel size was 40 mm x 15 mm x 20 mm. Spectral data analysis was carried out using jMRUI (version 6.0) with carnosine peaks fitted and expressed relative to the internal water signal. Carnosine content (mM) was calculated using following formula:
Table 1. Subject characteristics (mean ± SD).

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<th>Height (cm)</th>
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<tr>
<td></td>
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<tr>
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<td>± 25</td>
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<td>± 1.8</td>
<td>± 1.8</td>
<td>± 3.7</td>
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</table>
\[
C_m = \frac{(C_s)}{(H_2O_s)} \cdot \frac{(H_2O_{T1r})}{(CT_{1r})} \cdot \frac{(H_2O_{T2r})}{(CT_{2r})} \cdot H_2O_{\text{muscle}} \cdot H_2O_{\text{protons}}
\]

where \(C_m\) is the carnosine concentration, \(C_s\) is the carnosine signal, \(H_2O_s\) is the water signal, \(C_{T1r}, C_{T2r}, H_2O_{T1r}, H_2O_{T2r}\) are the relaxation correction factors for carnosine (earlier described by Baguet et al.\(^{219}\)) and water (earlier described by MacMillan et al.\(^{225}\)), \(H_2O_{\text{muscle}}\) is the concentration of water in muscle in muscle, which was deducted from the molar concentration of water (55,000 mM) and the approximate water content of skeletal muscle tissue (0.7 L/kg wet weight of tissue) and \(H_2O_{\text{proton}}\) is the number of protons in water. The CV for test-retest inter-day carnosine measurements (approximately 7 days apart) in our laboratory was 3.5% (soleus) and 4.3% (gastrocnemius; \(n = 15\) subjects). The carnosine concentration of the soleus and gastrocnemius was converted to a sex-specific carnosine Z-score relative to a control population of active, healthy non-athletes, (males: \(n = 38\); females: \(n = 30\)). A carnosine aggregate Z-score was then derived by taking the average of the two muscle-specific carnosine Z-score values and was used for all analyses.

**Race Performance Analysis**

Although participants had to be ranked in the world top-100 within the past four years of the present study, races between 2010-2019 were analyzed for each participant with their career best performance used for the final analysis. Nonetheless, all career bests were detected to have been achieved within 2 years of the MFT determining scanning. Races were analyzed from the following competitions: Australian National Open Championships 2010 – 2019; the Olympic Games: Rio de Janeiro, Brazil 2016; London, UK 2012; the World Championships:
Barcelona, Spain 2013; Kazan, Russia 2015; Budapest, Hungary 2017; the Commonwealth Games: Glasgow, UK 2014; Gold Coast, Australia 2018; the Pan Pacific Championships: Gold Coast, Australia 2014; and Tokyo, Japan 2018. Video footage and analysis was acquired from Swimming Australia Ltd (SAL); all race analyses were performed by SAL sports science practitioners (intra-tester 95% confidence limits; StT ± 0.11, TnT ± 0.26 and ToT ± 0.15 s). The StT was defined as the time from the starting signal until the crown of the swimmers’ head crossed the 15-m mark; the TnT was defined as the time from the crown of the swimmer’s head passing the 5-m line prior to contact with the wall to the crown of the head reaching the 10-m line from the wall on the subsequent lap, whilst ToT was identified as the time from initial contact with the wall during the turn segment to the crown of the head passing 10-m on the subsequent lap. In order to integrate the data into a single analysis including both male and female, as well as all strokes, and race distances, a reference database (i.e. control population) of 220 races (FINA points 950 ± 22) was compiled. Ten swimming performances from each gender, stroke, and distance were analyzed and the StT, TnT, and ToT calculated. The mean ± SD for each performance parameter in every event in the reference database was determined, from which, individual subject performance parameter Z-scores were calculated in order to allow for an integrated analysis of swimmers across different events.

**Statistical Analysis**

All values are presented as mean ± SD. Participants in the present study were divided into two groups based on their carnosine aggregate Z-score. Participants were assigned to the high or low carnosine aggregate Z-score group if their score was above or below the median value of all subjects. A linear mixed model was
then used to determine the effect of carnosine aggregate Z-score group (i.e. high, or low) on StT, TnT and ToT. To determine if the race distance influenced the performance parameters, a linear mixed model was employed with the absolute (i.e., s.ms) StT, TnT and ToT values. “Finally, as the relative importance of the start and turn to overall performance is greater in 100-m events compared to events of greater distance, we used a linear mixed model to determine the effect of carnosine aggregate Z-score group on the race performance parameter.” Where a significant $F$ value for an interaction, or main effect was identified, pairwise comparisons were performed with Bonferroni adjustments where ‘differences’ were detected. The effect size ($d$) was calculated to assess the magnitude of difference between high and low carnosine aggregate Z-score groups. All statistical analyses were performed on IBM SPSS Statistics 25 and significance was accepted at $P < 0.05$.

We used an Excel spreadsheet$^{226}$ to determine the mean performance differences between positive and negative carnosine aggregate Z-score groups for each event. Analyses were performed separately for male and female athletes and only for events with at least two observations in each group. Mean effects for male and female athletes were combined using a separate Excel spreadsheet.$^{227}$ Confidence limits are approximate with our small sample size.

### 3.5 Results

The carnosine aggregate Z-score for the high and low groups were $0.60 \pm 0.52$, and $-0.57 \pm 0.33$ ($d = 2.69$). When high and low carnosine aggregate Z-score groups were compared, there was no influence of carnosine aggregate Z-score on StT ($F=3.20$, $P = 0.08$), TnT ($F = 0.97$, $P = 0.33$), and ToT ($F = 1.06$, $P = 0.31$) Z-scores (table 2). There were no significant interactions between gender, stroke, and distance on the absolute start and turn times, but there were significant main effects
for gender (StT, F = 235.67; TnT, F = 135.22; ToT, F = 102.25, P < 0.001) stroke,
(StT, F = 70.56; TnT, F = 178.56; ToT, F = 307.00, P < 0.001) and distance (StT,
F = 39.84; TnT, F = 74.31; ToT, F = 44.56, P < 0.001).

Absolute 100-m StT, TnT, and ToT were significantly faster when compared with
200-m StT (P < 0.01), TnT (P < 0.001) and ToT (P < 0.001) as well as 800/1500-m
StT and TnT (p < 0.001) (table 3). When 100-m event performance parameters Z-
scores were independently entered into a linear mixed model, the high carnosine
aggregate Z-score group had a significantly lower StT Z-score (high StT = 0.75 ±
1.15; low StT = 1.81 ± 1.51) (F = 5.825, P = 0.02), but there was no significant
differences in the TnT or ToT Z-scores between the two carnosine aggregate Z-
score groups (TnT, F = 2.56, P = 0.12; ToT, F=2.60, P = 0.116) (figure 1).

In the 100-m freestyle events, females in the high carnosine aggregate Z-score
group were substantially faster in both the StT (absolute difference ± 90%
confidence limits (CI); 0.48 ± 0.25 s) and TnT (0.43 ± 0.39 s) compared to the low
carnosine aggregate Z-score group, but there was no clear difference in ToT (0.28
± 0.31 s). Substantial performance differences between carnosine aggregate Z-
score groups were not observed in male 100-m freestyle swimmers; StT (0.02 ±
0.28), TnT (0.08 ± 0.74) and ToT (0.01 ± 0.31). However, the combined male-
female performance differences in the 100-m freestyle event, showed clear
differences between carnosine aggregate Z-score groups in StT (0.25 ± 0.17 s), but
not TnT (0.20 ± 0.62) or ToT (0.01 ± 0.12 s).
Table 2. The mean (± SD) StT, TnT and ToT Z-score for high and low carnosine aggregate Z-score groups, for each distance (100-, 200-, 400- and 800/1500-m).

<table>
<thead>
<tr>
<th>Event Distance</th>
<th>Carnosine Aggregate Z-score Group</th>
<th>Mean Performance Parameter Z-score (All strokes: FR/BK/BR/FL)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Start</td>
</tr>
<tr>
<td>100-m</td>
<td>High</td>
<td>0.75 ± 1.15</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>1.81 ± 1.51</td>
</tr>
<tr>
<td>200-m</td>
<td>High</td>
<td>0.04 ± 1.34</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>0.91 ± 1.22</td>
</tr>
<tr>
<td>400-m</td>
<td>High</td>
<td>0.16 ± 1.74</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>0.03 ± 1.76</td>
</tr>
<tr>
<td>800/1500-m</td>
<td>High</td>
<td>0.85 ± 0.66</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>-0.23 ± 1.30</td>
</tr>
</tbody>
</table>
Table 3. Absolute start, turn and turn out times (s) (mean ± SD).

| Distance | Gender | Freestyle | | Times (s) | Backstroke | | | Breaststroke | | | Butterfly | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | StT | TnT | ToT | StT | TnT | ToT | StT | TnT | ToT | StT | TnT | ToT |
| 100-m | Male | 5.72 ± 0.15 | 7.01 ± 0.26 | 4.30 ± 0.15 | 6.29 ± 0.04 | 7.31 ± 0.27 | 4.37 ± 0.19 | 6.67 ± 0.23 | 9.11 ± 0.19 | 6.16 ± 0.16 | 5.67 ± 0.29 | 7.67 ± 0.32 | 5.10 ± 0.32 |
| | Female | 6.50 ± 0.25 | 7.98 ± 0.25 | 4.86 ± 0.18 | 7.38 ± 0.28 | 8.29 ± 0.15 | 4.99 ± 0.11 | 7.68 ± 0.27 | 9.82 ± 0.13 | 6.56 ± 0.13 | 6.70 ± 0.26 | 8.64 ± 0.38 | 5.75 ± 0.26 |
| 200-m | Male | 5.96 ± 0.17 | 7.51 ± 0.15 | 4.50 ± 0.11 | 6.64 ± 0.36 | 8.20 ± 0.45 | 4.90 ± 0.33 | 6.90 ± 0.05 | 9.51 ± 0.08 | 6.27 ± 0.05 | 6.05 ± 0.22 | 8.64 ± 0.15 | 5.62 ± 0.15 |
| | Female | 6.72 ± 0.28 | 8.37 ± 0.10 | 5.05 ± 0.12 | 7.58 ± 0.18 | 8.79 ± 0.27 | 5.16 ± 0.14 | 7.85 ± 0.05 | 10.52 ± 0.06 | 6.90 ± 0.11 | 6.73 ± 0.12 | 9.38 ± 0.25 | 6.19 ± 0.24 |
| 400-m | Male | 6.16 ± 0.19 | 7.91 ± 0.18 | 4.82 ± 0.16 | | | | | | | | | |
| | Female | 7.34 ± 0.10 | 8.82 ± 0.17 | 5.38 ± 0.04 | | | | | | | | | |
| 800/1500-m | Male | 6.58 ± 0.28 | 8.44 ± 0.37 | 5.09 ± 0.21 | | | | | | | | | |
| | Female | 7.56 ± 0.17 | 9.03 ± 0.19 | 5.46 ± 0.09 | | | | | | | | | |
Figure 1: Mean and 95% confidence interval of the 100-m events; StT Z-score (panel A), TnT Z-score (panel B) and ToT Z-score (panel C) for the high and low carnosine aggregate Z-score groups (* P = 0.02).
3.6 Discussion

The present study demonstrated that the degree to which MFT influences performance parameters in elite swimmers depends upon the event distance. The StT and TnT were significantly faster in 100-m events compared to both 200- and 800/1500-m events. During 100-m events, swimmers with a higher carnosine aggregate Z-score (i.e., faster muscle typology) had a significantly faster StT compared to swimmers with a low carnosine aggregate Z-score.

To date, the effect of MFT on start and turn performance in competitive swimming has not be investigated. The swim start is an explosive movement of the lower body musculature, which maximizes the net impulse and take-off velocity to augment performance. We found that elite swimmers in 100-m events had a faster StT, TnT and ToT than 200- and 800/1500-m events, and within 100-m events, swimmers with higher carnosine aggregate Z-scores had a significantly faster StT. In contrast, we found no influence of muscle fiber typology on the performance parameters when all distances were entered into a single linear mixed model. The lack of influence of muscle fiber typology in these analyses can be explained by the substantial differences between strokes, distances, and gender, which may have diluted the influence that muscle fiber typology has on these performance parameters. We aimed to reduce the influence that these factors have by calculating StT and TnT, and ToT Z-scores derived from truly world-class swimming performances (FINA points 950 ± 22). It is clear that 100-m swimmers place a larger emphasis on the start phase than swimmers of longer distance events, which is likely because the StT contributes ~12% of the overall 100-m performance time. In comparison, the StT contributes ~7% time in 200-m events, ~2.5% in 400-m event, and < 1.5% in 800/1500-m events. This is in agreement with other
research that has demonstrated that both the StT and TnT of 200-m events is slower than 100-m events.\textsuperscript{207} A faster StT has also been associated with measures of lower body power and strength, including countermovement jump (CMJ), squat jump (SJ) and 3-RM squat. \textsuperscript{86,91,92,229} Specifically, West et al.,\textsuperscript{92} found that lower body peak power and predicted 1-RM were significantly related to the StT, (15-m) in a cohort of international calibre male 50-m swimmers ($r^2 = -0.73$ and -0.55 respectively). Furthermore, the authors\textsuperscript{92} suggested that land-based strength programming should be included into a training program to improve the StT, and continued to advise that the specific hypertrophy of type II muscle fibers, and/or an individual with higher proportions of type II muscle fibers, would have an advantage in sprint swimming StT performance. A recent review of strength and conditioning practices in swimming highlighted that low-volume, high-velocity training focusing on the rate of force development showed a positive transfer to swimming performance.\textsuperscript{230} It is conceivable that this type of training may preferentially induce type II muscle fiber hypertrophy but this requires further experimental evidence. The results of the present study would confirm these suggestions, whereby 100-m swimmers with a faster muscle typology had a substantially faster StT compared to swimmers with a slower muscle typology.

The findings of the present study suggest that swimmers with higher carnosine aggregate Z-scores do not gain a significant advantage in the turn phase of swimming performance. Previous research has suggested that the technique of the turn has greater importance on overall turn performance than leg muscle power,\textsuperscript{231,232} which supports the findings of the present study. Furthermore, Nicol et al.,\textsuperscript{232} assessed the influence of 21 biomechanical parameters on turn performance and determined that the largest improvements in rotation TnT (i.e., FR) would result
from an emphasis on the force applied to the wall and in the tuck TnT (i.e., FL) by increasing the distance at which the point of surfacing occurs. The authors suggested that because the influence of each parameter was small to moderate in effect, a ‘holistic’ approach should be implemented to improve turn performance, with a high importance placed on technique. Swimmers with superior dry-land force and power characteristics have also been described to have superior turn performance, which was suggested to be associated with the number of years spent undertaking dry-land training, opposed to an underlying physiological or physical characteristic. These findings highlight that while TnT and ToT parameters are consistent with explosive movements, superior turn technique may be more influential on turning performance rather than maximizing muscle power output. The results of the present study, agree with this previous research, whereby swimmers with a faster muscle typology did not seem to have a superior turn performance. To improve the validity of our results, individualization of each competitors’ flight, surface, and underwater profiles could be distinctly identified and considered.

Athletes who possess a greater proportion of type II muscle fibers, compete in sports that require higher levels of explosive power, such as explosive track and field events, track cycling, and powerlifting. Interestingly, swimmers have been characterized as typically possessing greater proportions of type I muscle fibers compared to type II muscle fibers. Sprint oriented swimmers have been shown to have a large variation (30-56%) type II muscle fibers, and have also been shown to have higher proportions of type I fibers, compared other athletes of a sprint orientation. Despite the few studies characterizing the MFT of swimmers, previous research has not determined the
relationship between MFT and start and turn performance. Given that previous research has alluded to type II muscle fiber hypertrophy improving swimming performance, the early identification of MFT could help strength and conditioning practitioners develop individualized strength and conditioning training programs, which in turn maximize start and turn performance later into a swimmers’ career; further research is warranted in this domain. While classical research has suggested that swimmers rarely possess a high proportion of type II fibers, the present study has identified a distinct advantage for those swimmers that do possess a faster muscle typology given the faster StT of swimmers in the high carnosine aggregate Z-score group within 100-m events.

3.7 Practical Applications

In light of the findings of the present study, swimmers with a faster muscle typology have the potential advantage of a faster StT in sprint swimming events. The StT of a 100-m male or female freestyle swimmer with a high carnosine aggregate Z-score is on average 0.25 s (CI 90% 0.17 s) faster than a swimmer with a low carnosine aggregate Z-score. Coaches and sports scientists should heavily emphasize improving the technique of both the start and the turn, to ensure that the most efficient skill is executed during the race. As such, a swimmer with a faster muscle typology and a superior technique, will be able to take advantage of this trait during the start phase, and maximize their performance in sprint swimming events. Future research could investigate the different segments of start and turn performance in order to identify additional parameters that may be influenced by MFT (e.g., underwater or surface profiles, force application to the wall, or velocity at breakout).
3.8 Conclusion

The results of the present study suggest that elite 100-m swimmers with a faster muscle typology, perform the start in a faster time than swimmers with a slower muscle typology. These differences are likely to influence the overall performance time, due to the substantial relative contribution that the StT contributes to the overall performance time in 100-m events and suggest that muscle fiber typology is an important characteristic for elite sprint swimmers.

Acknowledgements

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Chapter 4: Investigative

Study 3
4.0 Declaration of co-authorship Thesis Chapter 4

This chapter includes a co-authored paper:

Adam Mallett$^{1,2}$, Phillip Bellinger$^{1,2}$, Wim Derave$^3$, Katie Mcgibbon$^2$, Eline Lievens$^3$, Ben Kennedy$^1$, Hal Rice$^4$, Clare Minahan$^1$ 'The influence of muscle fiber typology on the pacing strategy of 200-m freestyle swimmers.' (*Under review in International Journal Sport Physiology and Performance*) Sept 2020

In the case of Chapter 3, the nature and extent of my contribution to the work was the following:

<table>
<thead>
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<th>Extent of Contribution (%)</th>
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<tr>
<td>Study design</td>
<td>60%</td>
</tr>
<tr>
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<td>80%</td>
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<tr>
<td>Analysis and interpretation</td>
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**Candidate Signed:**

Adam Mallett

Date: 25/8/20

**Co-authorship declaration:**

<table>
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<td>Dr Phillip Bellinger</td>
<td></td>
<td>8th October 2020</td>
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<td>Prof Wim Derave</td>
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<td>Dr Katie McGibbon</td>
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<td>Eline Lievens</td>
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<td>A/Prof Clare Minahan</td>
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<td>8th October 2020</td>
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<td>Supervisor</td>
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4.1 Title: The influence of muscle fiber typology on the pacing strategy of 200-m freestyle swimmers

Authors: Adam Mallett¹,², Phillip Bellinger¹,², Wim Derave³, Katie Mcgibbon², Eline Lievens³, Ben Kennedy⁴, Hal Rice⁴, Clare Minahan¹

Affiliations:
¹Griffith Sports Science, Griffith University, Gold Coast, Queensland, Australia.
²Queensland Academy of Sport, Nathan, Queensland, Australia
³Department of Movement and Sports Sciences, Ghent University, Ghent, Belgium
⁴Qscan Radiology, Gold Coast, Australia

Correspondence:
Adam Mallett
School of Allied Health Sciences, Griffith University, Queensland, Australia, 4222.
Phone: +61 (0) 456782313
Email: adam.mallett@griffithuni.edu.au
Submission type: Original investigation

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Number of tables: 1

Number of figures: 2
4.2 Abstract

**Purpose:** To determine the influence of muscle fiber typology (MFT) on the pacing strategy of elite swimmers competing in the 200-m freestyle event. **Method:** The top-3 career best performances from twenty-five elite 200-m freestyle swimmers were analyzed; twelve women (1:58.0±0:01.3; m:ss.0), and thirteen men (1:48.4±0:02.5). Muscle carnosine concentration was quantified by proton magnetic resonance spectroscopy in the gastrocnemius and soleus muscles and expressed as a carnosine aggregate Z-score (CAZ-score) relative to an age and gender matched non-athlete control group to estimate MFT. Linear regression models were employed to examine the influence of MFT on the percent of overall race time spent in each 50-m lap. **Results:** Swimmers with a higher CAZ-score spent a greater percentage of race time in lap 3 compared to swimmers with a lower CAZ-score (0.1%, 0.0 to 0.2%; mean, 90% CI, p=0.02). For every 1% increase in the percent of race time spent in lap 1, the percent of race time spent in lap 3 decreased by 0.4% for swimmers with a higher CAZ-score (0.2 to -0.5%, p=0.00 r=-0.51), but not for swimmers with a lower CAZ-score (-0.1%, -0.3 to 0.1%, p=0.28, r=-0.18). The percent of race time spent in lap 4 decreased by 0.8% for higher CAZ-score swimmers (-0.5 to -1.0%, p=0.00, r=-0.66) and by 0.9% for lower CAZ-score swimmers (-0.6 to -1.3%, p=0.00, r=-0.65) when lap 1 percent increased by 1%. **Conclusion:** MFT may influence the pacing strategy of swimmers in the 200-m freestyle event, which provides an avenue for maximizing individualized pacing strategies of elite swimmers.
4.3 Introduction

In order to be successful in racing sports such as swimming, running and cycling at the international level, an athlete’s pacing strategy is a key determinant of performance. Pacing strategy refers to the distribution of energy expenditure over the duration of the event, where the power output or speed is plotted against time and the goal is to fully utilize all available energy resources and limit premature fatigue. The execution of an effective pacing strategy within swimming has previously been described as ‘critical,’ to successful performance, due to the low mechanical efficiency caused by the high resistive forces in water. Furthermore, compared to middle- and long-distance running as well as many track cycling events, swimmers are more isolated from their opponents. As such, swimmers are likely to be less concerned with race tactics and can adopt a preferential, self-selected pacing strategy to ensure a maximal performance is achieved.

Lasting between 100–120 s, the 200-m freestyle is one of the most demanding events in swimming competition considering that: i) The 4x200-m freestyle relay allows a greater number of swimmers to qualify for international competition, which in turn raises the level of competition at a domestic level compared to other events. ii) There is a complex relationship between the relative aerobic and anaerobic energy system contributions during each lap, and iii) 200-m swimmers ranked in the world top-20, also compete at a world level in events ranging from the 50- to 1500-m freestyle (~20 s to ~15 mins). With such a large diversity of swimming specialists competing in the 200-m freestyle event, it seems plausible that the pacing strategy among swimmers may be different in order to maximize performance. Previous research has shown that the 200-m freestyle event for men
requires significant contributions from both aerobic (65.9 ± 1.6\%: mean ± SD) and anaerobic energy metabolism (34.0 ± 1.4\%). More specifically, the contribution of energy from aerobic metabolism increased from 0-50-m (lap 1) to 50-100-m (lap 2), remained stable through 100-150-m (lap 3) and then decreased from 150-200-m (lap 4). The anaerobic alactic energy contribution decreased as a function of time, being highest in lap 1 and lowest in lap 4, while the anaerobic lactic energy contribution was highest in lap 4 compared to the previous laps. Interestingly, there appeared to be large between-subject variability in the energy system contribution to each lap of the 200-m freestyle time trials. As such, the variation in the proportion of energy derived from both aerobic and anaerobic metabolism may have important implications on pacing strategy for a given swimmer. However, the underpinning physiological characteristics that influence pacing and performance in 200-m freestyle swimmers have received little attention. A recent study divided the race strategy of 200-m freestyle swimmers into the start lap strategy and pacing strategy. The start lap strategy was described as fast, average or slow depending on the percent of overall time spent on lap 1, while the pacing strategy was described as even, negative or positive depending on the percent of race time spent in laps 2-4. The results from this study demonstrated that a fast start lap strategy was associated with higher pacing variability compared to both an average and slow start lap and resulted in a slower race time compared to a slow start lap strategy, pacing variability was then expressed as a coefficient of variation using the percentage of overall race time spent in laps 2, 3, and 4, which highlight the intra-individual variability of pacing between each lap. Pacing variability was then expressed as a coefficient of variation using the percentage of overall race time spent in laps 2, 3, and 4, which highlight the intra-individual variability of pacing between each lap. While, there was no influence of the pacing strategy on 200-m
performance time in male swimmers, positive pacing yielded slower 200-m times than both even and negative pacing in females swimmers. Interestingly, ~25% of the swimmer’s displayed a fast or slow start strategy, while ~50% then adopted an even pacing strategy. It should also be noted that there is high variability of stroking parameters throughout a 200-m freestyle event, which could play a role in the different pacing strategies of laps 2-4. However, it remains unclear as to whether the variation in pacing strategy between swimmers can be explained by a variation in underlying physical or physiological characteristics.

One of the key physiological characteristics that may influence energy system contribution and therefore pacing, is the proportion of type I and type II muscle fibers (i.e., muscle fiber typology; MFT). Type II muscle fibers have superior muscle buffer capacity,244 greater creatine phosphate content245 and capacity for anaerobic metabolism246 as well as superior mechanical properties247 compared to type I fibers.248 Elite athletes competing in middle-distance events possess a much greater between-athlete variation in MFT compared to their sprint and endurance athlete counterparts.223,249 For example, Costill et al.,249 reported a much greater range in the proportion of type I fibers of 800-m runners (40.5–73.3%), compared to sprinters (21.0–28.2%) and distance runners (63.4–73.8%). While there is less definitive evidence to support the same notion for middle-distance swimmers, historical evidence does show similar levels of variability in middle-distance (100- and 200-m) swimmers who also seemed to possess a wide range in the proportion of type I fibers (35 – 65%).32 In light of the diversified specialization of swimmers competing in the 200-m freestyle event and the wide variability in energy system contributions in the 200-m freestyle event, the aim of the present study was to investigate whether the pacing strategy implemented by swimmers in the 200-m
freestyle event is associated with the variability in MFT. The findings from this study will provide coaches and sports scientists with practical information to assist in the optimization of pacing strategy for their athletes.

4.4 Methodology

Subjects

Twelve female and thirteen male elite 200-m freestyle swimmers, who were still competitive, volunteered to participate as subjects in the present study. The subjects’ mean ± SD, age, height and body mass were: female 24.6 ± 2.6 years, 173 ± 5.4 cm and 66.5 ± 6.4 kg; male 24.0 ± 3.0 years, 188.8 ± 5.3 cm, and 83.5 ± 7.1 kg, respectively. Mean career best performance times (min:sec) in the 200-m long course freestyle event for female subjects was 1:58.0 ± 0:01.3, and for male subjects was 1:48.4 ± 0:02.5, with a World Record Ratio (WRR) of 104.4 ± 1.2 and 106.3 ± 2.5% respectively. All subjects gave their written informed consent before participation, and ethical approval was granted by Griffith University Human Research Ethical Committee.

Research Design

An observational research design was employed in the present study. Subjects attended a radiology clinic on one occasion for their MFT to be estimated using the $^1$H-MRS measurement of muscle carnosine content in the gastrocnemius and soleus. Race data, including overall time and 50-m split times, from each subjects’ top-3 career best 200-m freestyle performances (long-course) were collated from publicly available online sources. The second and third fastest swims
for each subject were all within 2.1% of their career best time. The percent of race
time spent in each lap was calculated using the 50-m split times.

**Data Collection**

Muscle carnosine content was measured by $^1$H-MRS in the soleus and
gastrocnemius medialis muscle of each subject’s right limb in order to estimate
MFT. $^1$H-MRS measurements were performed on a 3-T whole body MRI scanner
(Philips Medical Systems Best, The Netherlands). Subjects were lying in a supine
position, while their lower leg was fixed in a spherical knee-coil. All the spectra
were acquired using single voxel point-resolved spectroscopy (PRESS) with the
following parameters; repetition time (TR) of 2000 ms, echo time (TE) of ~40 ms,
number of excitations was 128 (carnosine) and 16 (water), spectral bandwidth was
2048 Hz, and a total acquisition time of 4 min 16 s (carnosine) and 32 s (water).
The voxel size was 40 mm x 15 mm x 20 mm. Spectral data analysis was carried
out using jMRUI (version 6.0) with carnosine peaks fitted and expressed relative to
the internal water signal. Carnosine content (mM) was calculated using following
formula:

$$C_m = \frac{C_s}{(H_2O_s)} \cdot \frac{(H_2O_{T1r})}{(CT_{1r})} \cdot \frac{(H_2O_{T2r})}{(CT_{2r})} \cdot H_2O_{\text{muscle}} \cdot H_2O_{\text{protons}}$$

where $C_m$ is the carnosine concentration, $C_s$ is the carnosine signal, $H_2O_s$ is the
water signal, $CT_{1r}$, $CT_{2r}$, $H_2O_{T1r}$, $H_2O_{T2r}$ are the relaxation correction factors for
carnosine (earlier described by Baguet et al.$^{219}$) and water (earlier described by
MacMillan et al.$^{225}$), $H_2O_{\text{muscle}}$ is the concentration of water in muscle, which was
deducted from the molar concentration of water (55,000 mM) and the approximate
water content of skeletal muscle tissue (0.7 L/kg wet weight of tissue). \( \text{H}_2\text{O}_{\text{proton}} \) is the number of protons in water. The CV for test-retest inter-day carnosine measurements in our laboratory was 3.5% (soleus) and 4.3% (gastrocnemius; n = 15 subjects). The carnosine concentration of the soleus and gastrocnemius muscles was converted to a sex-specific Z-score relative to a control population of active, healthy non-athletes (men: n = 38; women: n = 30), from which a carnosine aggregate Z-score (CAZ-score) was derived by calculating the mean of the two muscle Z-scores. Participants were assigned to the ‘high’ or ‘low’ CAZ-score group if their score was above or below the median value of all subjects. Percent of time spent on each lap was determined from the overall time divided by the lap-split time.

**Statistical analysis**

Linear regression models and Pearson’s correlations were used to examine relationships and differences between 200-m performance time, the percent of race time spent in each 50-m lap, high and low CAZ-score groups, and CAZ-score. Gender was included as a fixed effect only when it had a significant effect on the linear model and if the Akaike information criterion (AIC) and Bayesian information criterion (BIC) were lower with it included. Visual inspection of residual plots did not reveal any obvious deviations from homoscedasticity. Results are reported either as mean ± SD or mean and 90% confidence interval (CI). All statistics were calculated using R software.\(^{250}\) Pacing variability was expressed as a coefficient of variation (CV) using the percentage of overall race time spent in laps 2, 3, and 4. The smallest worthwhile change (SWC) in swimming performance at international competitions has been established as 0.4%,\(^{251}\) which equates to approximately 0.4 s and 0.5 s in men’s and women’s 200-m freestyle events.
respectively. This threshold was used to determine whether performance changes were practically meaningful in elite swimming.

4.5 Results

Swimmers in the low group typically recorded 200-m swim times that were 0.3s (-1.3 to 0.6 s; 90% CI, p=0.59) faster than swimmers in the high group but the difference was not statistically significant.

There were no significant differences between high and low groups in the percent of race time spent in laps 2 or 4 (p≥0.52). The percent of race time spent in lap 1 was typically 0.2% or 0.2 s higher for swimmers in the low group than those in the high group (0.0 to 0.3%, p=0.06), and gender was included as a fixed effect (p=0.02). Swimmers in the high group spent a significantly greater percent of race time in lap 3 than those in the low group (0.1%, 0.0 to 0.2%; mean, 90% CI, p=0.02) (Figure 1). Gender was not included as a fixed effect (p≥0.12).

The percent of race time spent in laps 1, 2, 3 and 4 were not substantially impacted by a change in CAZ-score of 1 (p≥0.17). For all laps, gender did not have a significant effect on the model and therefore was not included as a fixed effect (p≥0.07).

For every 1% increase in the percent of race time spent in lap 1, the percent of race time spent in lap 3 decreased by 0.4% for swimmers in the high group (0.2 to -0.5%, p=0.00 r=-0.51), but not for swimmers in the low group (-0.1%, -0.3 to 0.1%, p=0.28, r=-0.18) (Figure 2). For every 1% increase in the percent of race time spent
in lap 1, the percent of race time spent in lap 4 decreased by 0.8% for swimmers in the high group (-0.5 to -1.0%, p=0.00, r=-0.66) and by 0.9% for swimmers in low group (-0.6 to -1.3%, p=0.00, r=-0.65).

The difference in the percent of race time spent in laps 2 and 3 was higher for swimmers in the high group compared to the low group (0.1%, 0.0 to 0.2%, p=0.12) (Table 1). The difference in the percent of race time spent on laps 3 and 4 was 0.2% in the high group compared to low group (0.0 to 0.4%, p=0.12).

Figure 1: Mean (SD) percent of race time spent in each 50-m lap for high and low CAZ-score groups. * denotes significance between groups (p=0.02).
Table 1. 200-m swimming performance times and pacing-strategy characteristics of elite male and female swimmers with High or Low group CAZ-score. Values presented at (mean ± SD).

<table>
<thead>
<tr>
<th></th>
<th>High</th>
<th>Low</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Men (n=5)</td>
<td>Women (n=7)</td>
</tr>
<tr>
<td>200-m time (m:ss.0)</td>
<td>1:48.8 ± 0:03.6</td>
<td>1:58.0 ± 0:01.5</td>
</tr>
<tr>
<td>FINA points</td>
<td>856 ± 58</td>
<td>847 ± 48</td>
</tr>
<tr>
<td>CAZ-score</td>
<td>0.4 ± 0.6</td>
<td>-0.6 ± 0.3</td>
</tr>
<tr>
<td>Lap 2 to 3 diff</td>
<td>0.5 ± 0.3%</td>
<td>0.3 ± 0.3%</td>
</tr>
<tr>
<td>Lap 3 to 4 diff</td>
<td>-0.3 ± 0.5%</td>
<td>-0.1 ± 0.6%</td>
</tr>
<tr>
<td>CV laps 2 to 3</td>
<td>1.1 ± 0.4%</td>
<td>0.9 ± 0.3%</td>
</tr>
<tr>
<td>CV laps 3 to 4</td>
<td>1.0 ± 0.6%</td>
<td>1.2 ± 0.5%</td>
</tr>
<tr>
<td>CV laps 2 to 4</td>
<td>1.3 ± 0.8%</td>
<td>1.5 ± 0.7%</td>
</tr>
</tbody>
</table>

Key: Career Best 200-m Freestyle performance, FINA (International Swimming Federation) points, Carnosine Aggregate Z-score (CAZ-score); differences in the percent of race time spent in laps 2 to 3, and 3 to 4 and CV between laps, 2 to 3, 3 to 4 and 2 to 4 across the high and low CAZ-score groups.
Figure 2: Relationship between the percent of race time spent in lap 1 and lap 3 (top), and lap 1 and lap 4 (bottom) for high (solid linear trend line) and low (dashed linear trend line) CAZ-score groups.
4.6 Discussion

The present study aimed to determine whether MFT was associated with variability in pacing strategies in 200-m freestyle swimmers. The relative percentage of time spent in lap 3 was significantly higher for swimmers with a higher CAZ-score (i.e., higher estimated proportion of type II fibers). For every increase in the percent of race time spent in lap 1, the percent of race time spent in lap 3 decreased significantly by 0.4% for swimmers in the high group, but not for swimmers in the low group. These findings suggest that MFT may influence the pacing strategy of elite 200-m freestyle swimmers, and therefore individualized pacing strategies should be developed by coaches and sport scientists to help maximize performance.

Given there were no significant differences in the overall performance times between gender-matched swimmers in the high and low groups, this may suggest that MFT is not a determining factor for overall 200-m freestyle performance. However, the SWC in male 200-m freestyle swimming equates to 0.4 s; therefore, the average 0.8 s difference between the males in the high and low groups could suggest that male swimmers with a higher estimated proportion of type I fibers (i.e., swimmers in the low group) possess a factor that is governing success in 200-m freestyle events. However, given the small sample size of male 200-m swimmers in the present study, further research is required to confirm this inference. Historical muscle biopsy research studying swimmers has suggested that male and female 200-m freestyle swimmers possessed a relatively even muscle fiber type distribution with 47.8 ± 1.5% and 52.0 ± 6.1% type I fibers in the vastus lateralis, respectively. Similarly, runners competing in the duration equivalent track running event (i.e., 800-m) also possess a relatively even muscle fiber type distribution when assessing the mean group value with 60.6% (range; 44.0% – 73.3%) and 51.9% (40.5% – 69.4%) type I fibers in the gastrocnemius lateralis of
female and male runners, respectively.\textsuperscript{249} This suggests that possessing a high proportion of a given fiber type is not necessarily advantageous for 800-m running performance. Interestingly there was a wide range in the MFT reported in this study and in the study on swimmers by Gerard et al.\textsuperscript{32} However it should be noted that 200-m freestyle swimmers were not studied individually, rather grouped with 100-m swimmers and there was only a small sample size (n = 5 male and 3 female). In the present study the CAZ-score range was large -1.22 to 1.67; however 18 of the swimmers possessed values between -0.6 and 0.6. While there was a degree of between-swimmer variability in MFT, more research is required to determine whether possessing a higher or lower proportion of a given fiber type is advantageous for 200-m freestyle performance.

Results of the present study suggest that swimmers in the high group spent a significantly greater percentage of time on lap 3 than those in the low group. Previous research has determined that a faster third lap in 200-m freestyle events is associated with faster performances ($r \geq 0.7$) in international finalists and semi-finalists.\textsuperscript{252} It has also been suggested that a conservative start is associated with faster performances in the 200-m freestyle event.\textsuperscript{240} The conservation of energy at the start of a 200-m freestyle could play an important role in the distribution of energy across the entirety of the event, as the relative contribution of the anaerobic and aerobic energy systems have been reported to significantly differ between laps.\textsuperscript{243} The greatest contribution from aerobic energy metabolism occurred on lap 3 (83.3\%) and anaerobic lactic metabolism on lap 4 (28.1\%). In comparison to type I muscle fibers, type II fibers rely more heavily on the energy contribution from anaerobic metabolism.\textsuperscript{248} In the present study, the significant difference in the percent of overall time spent on lap 3, could be associated, in part, with the relative
increase in the contribution of the aerobic energy system during lap 3. Additionally, swimmers in the high group were able to reduce the percent of time spent on lap 3 by increasing the relative race time on lap 1, but not the swimmers in the low group. The relative increase of time spent on lap 1, is likely to be associated with a reduced contribution of energy provisions from anaerobic metabolism. It has been postulated that a fast start may increase the metabolic perturbations that result in a deterioration of technique and swimming velocity in subsequent laps which would result in a greater relative time spent on lap 3. However further research is required to determine how to maximise the balance of starting strategy with overall performance in swimmers that have divergent MFT.

While the absolute range in CAZ-score values was large in female (-1.22 to 1.41) and male swimmers (-1.21 to 1.67) in the present study, the vast majority (n=18) of subjects were between -0.6 and 0.6 indicating a relatively homogenic MFT in this sample of elite 200-m freestyle swimmers. As such, the homogeneity in the MFT of the subjects within the present study may have contributed to the lack of differences found between high and low groups in pacing strategy parameters. Furthermore, the lap to lap variability in this cohort of swimmers was extremely low and it is likely that the lack of variability in both our dependent (pacing strategy variables) and independent variables (MFT) contributed to the absence of substantial differences. However, given the high calibre of the recruited swimmers in this study (mean career best performance time within 5.6% of the world record); the lack of variability in pacing may be due to finely tuned pacing strategies already utilised by these swimmers.
4.7 Practical Applications

The results of this study suggest that there may be a difference in the pacing strategy of swimmers, who have different MFT. Coaches and sports science practitioners should ensure race strategies are individualised to suit the characteristics of each swimmer rather than employing a ‘one-size fits all’ philosophy. It may also be beneficial to start the 200-m freestyle more conservatively in order to maintain velocity in the latter stages of the race. Further interventional research should be conducted to determine optimal pacing strategies for swimmers with divergent MFT.

4.8 Conclusion

Muscle fiber typology may affect the pacing strategy of 200-m freestyle swimmers. The knowledge that a genetically determined physiological characteristic influences the pacing strategy highlights the need for the individualisation of pre-planned pacing strategies for elite swimmers.

Acknowledgements

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Chapter 5: Investigative

Study 4
5.1 Title: Adaptations to concentrated overload training in elite swimmers: Does muscle fiber typology play a role?

5.2 Introduction

The physical training programs of athletes are multi-faceted but can be broadly characterised by the intensity, duration, and frequency of the training sessions.\textsuperscript{37,144-147} It is the effective combination of these training variables that promotes adaptations in the physiology of athletes and subsequently improvements in performance. The integration of training intensity and volume (i.e., training load) within the overall training program is highly dependent on the discipline-specific competition, which dictates the physiological requirements of the event.\textsuperscript{148} In regards to swimming competition at an elite level, events typically last between 22 s and 16 min (50 m – 1500 m, respectively) which imposes a wide variation in the relative importance of aerobic and anaerobic metabolism throughout the range of events.\textsuperscript{149} The training load of elite swimmers has been considered as high,\textsuperscript{254} particularly for swimmers competing primarily in short-distance events (50- to 200-m swimmers), whereby the relative duration of these competitive events is brief (~22 s to 2.0 min).\textsuperscript{254}

The efficacy of increased training load has been demonstrated in rowers and runners in a number of longitudinal studies (>12 wk)\textsuperscript{255-257} while the findings of more short-term alterations in training load are more equivocal, particularly in swimming.\textsuperscript{29,37,144} For example, Faude et al.\textsuperscript{144} reported no differences in a 100- or 400-m freestyle time trial (TT) following a period of high-volume training (81.2 vs 167.8 km·4 wk\textsuperscript{1}), while Houston et al.\textsuperscript{29} observed no significant differences in performance in 22.9-, 91.4-, and 457.0-m freestyle TTs between normal training
and high-volume training (i.e., additional 1350 m session⁻¹).²⁹ Furthermore, Costill et al.⁵ did not find significant improvements in 45.7- to 182.9-m TTs after normal (4950 m·d⁻¹) or high-volume (9435 m·d⁻¹) training, despite increases in citrate synthase activity in the deltoid muscle after high-volume training.³⁷ Similarly, research by Fitts et al.²⁵⁸ found that 10 d of increased training volume (4.3 vs 9.0 km·d⁻¹) augmented citrate synthase activity as well as reduced the diameter and maximal shortening velocity of type II muscle fibers without influencing swim performance. Another study in swimming found that weekly training volume increases of 30-40% over 4 wk induced diverse responses in swimmers, whereby 33% of swimmers developed symptoms of overreaching.¹⁵⁵ It is important to note that in all of these studies, only training ‘volume’ was increased during the high-volume training phase whereas training ‘intensity’ remained consistent. Therefore, it could be suggested that short-term increases in training load, via the manipulation of training volume, does not result in systematic improvements in swimming performance. However, there appears to be a large degree of inter-individual responses that may mask changes in TT performance at the group level and/or the time course for performance improvement.

A potential explanation for the differences in response to training overload among elite-level swimmers may be related to the inter-individual variation in muscle fiber type composition (i.e., the proportion of type I and type II fibers; muscle fiber typology, MFT). MFT has recently been shown to be related to the incidence of overreaching and performance super-compensation following high-volume training and a taper in middle-distance runners¹⁵. In this study, trained middle-distance runners who became overreached had a higher gastrocnemius carnosine Z-score (i.e., estimated to have a higher proportion of type II fibers) compared to those that
better tolerated the increase in training volume. Type II fibers have greater fatiguability,\textsuperscript{52,259} take longer time to recover from exercise\textsuperscript{52,258} and may adapt more favourably to low-volume, high frequency contractions.\textsuperscript{260} As such, the variation in TT performances in swimmers observed after increases in training volume may be related to inter-individual differences in MFT. Importantly, MFT can be estimated by non-invasive \textsuperscript{1}H-MRS technology, through the quantification of muscle carnosine content.\textsuperscript{219} We have previously shown that elite swimmers with a higher carnosine aggregate Z-score (CAZ-score; i.e., estimated to have a higher mean proportion of type II fibers in gastrocnemius and soleus) had a significantly faster start time in sprint events compared to swimmers with a lower CAZ-score.\textsuperscript{261} However, whether variation in MFT is also related to variation in TT performances following high volume training in elite swimmers is yet to be explored.

The purpose of the present study was to: i) Measure 200-m freestyle TT performance before and after high-volume training, ii) Identify if MFT is a moderating factor for the changes observed in a 200-m TT before compared to after high-volume training, and iii) Determine if high-volume training resulted in changes to other swimming performance-related and physical tests. We hypothesized that MFT would be associated with changes in 200-m TT performance after a period of concentrated overload training. The findings of this study will allow coaches and sports-science practitioners to better understand the individual responses to training manipulation in elite swimmers.
5.3 Methodology

5.3.1 Participants
Ten highly-trained swimmers (2 women, 8 men; 19.9 ± 3.0 yr; mean ± SD) volunteered to participate as subjects in this study (Table 1). All subjects were members of the same swimming club in Queensland, Australia. Inclusion criteria specified that subjects had been training consistently for 2 yr before the commencement of the study and had been without a major injury or illness interruption in the past 3 mo.

Table 1: Individual swimmer characteristics

<table>
<thead>
<tr>
<th>Gender</th>
<th>Age (yr)</th>
<th>Height (cm)</th>
<th>Body mass (kg)</th>
<th>Dominant stroke</th>
<th>FINA points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Woman</td>
<td>20</td>
<td>168</td>
<td>58</td>
<td>Freestyle</td>
<td>775</td>
</tr>
<tr>
<td>Woman</td>
<td>17</td>
<td>185</td>
<td>75</td>
<td>Freestyle</td>
<td>780</td>
</tr>
<tr>
<td>Man</td>
<td>18</td>
<td>187</td>
<td>76</td>
<td>Freestyle</td>
<td>782</td>
</tr>
<tr>
<td>Man</td>
<td>19</td>
<td>175</td>
<td>68</td>
<td>Backstroke</td>
<td>700</td>
</tr>
<tr>
<td>Man</td>
<td>28</td>
<td>185</td>
<td>82</td>
<td>Freestyle</td>
<td>678</td>
</tr>
<tr>
<td>Man</td>
<td>18</td>
<td>181</td>
<td>69</td>
<td>Freestyle</td>
<td>791</td>
</tr>
<tr>
<td>Man</td>
<td>20</td>
<td>174</td>
<td>69</td>
<td>Freestyle</td>
<td>706</td>
</tr>
<tr>
<td>Man</td>
<td>19</td>
<td>188</td>
<td>78</td>
<td>Backstroke</td>
<td>648</td>
</tr>
<tr>
<td>Man</td>
<td>18</td>
<td>183</td>
<td>76</td>
<td>Freestyle</td>
<td>738</td>
</tr>
<tr>
<td>Man</td>
<td>22</td>
<td>190</td>
<td>86</td>
<td>Breaststroke</td>
<td>824</td>
</tr>
</tbody>
</table>

* Dominant stroke = stroke in which the swimmer scored their highest FINA points. FINA = Fédération Internationale de Natation.*210
5.3.2 Study design
The study period was 7 wk, which was divided into four training phases: i) NormTr = normal training; 2 wk of monitored normal training (it should be noted that the 3 wk before the study was also classified as NormTr), ii) TapTr1 = taper training 1; a 1-wk taper comprising an exponential reduction in training volume from NormTr over 7 d resulting in a 30% decrease from NormTr, iii) HVTr = high-volume training; 3 wk of increased training volume comprising a step increase in training volume resulting in a 30% increase from NormTr, and iv) TapTr2 = Taper training 2; a 1-wk taper comprising an exponential reduction in training volume over 7 d resulting in a 30% decrease from HVTr (Figure 1). Examples of alterations in training volume between NormTr to HVTr are highlight in Table 2 and the intended session rate of perceived exertion (RPE) is indicated in Table 3. On the first and second day of each training phase, swimmers performed a 200-m freestyle TT and a series of tests to interrogate various performance-related and physical determinants of swimming. In addition, swimmers attended a radiology clinic on one occasion; in the week post-TapTr2 to have their MFT estimated using $^1$H-MRS.

![Figure 1. Schematic representation of training volume through each training phase.](image-url)
Table 2: An example of the volume increases applied between a NormTr and a HVTr training session

<table>
<thead>
<tr>
<th>Session</th>
<th>NormTr</th>
<th>HVTr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warm up (~60-70% HR&lt;sub&gt;max&lt;/sub&gt;)</td>
<td>1500 m</td>
<td>1950 m</td>
</tr>
<tr>
<td>Heavy intensity (~80% HR&lt;sub&gt;max&lt;/sub&gt;)</td>
<td>8 x 400 m @ 40 bbm, rest 10 s</td>
<td>10 x 400 m @ 40 bbm, rest 10 s</td>
</tr>
<tr>
<td>Severe intensity (~90% HR&lt;sub&gt;max&lt;/sub&gt;)</td>
<td>18 x 100 m @ 10-20 bbm, rest ~40 s</td>
<td>23 x 100 m @ 10-20 bbm, rest ~40 s</td>
</tr>
<tr>
<td>Extreme intensity (all-out effort)</td>
<td>10 x 35 m @ maximal effort, rest ~3 min</td>
<td>13 x 35 m @ maximal effort, rest ~3 min</td>
</tr>
</tbody>
</table>

NormTr = normal training; HVTr = a step increase in training volume resulting in a 30% increase from NormTr

bbm = ‘beats below maximum’ i.e., number of heart beats below a swimmer’s maximum heart rate.

5.3.3 Testing procedures

Subjects performed a 200-m freestyle TT and a sequence of performance-related and physical tests on the first (Day 1) and second day (Day 2) after each of the training phases. Day 1 of testing comprised of the TT and after ~1.5 h of rest, two dry-land tests to assess upper- and lower-body muscle power: i) A chin up for maximal velocity, and ii) A squat jump for maximal height. Day 2 consisted of a 10- and a 30-s all-out tethered swim test and after a 15-min rest, swimmers performed a ‘modified 3-min all-out swim test’ (3-min all-out test). There was no training completed in the 48 h before Day 1 of testing and 12 h prior to testing on Day 2.
Table 3: Weekly training intensity targets i.e., session-RPE

<table>
<thead>
<tr>
<th>Day</th>
<th>Morning session</th>
<th>Afternoon session</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monday</td>
<td>4</td>
<td>&gt;9</td>
</tr>
<tr>
<td>Tuesday</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Wednesday</td>
<td>&gt;9</td>
<td></td>
</tr>
<tr>
<td>Thursday</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Friday</td>
<td>&gt;9</td>
<td>3</td>
</tr>
<tr>
<td>Saturday</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>Sunday</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5.3.4 200-m freestyle time trial
Swimmers completed a standardised 3-km warm-up before each TT, comprised of a 2 km of submaximal intensity (RPE <4) swimming, and kick and pull drills, before completing 4 x 200-m efforts with increasing intensity (i.e., RPE 4, 5, 6, 7-8). Each of the 200-m freestyle TTs were timed using a handheld stopwatch (Seiko, Japan) by an experienced (>5 yr) swimming coach.

5.3.5 Performance-related and physical tests
Chin up
A GymAware optical encoder (Kinetic, Canberra, ACT) was used to determine the displacement data of the swimmer’s chin-up. The device was located directly beneath the swimmers’ centre of gravity and attached to the swimmers’ waist via a belt and nylon cord. Subjects self-selected their hand position on an overhead bar before performing a maximal velocity chin-up, each swimmer completed three efforts, separated with a 2-min passive rest. The repetition with the highest mean velocity (m.s\(^{-1}\)) was used in the data analysis. The swimmers chin reaching the height of the overhead bar described a successful repeat. The mean velocity for each repetition was recorded using commercially available GymAware software.
Squat jump
Squat jumps were performed on a force platform (ForceDecks, London, United Kingdom) with a sample rate of 1000 Hz. Swimmers started in an upright position with their hands on their hips, before being instructed to move into a squat position using a self-selected depth; this position was held for 3 s before they attempted to jump as high as possible. A successful trial was defined when the force trace did not display any countermovement at the start of the jump phase. All subjects were asked to perform three maximal jumps, with the highest jump used for data analysis. The ground force data from the squat jump were analysed using commercially available ForceDecks software. Jump height was determined by the conventional impulse-momentum method (Jump Height = v²/2 g, where v = velocity at take-off, and g = gravitational acceleration).

10- and 30-s all-out tethered swim tests
The tethered swim system consisted of a load-cell (IMADA, Northbrook, IL, USA) attached via a custom designed support to the starting block and computer. The swimmers were tethered to the load-cell, using 5 m of nylon cord attached at the waist via an adjustable belt. Force data were recorded using the Force Recorder Standard Software package (IMADA, Northbrook, IL, USA). Swimmers were instructed to complete two all-out freestyle efforts (10 and 30 s), each separated by 200 m of recovery swimming, and 5 min of passive rest. Force data were filtered using Butterworth band filter (0.5 - 2.0 Hz) and the mean force from each trial was calculated and used for data analysis.

Modified 3-min all-out swim test
Swimmers performed the ‘modified 3-min all-out swim test’, as described by Mitchell et al., (i.e., 3-min all-out test) on Day 2 of each training phase.
Briefly, the test consisted of 12 x 25-m efforts separated by a rest period of 5 s (verbally controlled by a member of the research team). Prior to the test swimmers were instructed by their coach to swim each 25-m effort maximally, i.e., “like a sprint, without pacing at all.” The time for each 25-m effort was measured by a swimming coach using a handheld stopwatch. Peak velocity (mean velocity on the first 25-m segment), critical speed (CS; the mean velocity of the slowest two 25-m efforts of the final four) and supra-CS distance capacity ($D'$; calculated as the integration of speed-time model) were determined using the methodology outlined by Mitchell et al.123,124

**Determination of muscle fiber typology**

Muscle carnosine content was measured by $^1$H-MRS in the soleus and gastrocnemius medialis muscle of each subject’s right limb in order to estimate MFT. No swimmer reported being vegan or vegetarian or having consumed β-alanine supplementation in the 3 months before the MFT scan. $^1$H-MRS measurements were performed on a 3-T whole body MRI scanner (Philips Medical Systems Best, The Netherlands). Subjects were lying in a supine position, while their lower leg was fixed in a spherical knee-coil. All the spectra were acquired using single voxel point-resolved spectroscopy (PRESS) with the following parameters; repetition time (TR) of 2000 ms, echo time (TE) of ~40 ms, number of excitations was 128 (carnosine) and 16 (water), spectral bandwidth was 2048 Hz, and a total acquisition time of 4 min 16 s (carnosine) and 32 s (water). The voxel size was 40 mm x 15 mm x 20 mm. Spectral data analysis was carried out using jMRUI (version 6.0) with carnosine peaks fitted and expressed relative to the internal water signal. Carnosine content (mM) was calculated using following formula:
\[
C_m = \frac{(C_s)}{(H_2O_s)} \cdot \frac{(H_2O_{T1r})}{(C_{T1r})} \cdot \frac{(H_2O_{T2r})}{(C_{T2r})} \cdot H_2O_{muscle} \cdot H_2O_{protons}
\]

where \( C_m \) is the carnosine concentration, \( C_s \) is the carnosine signal, \( H_2O_s \) is the water signal, \( C_{T1r}, C_{T2r}, H_2O_{T1r}, H_2O_{T2r} \) are the relaxation correction factors for carnosine (earlier described by Baguet et al.\textsuperscript{219}) and water (earlier described by MacMillan et al.\textsuperscript{225}), \( H_2O_{muscle} \) is the concentration of water in muscle in muscle, which was deducted from the molar concentration of water (55,000 mM) and the approximate water content of skeletal muscle tissue (0.7 L/kg wet weight of tissue) and \( H_2O_{proton} \) is the number of protons in water. The CV for test-retest inter-day carnosine measurements (approximately 7 d apart) in our laboratory was 3.5% (soleus) and 4.3% (gastrocnemius; \( n = 15 \)). The carnosine concentration of the soleus and gastrocnemius was converted to a sex-specific carnosine Z-score relative to a control population of active, healthy non-athletes, (30 women, 38 men). A CAZ-score (i.e., carnosine aggregate Z-score) was then derived by taking the mean of the two muscle-specific carnosine Z-score values and was used for all analyses.

**Statistical analysis**

The interaction between, and the main effect of, training phase (i.e., NormTr, Tap1Tr, HVTr, and TapTr2) and CAZ-score (i.e., continuous variable) on the absolute values of training volume, 200-m TT performance, and the performance-related and physical tests were explored using a repeated measures ANCOVA. Where an interaction was identified as being statistically significant, Pearson’s correlation coefficients were calculated to identify relationships involving the percent change in test score/value from TapTr1, and CAZ-score. Where an
interaction was not identified, but a main effect of training phase was observed, least squares difference pairwise comparisons between the four training phases were performed. No main effect of CAZ-score was identified for any dependent variable autonomous of an interaction effect. All alpha values were set at 0.05.

5.4 Results

5.4.1 Muscle fiber typology and training volume
Participants in the present study recorded a mean CAZ-score of -0.40 ± 0.36 (range -0.82 to 0.20) with eight of the ten swimmers recording a negative CAZ-score in comparison to age and gender matched controls. As expected, training volume was not affected by an interaction between training phase and CAZ-score (F = 1.867, p = 0.162). However, as prescribed, training phase exerted a main effect on training volume (F = 26.879, p < 0.001) whereby the mean training volume recorded for each training phase were significantly different from each other: NormTr = 40.4 ± 11.3; TapTr1 = 29.2 ± 7.9; HVTr = 50.5 ± 13.1 and TapTr2 = 35.5 ± 9.3 km; p < 0.05).

5.4.2 200-m freestyle time trial
There was a significant interaction between training phase and CAZ-score (F = 4.788, p = 0.009) on 200-m TT. CAZ-score was not significantly associated (r = -0.496, p = 0.145) with the percent change in individual 200-m TT performances from NormTr (2:13.8 ± 00:07.2 m:ss.0) to TapTr1 (2:13.3 ± 00:07.3 m:ss.0). However, the percent change in TT measured from TapTr1 to HVTr (2:16.0 ± 00:08.4 m:ss.0) was positively associated with CAZ-score (r = 0.697, p = 0.025), whereby CAZ-score accounted for almost 50% ($R^2 = 0.49$) of the variability (Figure 2). CAZ-score was not significantly associated (r = -0.110, p = 0.762) with the
percent change in individual 200-m TT performances from TapTr1 to after the second 1-wk taper phase (TapTr2 = 2:13.4 ± 00:08.0 m:ss.0).

5.4.3 Chin-up and squat jump
There was no interaction effect of training phase and CAZ-score on mean chin-up velocity (F = 0.155, p = 0.926) or squat-jump height (F = 1.697, p = 0.194). Furthermore, there was no effect of training phase on chin-up velocity (F = 0.758, p = 0.529) or squat-jump height (F = 0.147, p = 0.931).

Figure 2. Relationship between CAZ-score and the percent change in 200-m freestyle TT performance from TapTr1 to HVTr. CAZ-score = carnosine aggregate Z-score (estimate of muscle fiber typology); TapTr1 = an exponential reduction in training volume resulting in a 30% decrease from normal training; HVTr = a step increase in training volume resulting in a 30% increase from normal training.
5.4.4 10- and 30-s all-out tethered swim tests

There was no interaction effect of training phase and CAZ-score on the mean force measured during the 10- (F = 0.272, p = 0.845) or the 30-s (F = 2.350, p = 0.098) tethered swim tests. Furthermore, there was no effect of training phase on the mean force measured during the 10-s tethered swim test (F = 0.165, p = 0.919). However, there was a main effect of training phase on the mean force measured during the 30-s tethered swim test (F = 3.045, p = 0.048; Figure 3). Specifically, the mean force measured during the 30-s tethered test was significantly higher during NormTr (124.16 ± 18.48 N) when compared with force values measured during the TapTr1 (119.14 ± 15.71 N; p = 0.027), HVTr (116.05 ± 19.38 N; p = 0.002), and TapTr2 (118.22 ± 18.52 N; p = 0.035) training phases. There were no other

![Figure 3](image)

**Figure 3.** Mean force (N) measured during the 30-s tethered swim test expressed as a relative (%) change from TapTr1. NormTr = monitored normal training; TapTr1 = 1-wk taper i.e., an exponential reduction in training load from NormTr over 7 d resulting in a ~30% decrease in volume (only) from NormTr; HVTr = a step increase in training volume resulting in a 30% increase in volume (only) from NormTr; TapTr2 = 1-wk taper i.e., an exponential reduction in training load from NormTr over 7 d resulting in a ~30% decrease in volume (only) from HVTr.
differences in mean force measured during the 30-s tethered test among any other training phases.

5.4.5 Modified 3-min all-out swim test
Peak velocity measured during the 3-min all-out test was not affected by an interaction between training phase and CAZ-score (F = 0.155, p = 0.926) or a main effect of training phase (F = 0.758, p = 0.529). While there was no interaction effect of CAZ-score and training phase on D’ (F = 2.191, p = 0.115), D’ was affected by training phase (F = 5.189, p = 0.007; Figure 4). D’ measured during the 3-min all-out test was significantly higher during NormTr (20.03 ± 10.72 m) when compared to TapTr1 (15.45 ± 6.71 m; p = 0.041) and HVTr (15.01 ± 6.66 m; p = 0.043) training phases but not the TapTr2 (15.32 ± 5.25 m; p = 0.065) training phase. There were no other differences in D’ measured during the 3-min all-out test among any other training phases. Finally, CS measured during the 3-min all-out test was unaffected by the interaction between training phase and CAZ-score (F = 0.249, p = 0.861) or a main effect of training phase (F = 0.325, p = 0.807).
We were particularly interested to understand if the proportion of type I and type II muscle fibers moderated the magnitude of change in performance measured after concentrated overload training. The main finding of
the present study was that the magnitude of change in 200-m TT performance after HVTr was associated with MFT. Therefore, swimmers with a higher estimated proportion of type II muscle fibers (i.e., higher CAZ-score) had a greater reduction in 200-m TT performance. In addition, some, but not all, performance-related and physical tests were affected by alterations to training volume, yet the results were not consistent. Furthermore, the magnitude of change in the performance-related and physical tests across training phases were not moderated by CAZ-score. Finally, it is evident from the results of the present study that a progressive non-linear taper over 7 d is not sufficient to promote performance supercompensation in elite swimmers.

The magnitude of change in TT performance, as well as performance-related and physical tests, among training phases was reported as a relative (%) change to help control for differences anticipated in absolute results between women (n = 2) and men (n = 8) swimmers in the present study. Furthermore, the change from the TapTr1 phase was of primary focus as the 1-wk taper period was intended to produce best performances, as well as to avoid the potential of habitually ‘stale’ (i.e., overreached) performances during the NormTr phase. As such, we observed relative changes in 200-m TT ranging from -0.79 to 10.18%, whereby eight of the ten elite swimmers participating in the present study had a decrease in their 200-m TT performance after 3 wk of HVTr when compared to TapTr1. Previous studies that have applied a similar duration (2-4 weeks) and magnitude (30-40%) of training volume overload to athletes have reported performance decrements in about one-third, one-half or all of their participants. In contrast, others have reported no change in TT performance after a period of HVTr. There is a wide variety of findings among previous studies and the present
study regarding performance changes after a period of HVTr. This could be due to the mode of performance testing (i.e., running\textsuperscript{156,269} cycling,\textsuperscript{268} swimming\textsuperscript{144}), sport of the athlete and type of training (i.e., triathlete,\textsuperscript{268} runners,\textsuperscript{156} swimmers\textsuperscript{144}), as well as the calibre, gender, and/or age of the athletes participating. For example, participants in the study by Faude et al.\textsuperscript{144} comprised young (16.6 ± 1.4 yr) competitive swimmers (<42 in national age-group ranking) with an average weekly training volume of 33.0 ± 4.8 km, whereas the present study included highly-trained adult (19.9 ± 3.2 yr) swimmers with an average weekly training volume of 40.4 ± 11.3 km. The mean training volume reported by swimmers in the present study is commensurate with previous reports of training volume reported by Australian swimmers ranked within the top 10 at their national championships.\textsuperscript{265} Other studies demonstrating performance decrements after a concentrated overload training have also included older\textsuperscript{269}, and/or more highly-trained athletes when compared with athletes in the study by Faude et al.\textsuperscript{144}

Despite variability in the findings among studies, perhaps what is more curious is the variability in the change in performance after HVTr observed among athletes within each study. Although Le Meur et al.\textsuperscript{269} reported a 100\% chance of a decline in performance after a 3-wk period of HVTr in trained triathletes, the coefficient of variation (CV) of the within-group change was about 30\% (estimated from 90\% confidence intervals provided). While the authors provide robust evidence and rationale to explain the group mean decline in performance, there is little evidence to explain the within-group variability. Interestingly, the variability observed in R-R intervals of morning heart rate recordings among subjects in the study by Le Meur et al.\textsuperscript{269} were explained, in part, to be as a result of a combination of parasympathetic hyperactivity, variability in other sensory systems and/or poorly controlled
measurements performed independently by the participants. Inter-individual variability in the responses to training have been previously described as the ‘high-responders’ and low-responders’ phenomenon. Indeed, it is now understood that probing individual athlete responses to training provides important information about training adaptation, including the mechanisms that underpin the responses to exercise and recovery which can inform methods of training prescription. In the present study, the relative change in 200-m freestyle TT performance from before to after HVTr was wildly variable (i.e., CV = 158%). In a 2014 review, Mann et al. eloquently explains that inter-individual variability in response to exercise training could be associated with a number of genetic factors, the expression of pre-training phenotypes, training readiness, and/or measurement error. In the present study, inter-individual variability could be explained by measurement error in the hand-held timing or swimmers’ acute health and motivation at the time of testing. Nonetheless, we determined that the relative change in 200-m TT performance between TapTr1 and HVTr observed in the present study was associated with the swimmers’ MFT. In particular, about 50% of the variability in the relationship could be explained by CAZ-score, whereby swimmers with an estimated higher proportion of type II fibers (i.e., higher CAZ-score) have a greater decline in TT performance after HVTr. These findings suggest that swimmers with an estimated higher proportion of type II fibers are less resistant to concentrated overload training manifest by increasing volume only. Findings of the present study are directly comparable to a previous study conducted in our laboratory that employed a similar training stimulus (i.e., 3 wk of HVTr) and also used non-invasive ³¹H-MRS technology to estimate MFT through the quantification of muscle carnosine content. Bellinger et al. demonstrated that well-trained middle-distance runners with an estimated higher proportion of type I fibers were better able to
maintain incremental running performance in response to HVTr training compared to runners with a higher proportion of type II fibers. As previously explained by Bellinger et al.,156 in comparison to type I fibers, “type II fibers have greater fatigability,259 take longer to recover258 and may adapt optimally to low-volume, high-frequency contractions”.260 Furthermore, Fitts et al.258 demonstrated impairments to type II muscle fiber shortening velocity and diameter after a 10 d period of increased volume training in swimmers, whereas type I muscle fiber characteristics were unaffected. More recently, Lievens et al.52 confirmed greater fatigability and recovery time in subjects with a higher proportion of type II fibers after intermittent sprint-cycling exercise. The amalgamation of results from the present study and previous findings,258-260,271,272 provide rationale for the hypothesis that, residual fatigue caused by HVTr impairs adaptations and/or recovery of type II muscle fibers to a greater extent that type I fibers, which may result in larger decrements in performance time.

Periods of HVTr are typically employed by coaches to strategically enhance performance. Although concentrated overload training can result in an acute decline in performance, it may elicit larger increases in performance if adequate recovery strategies are employed when compared to maintaining normal training volumes.267 In order to achieve adequate recovery from concentrated overload training, coaches use the technique of tapering (i.e., a gradual reduction in training load).265 The purpose of the taper is to reduce residual physiological and psychological fatigue accumulated in training so that sport performance can be optimized. Surprisingly, neither a change in performance from NormTr to TapTr1 or from TapTr1 to TapTr2 was observed in the present study. This suggests that the first taper employed in the present study did not induce a performance enhancement over-and-above NormTr,
and that TapTr2 did not elicit performance supercompensation whereby performance is expected to surpass TapTr1. It has been suggested that greater gains in performance are achieved when the taper is immediately preceded by a period of training performed at a higher intensity and/or volume compared to normal training loads.\textsuperscript{267} Importantly, these improvements in performance can be masked if athletes are considered to be functionally overreached (F-OR).\textsuperscript{156,267} These factors may explain the TT performance results in the present study as TapTr1 was preceded by NormTr and although swimmers were not assessed for F-OR, the maintenance of TT performance from NormTr to TapTr1 would suggest they were not. Nonetheless, it is not clear why a performance supercompensation was not observed after TapTr2 in the present study despite 3 wk of HVTr and a 1-wk taper. These findings are in contrast with two previous studies demonstrating a positive effect (i.e., performance improvement) of a 1-wk taper after 3 wk of high-volume training, like that employed in the present study.\textsuperscript{156,269} Athletes in the study by Le Meur et al.\textsuperscript{269} demonstrated an \textasciitilde 8% performance supercompensation after a 1-wk taper while Bellinger et al.\textsuperscript{156} also showed performance supercompensation following 3 wk of HVTr and a taper in trained middle-distance runners. Similarly, Coutts et al.\textsuperscript{273} compared performance changes in well-trained triathletes after overload training and a 2-wk taper demonstrating that while 4 wk of overload training resulted in a 4% decrease in 3-km running TT performance, a gain in performance of 7% was observed after the 2-wk taper. Nonetheless, it should be highlighted that these studies were conducted in triathletes\textsuperscript{273} and middle-distance runners,\textsuperscript{156} respectively. Furthermore, a lack of performance supercompensation, as indicated in the present study, may be explained by two main factors: i. Non-specific training adaptations during training, and/or ii. Persistent fatigue during the taper. It is possible that increased training volume did not stimulate specific physiological
and/or neurological mechanisms required to induce performance enhancement during taper. Although the training prescription aimed to increase volume (via increases in swim distance) while maintaining intensity (i.e., swim speed), we cannot be sure that intensity was sustained during the final repetitions, or that a pacing strategy was not employed by the swimmers. If intensity was reduced during the HVTr compared to NormTr, it is reasonable to suggest that the principle of specificity, regarding the metabolic and neural requirements for the 200-m TT performance test, was not met. Furthermore, as specificity also relates to the muscle groups trained, three of the participants in the present study were not freestyle specialists. Therefore, it could be assumed that some of their training was performed using different muscle groups to those required for the 200-m freestyle TT performance test.

In addition to differential adaptation resulting from non-specific training, cumulative fatigue may have i. been present during HVTr thereby diminishing training quality/specificity (as previously discussed), or ii. persisted into TapTr2 thereby directly affecting TT performance and masking any performance supercompensation in comparison to TapTr1. Decrements in strength, speed, and endurance could be induced by metabolic, neurological, immunological, and/or psychological disturbances related to HVTr. In the present study, measures of upper- and lower-body power as well estimates of anaerobic and aerobic metabolism were determined to provide a mechanistic rationalization to changes in TT performance. However, the results of the present study do not provide a clear physiological or physical explanation as to why 200-m TT performance was reduced with HVTr, did not improve after TapTr, or why relative changes in TT performance from TapTr1 to HVTr were associated with MFT. Indeed, chin-up
velocity, squat-jump height and 10-s mean swim force, was not attenuated by HVTr or improved after TapTr2. This suggests that training load had no influence on muscle force production in the present study. While significant improvements in force and power seem to be the main adaptations after taper, increased swimming power is not always observed. For example, Costill et al. reported no change in short-distance (~23 m) swim power (W) after HVTr and a taper period. Although there are previous indications to suggest that concentrated overload training may result in a reduction to muscle force, Costill et al. suggested that the loss of muscle strength after HVTr may be temporary and return to normal after a few days of recovery. Furthermore, ‘dry-land’ strength training load was unchanged throughout the present study therefore, muscle groups used in the chin up and squat jump may have been largely unaffected by the relatively low velocity/intensity of swimming during HVTr.

As the 200-m freestyle event is fueled predominantly by aerobic energy sources, we used a modified 3-min all-out swimming test to determine if changes in training volume affected CS. Although the group mean CS was unaffected by training phase, the relative change in CS determined after HVTr compared to TapTr1 was highly variable (0.48 ± 2.68 m·s⁻¹; CV = 554%). Nonetheless, this variation could not be explained by the swimmers’ MFT. However, these results suggest that inter-individual responses to training should be considered before applying a generic training program. Nonetheless, there is little evidence to suggest that endurance is affected by high-volume training and the subsequent taper in swimmers. This contrasts with the findings of Bellinger et al. who demonstrated an increase in peak aerobic power following HVTr and a subsequent taper in middle-distance runners. It is possible that measures of peak aerobic power are more sensitive to
changes in training volume compared to CS, or that adaptations to endurance are sport specific. However, the increase in peak aerobic power demonstrated in the study by Bellinger et al.\textsuperscript{156} was accompanied by a performance supercompensation, whereas both TT performance and CS were unchanged in the present study which is consistent with the majority of training studies in swimming that have manipulated training volume.\textsuperscript{37,144}

Despite a smaller contribution to the overall energy demand, anaerobic metabolism (~35\%) plays an important role during the 200-m freestyle event.\textsuperscript{119} Determination of D’ (i.e., supra-CS) during the ‘modified 3-min all-out swimming test’ and mean force during the 30-s tethered swim test provided us with information about the affect of training volume manipulation on the capacity of the glycolytic-anaerobic energy system during swimming. It should be noted that while some investigators consider the magnitude of D’ to be synonymous with anaerobic capacity,\textsuperscript{277,278} there is still a great deal of uncertainty regarding the physiological determinants of D’.\textsuperscript{279} The present study demonstrated that both D’ and 30-s mean force decreased from NormTr to TapTr1 and then remained unchanged for the remaining training phase. While it is almost certain that D’ and by extension, mean force measured during a 30-s swim test, are altered by oxygen availability, and cannot be considered ‘true’ measures of anaerobic capacity,\textsuperscript{279} it is likely that energy supply at supra-CS exercise intensities are largely supplied by anaerobic metabolism. Therefore, the findings of the present study suggest that glycolytic-anaerobic energy production was adversely affected by TapTr1 and remained suppressed compared to NormTr for the remainder of the training program. This is in contrast to the findings of Papoti et al.,\textsuperscript{263} who reported a 3.6\% increase in swim force measured during a 30-s tethered swim test after a taper that immediately followed concentrated overload.
training. Although the underlying reasons explaining the lack of supercompensation in D’ and 30-s mean force measured after TapTr2 in the present study remains to be elucidated, it is not surprising given the absence of TT performance supercompensation over the same time period. Perhaps what is of further interest is the decrease in D’ and 30-s mean force from NormTr to TapTr. While an increase in D’ and 30-s mean force from NormTr to TapTr was perhaps not expected, given the inability of swimmers to increase TT performance during TapTr1, it is difficult to explain why surrogate measures that may reflect glycolytic-anaerobic energy production may have decreased between these training phases. Accordingly, a closer examination of the underlying mechanisms driving decreases in anaerobic energy production associated with short-duration tapers following normal training is warranted.

As highlighted by Faude et al.,144 one issue of controlled training studies in elite athletes is the recruitment of an adequate sample size to provide sufficient statistical power. It should be noted that the present study recruited similar sample size to previous investigations studying training interventions in swimming.29,144 We chose to only include elite-calibre swimmers who recorded 100% compliance with all training and testing requirements, perhaps at the expense of including a larger sample size and possibly obtaining more statistical power. As such, the results of this study suggest that 200-m freestyle TT performance may be attenuated by a 3 wk of HVTr and there is some evidence to suggest that the magnitude of performance impairment is associated with inter-individual variation in MFT.
Chapter 6: Summary and Contextualization
6.1 Summary of Research

The physical characteristics of world-class athletes has always been an area of research that has fascinated coaches, sports scientists and researchers alike. However, the availability of populous sample sizes is rarely accessible outside of major sporting competitions and given that athletes and coaches are solely focused on competing at these times, they are less than willing to spend time on research projects. The plethora of world-class swimmers living and training in South-East Queensland, Australia, has allowed for the studies in this thesis to employ innovative technology to develop a greater understanding of the influence that MFT has on swimming performance determinants at the world class and elite level.

The main aim of this thesis was to determine whether inter-individual variation in the MFT of world-class and elite swimmers influenced competitive and training performance. The first study in this thesis determined whether age, height and body mass (most consistently reported characteristics of swimmers) could differentiate between world-class and elite swimmers and if these characteristics have changed over a 50-year period. The experimental studies within this thesis have created a platform of research exploring the influence that MFT and has on swimming performance. The studies used innovative \(^1\)H-MRS technology to estimate the MFT of elite swimmers and demonstrated that variation in these characteristics is associated with start performance and pacing strategy of elite swimmers as well as the inter-individual variation in the performance responses to a period of HVTr.
6.2 Key findings

- Both female and male FR swimmers were taller at the 1992 (175.0 ± 6.1 cm and 189.0 ± 6.7 cm) Olympic Games compared to FR swimmers at the 1968 (168.2 ± 4.1 cm and 180.9 ± 5.8 cm) Olympic Games. There was no further change in height from 1992 to 2016 for male and female FR swimmers (173.2 ± 6.5 cm and 189.0 ± 6.3 cm). Body mass followed a similar pattern with body mass of females and males increasing from 1968 to 1992 (58.8 ± 0.8 kg to 63.6 ± 0.9 kg; 76.0 ± 0.8 kg to 80.5 ± 0.9 kg respectively) and then plateauing from 1992 to 2016 (2016: 64.6 ± 0.7 kg and 80.5 ± 0.8 kg). Comparatively, the age of female swimmers has continued to increase from 1968 to 1992 to 2016 (16.7 ± 2.1, 19.7 ± 2.4 to 22.7 yr) whereas the male swimmers’ age followed a similar trend to height and body mass (20.1 ± 2.4, 21.8 ± 2.9 to 22.6 ± 2.8 yr).

- Gender, stroke and event distance did not significantly interact with the MFT and start, turn and turn out performance, however there was a significant main effect for gender (StT, TnT and ToT, p < 0.001), stroke (StT, TnT and ToT, p < 0.001) and event distance (StT, TnT and ToT, p < 0.001).

- 100-m StT, TnT and ToT were significantly faster when compared with 200-m StT (p < 0.01), TnT (p < 0.001) and ToT (p < 0.001).

- MFT had a significant influence on the start time to 15 m in 100-m swimming events, with those swimmers who possessed a greater estimated proportion of type II fibers, faster to 15 m (p = 0.02). Specifically, the StT in 100-m freestyle swimmers was 0.25 s faster in swimmers with a greater estimated proportion of Type II muscle fibers (CI 90%, 0.17 s).
• The pacing strategy in 200-m freestyle events is different between swimmers who vary in MFT. Specifically swimmers with a greater estimated proportion of type II fibers swam the third lap slower than those swimmers with a greater estimated proportion of type I muscle fibers (p = 0.02). Whilst there was a difference in the pacing strategy, there were no difference in overall performance time between the two groups. This finding highlights the necessity to individualize pacing strategy between swimmers.

• Increases in training volume of ~ 30% for 3 wk result in significant impairments in 200-m freestyle TT performance (p < 0.01).

• The change in TT performance from pre- to post-HVTr was positively associated with MFT (r = 0.697, p = 0.025). That is, swimmers with a greater estimated proportion of type II muscle fibers had larger decrements in performance.

The first study of this thesis had a two-fold aim: i) to evaluate previously published literature on the age, height and body mass of world-class swimmers, and ii) to provide insight into how changes in age, height and body mass of world-class and elite-level swimmers over the past 50 years might have contributed, in part, to the concomitant improvements observed in swimming performances. It was determined that there has been a plateau in the age of Olympic swimmers, with men and women both at the same age in 2016. The height and body mass of swimmers increased between 1968 and 1992, however there were no further increases between 1992 and 2016, suggesting that these characteristics have begun to plateau amongst this population. Without measures of body composition, it is difficult to determine whether these changes in body mass were a result of lean mass changes. These finding evoked the curiosity into what other physical characteristics determine
performance, since the stereotypical height and body mass characteristics are now likely redundant in distinguishing performance differences in world-class and elite swimmers. As such, given that these basic characteristics seem to have plateaued we explored new technology to better understand the underpinning determinants of swimmers’ performance. In particular, whether MFT was determinant in race and training performance.

The second and third studies of this thesis employed $^1$H-MRS to determine MFT to investigate the influence this characteristic had on key determinants of swimming performance. Study two specifically explored the influence that MFT has on start and turn performance of world-class swimmers from a wide range of events. Start and turn performance are two of the most researched performance characteristics of swimmers due to the relative ease with which they can be assessed. The results of study two showed that world-class swimmers competing in 100 m events had a faster start time to 15 m if they possessed a larger estimated proportion of type II muscle fibers. Specifically, swimmers competing in 100 m events were on average 0.25 s quicker to the 15 m if they had a greater estimated proportion of type II muscle fibers. The time difference between finishing positions in 100-m swimming events is often less than 0.25 s, which highlights the large influence MFT may have on swimming performance and results. Study 3 explored the influence MFT had on the pacing strategy of one of the most competitive and diverse swimming events, the 200-m freestyle. This study found that there were differences in the pacing strategy between swimmers of divergent MFT. Although statistically insignificant ($p = 0.06$), swimmers with a higher estimated proportion of type I fibers swam lap 1, 0.2% slower that those with a higher estimated proportion of type II fibers. However, on the third lap, swimmers with greater estimated proportions of type I
fibers spent a proportionally significantly smaller percent of overall race time on this lap compared to those swimmers with greater estimated proportions of type II fibers (p = 0.02). The rationale behind these findings could be related to the energetic demands of the event and the metabolic characteristics of different fiber types. The third lap of the 200-m freestyle event relies heavily on the energy from aerobic energy metabolism, which is the primary source of energy for type I fibers, conversely type II fibers have a preference towards anaerobic energy metabolism. One of the key findings of this study was that there was no difference in the overall performance time, between swimmers of divergent MFT. This may suggest that MFT is not deterministic for overall 200-m freestyle performance, but different pacing strategies may be required to maximize performance in elite swimmers with divergent MFT. For example, do swimmers with greater proportions of type II muscle fibers require a greater number of years to develop a more acutely defined pacing strategy to be able to maintain velocity in the 3rd lap of the 200-m freestyle event. Future research could be directed down this avenue.

Whilst study 2 and 3 were determined the influence of MFT on racing performance determinants, the emphasis of study 4 was to determine if swimmers with divergent MFT had polarized responses following a period of HVTr. The results of this study found that swimmers with a higher estimated proportion of type II muscle fibers, had larger decrements in TT performance compared to those swimmers with higher estimated proportions of type I fibers following a period of HVTr. Despite the relatively small inter-individual variation in MFT, we observed a significant association with the decrement in performance following HVTr and MFT.
The studies included in this thesis highlight the application of $^1$H-MRS derived estimates of MFT are influencing performance and training determinants of elite swimmers, highlighting its effectiveness for application in elite athlete populations. In particular, research aimed at determining individualized training and racing strategies based on variation in MFT, as well as talent identification models could be developed.

6.3 Practical Applications

This thesis was an initial exploration into MFT and swimming performance determinant. Having concluded that there is a potential plateau in other characteristics such as age, height and body mass. While there are other physical characteristics that may also be influential to the performance of elite swimmers, like many initial explorations, this thesis has provided novel findings from which future applied swimming research can extend, advance applied swimming performance. The key practical applications of this body of research are highlighted below:

1. $^1$H-MRS technology can be used to determine MFT in world-class and elite-level populations of swimmers, whereby coaches are more accepting of the non-invasive nature of this methodology of MFT determination.

2. In light of the results of investigative study 2 “Muscle fiber typology and its association with start and turn performance in elite swimmers,” swimmers who competing in sprint events (100-m events) who possess a higher estimated proportion of type II fibers have a distinct advantage in the execution of the start segment of the race.
3. The notable difference in start time of 100-m freestyle time of 0.25 s (CI 90% ± 0.17 s) highlights how crucial the influence of MFT is in overall performance given that 0.25 s can be the difference between 1st and 8th at an international swimming competition. Due to the increased proportion of time spent in the start phase of 100-m events compared to events of greater distance, swimmers who possess greater proportions of type II fibers have a distinct advantage and therefore could be directed to compete in events of shorter distance.

4. The early identification of swimmers who possess larger proportions of type II muscle fibers, could allow earlier specialisation in sprint events in order to maximise the physical characteristics of the swimmer. If the determination of MFT through non-invasive technology became readily available to both swimming and other sporting groups, this physical characteristic could be added to talent identification models.

5. 200-m freestyle swimmers with divergent MFT pace their races differently during their career best performance, despite achieving equally exceptional performance times. This highlights that individualised pacing strategies are important to racing performance, and coaches may be able to reverse engineer the pacing strategy of the 200-m freestyle, to determine MFT. This would need further research to accurately identify this.

6. Additional experimental studies could lead to individualised pacing strategies world-class and elite level swimmers based on MFT. It should be noted that from a practical perspective, the race strategy of swimmers may change with training age and experience depending on their physiological development, and therefore it is important for coaches and sports science
practitioners to have an understanding of how to maximise performance in these situations.

7. Overloading the volume of training has a larger negative impact on 200-m time trial performance in swimmers with a greater estimated proportions of type II fibers. Better understanding the responses to overload training in swimmers, could assist coaches and applied sports scientists in periodising training. Further experimental studies could individualise the content of training with respect to variation in the MFT of swimmers.

In summary, the practical applications of the studies in this thesis highlight that in order to maximise performance at a world-class and elite level, racing and training should be individualised in swimmers. MFT is a performance determining physical characteristic and can be measured non-invasively by sporting organisations and governing bodies to help improve and maximise racing performance, talent identification and training programs of world-class and elite-level swimmers.

6.4 Research Limitations and Difficulties

The recruitment of world-class and elite-level athletes in any sport can create a homogeneity among the sample. This could be perceived as both a positive and as a limitation. For example, a group of world-class athletes may be world class because of their genetic, physiological or physical characteristics, and therefore attempting to identify differences between these subjects can sometimes be difficult. This could be a reason for some underpowered studies in this thesis. In particular, study 3 and 4, where not only were the sample sizes relatively small, but also comparatively homogeneous in MFT. Alternatively, it could be hypothesized that if such characteristics were not deterministic to overall performance, then there
would be greater diversity within the sample, and therefore the homogeneity in itself may be an important discovery.

High-performance sport is multi-faceted. Physiological, psychological and biomechanical aspects need to be acknowledged when conducting research with these world-class and elite-level athletes. In order for research to be highly predictive of world-class performance, all of these parameters need to be considered, and statistical models should incorporate all of these parameters where possible, especially if they are to be used in talent identification processes. Statistically significant findings within world-class populations can sometimes be hard to find: and more often than not, the anomalous results, or the result that doesn’t fit the trend is the ‘super-talent,’ therefore when interpreting data and research on world-class athletes, coaches and sports science practitioners should be aware of the potential outliers. For example, Kyle Chalmers at 18 years of age is an outlier in terms of the age of the 100-m freestyle gold medal winners at the 2016 Olympic Games. Therefore, whilst talent identification models could benefit from technological improvements and advancements, (such as \(^1\text{H-MRS}\)); researchers have to ensure they do not exclude the anomalous ‘super-talents’ and we should they should always strive to better understand anomalous world-class performance.

Whilst I was able to attend every training session of study 4, the ability to create a clinical environment for the duration of the intervention is near impossible when working with human subjects. The time spent at the training session and testing facilities can be monitored and controlled, however the other 18-21 hour per day cannot, and changes in the subjects’ routine, nutrition or non-training stresses could
significantly affect results, especially in small sample sizes. Whilst these factors were considered and accounted for within this body of research, there will always be external influencing factors.

Another hurdle which was presented throughout this thesis, was the buy-in from swimming coaches. When approached about involving their swimmers in the research projects, the question they often returned with was, ‘how is this going help achieve or improve the result in 1-2 years’ time (the next Olympics)?’ To which the answer was that, it is about possibly gaining a greater understanding so that future generations of swimmers could benefit. Whilst the use of non-invasive technology helped in the recruitment of world-class swimmers, the majority of coaches want immediate to short-term assistance from research, which was not always possible.

The final major difficulty occurring throughout the studies in this thesis was the swimmers’ use of β-alanine. The majority of world-class and elite-level swimmers are aware of the benefits of consuming β-alanine and many swimmers that we hoped to scan were ingesting this supplement periodically throughout the season. This created limited windows of opportunity to determine their MFT using $^1$H-MRS given the influence that β-alanine has on muscle carnosine levels, as well as the relatively slow washout period. As such, both the study sample size and the timing of $^1$H-MRS measurements could have been improved, but the calibre of athlete was always the main priority of these studies.
6.5 Future Directions

Firstly, a large-scale validation study comparing the non-invasive estimation of MFT from $^1$H-MRS using the Phillips scanners used in this study, against the current gold standard MHC composition would be advantageous. Whilst peer-reviewed studies allude to this methodology being appropriate in the determination of MFT, it is important to validate this technique across multiple laboratories.

Within this thesis, variation in the MFT of world-class and elite-level swimmers was associated with variation in racing and training performance. Our ongoing research in this area will characterize a larger group of world-class and elite swimmers in order to determine whether swimmers who compete in sprint events are characterized by a greater proportion of Type II muscle fibers, compared to those swimmers who specialize in the endurance based events. Alternatively, whether there are differences in the MFT of swimmers who specialize in different strokes. Stemming from the characterization of swimmers, the MFT measure could accompany anthropometric parameters and identify an optimal model of multi-dimensional physical characteristics of world-class swimmers. This would allow researchers to evaluate the optimal characteristics of a swimmer.

Further research should investigate individualized responses to training stimuli, and the relationship these responses have with MFT. Some examples of this could be to determine the optimum velocity/stroke rate/stroke length to train at in order to develop the knowledge base of unpinning physiological characteristics important for swimming performance. Another example could be to determine the acute recovery time course between intense swimming training sessions and whether this could be individualized based on variation in MFT. Other race variables such as
stroke rate and distance per stroke could be associated with MFT, in order to develop a model which could help maximize performance in world-class and elite swimmers.

MFT research could also incorporate anthropometric data to MFT research to add to the collective combination of physical characteristics required to maximize the performance of world-class swimmers. Further research could investigate the relationship between swimmers’ anthropometric measures, race analysis and MFT, to determine if there is a cohesive relationship between these characteristics. For example, can a swimmer who is shorter but has greater proportions of type II muscle fibers swim their event at a higher stroke rate compared to a taller person, and therefore complete the race in a faster time, even though they are shorter?

In relation to the studies presented in the present thesis, start and turn analysis could be undertaken with wet plate and video analysis, to determine if the specific phases of these swimming skills are affected by MFT. This could lead to intervention studies that aim to either develop the specific areas of the skill (i.e., flight distance, reaction time or entry point), or aim to develop the specific force production capacities of a swimmer, in order to maximize their MFT.

Similarly, the pacing study presented in Chapter 4 of the present thesis could be developed to incorporate multiple event distances. Aims for future research in this area should be to explore the pacing strategies of other distances and strokes, to determine if there are differences in the pacing strategies of these events. Another aim would be to determine if there is a relationship between the pacing strategies of a swimmer across multiple events. For example do swimmers with a higher
proportion of type II fibers swim the same type of pacing strategy across all event
distances, or does the physiology of differing MFT mean that as event distance
changes they have to alter the pacing strategy.

Individual case studies on world-class swimmers could be performed to determine
how MFT is affecting training adaptations, race-skills performance, and pacing
strategies. It is these athletes who are at the top of their field which need to be
analyzed in a holistic manner, as they are the athletes that have the best combination
of physical, physiological and psychological aspects. Consequently, the case
studies of 5-6 of the best swimmers in the world, incorporating the determination
of MFT would be of significant value to the research and sports science domains.

Finally, the expense incurred in determining the MFT of swimmers is high.
Therefore, developing a series of tests that can accurately predict MFT through
training or swimming test methods would be beneficial so that coaches can readily
implement the testing. For example, we could ask the question, ‘are there certain
parameters measured in the 12 x 25-m swim test that highly relate with either type
I or type II muscle fibers?
6.6 Conclusion

The studies emanating from this thesis could be summarized as ‘MFT can moderate the race and training determinants of world-class and elite-level swimmers’. The advancements of MFT determining technology should be utilized in order to be able to identify and maximize talent identification, race performance and training prescription in swimming. This thesis provided an initial exploration into the influence that MFT has on swimming performance and clearly demonstrates the potential for this methodology to enhance swimming results in the future.
References


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