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Assessing the Applicability of a Three-Minute All-Out Swimming Test in Collegiate Swimmers

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by

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ABSTRACT

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Performance tests are used to gauge swimmer fitness and guide training prescription. While some traditional protocols, such as, best average swimming (Bavg) lack scientific support, the three-minute all-out test (3MT) is validated to measure critical speed (CS) and distance capacity above CS (D') from a single maximal swimming bout. In collegiate swimming, a 3MT could be convenient and time efficient. Yet, issues arise with calculating 3MT parameters. Moreover, anthropometry, resistance training, and stroke technique may influence swimming performance and physiological thresholds including 3MT parameters. Hence, this dissertation focused on evaluating the 3MT parameter calculation methods using the interval and lap split methods. Then, we assessed the influence of body anthropometrics, resistance training, and stroke techniques on 3MT parameters throughout a season. Bland-Altman plots showed that CS did not present remarkable behavior while D' had systematic bias. Furthermore, there were no statistical differences between CS calculation methods ($p = 0.83$). However, D' had moderate effect differences ($p = 0.01$, $d = -0.70$). Bavg showed very large correlations with maximum sprint speed (MSS) ($r = 0.78$) and CS ($r = 0.81$), but improvements after 6-weeks of concurrent training ($p < 0.001$, $d = -0.85$) seemed mainly driven by CS ($p < 0.001$, $d = -1.68$). Significant moderate to near perfect correlations were found between anthropometrics, 3MT parameters, and medicine ball pulldown throw (MBT) performance during pre- and post-season. Body composition changes may have influenced MBT performance changes ($r = 0.46 – 0.55$). CS increased at the expense of D' while both reached stabilization point with no changes in MSS.

There were moderate to large differences in 3MT parameters for the backstroke, but only MSS and CS differed in breaststroke, with no D’ differences in either group. Large to near perfect correlations were found between freestyle and secondary stroke 3MT parameter counterparts ($r = 0.62 – 0.93$), except for D’ in backstroke. Actual and predicted CS in both backstroke ($p = 0.27$) and breaststroke ($p = 0.97$) did not significantly differ. The lap split method during a 3MT seems like a practical and useful protocol to monitor CS and D’ in collegiate swimmers.

DEDICATION

I would like to dedicate this project and journey to my late father Concepción Rodriguez. When I was 9 years old, I told you that I wanted to become a doctor one day. After you passed away when I was 19 years old, I promised myself to fulfill this to make you proud. Twenty years after your passing and 30 years from that moment, this one is for you. I hope I have made you a proud father. I miss you and I love you!

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Chapter 1. Introduction

Performance testing has been one of the main topics pondered by scientists and coaches studying competitive swimming (Pelayo & Alberty, 2011). A myriad of methods have been used by practitioners to inform, assess and monitor swimming performance adaptations and progress to a prescribed program (Anderson et al., 2006; Pyne et al., 2000). Physiological performance variables, such as, maximum oxygen consumption ($\dot{V}O_2max$) and thresholds (i.e., lactate threshold [LT] and maximum lactate steady state [MLSS]) have been measured in lab and pool settings by scientists seeking to individualize training prescription (Espada & Alves, 2010; Lavoie et al., 1985; Pyne et al., 2001). Despite the efforts, environmental constraints, high costs, lack of expertise and time have made these options challenging for coaches who eventually return to traditional testing sets with limited theoretical evidence to support their use. This is especially true for collegiate swimming where training time is regulated and limits the opportunities to garner more information from testing making the more complex, sophisticated tests impractical.

A common traditional testing set used by coaches has been the best average swimming test (Bavg). It consists of swimming 10 repetitions of 100 m as fast as possible with 10 – 20 s rest intervals depending on the send out time (i.e., 80 – 100 s dependent on athlete level). A few logistical problems arise with this type of test: 1) it is time consuming (± 90 – 100 minutes to test 32 athletes in an 8-lane pool), 2) additional testing still needed to measure maximum sprinting speed (MSS; consuming more time), 3) the resulting speed (Bavg) is constituted by a combination of multiple physical and physiological elements (MSS, anaerobic speed reserve [ASR], aerobic profile [i.e., aspects of VO2max, LT, and recoverability], biomechanics, body anthropometrics, etc.) making it challenging to determine the underlying mechanism of performance alterations.

Alternative field tests can provide coaches performance markers that may indicate training effects, such as, the velocity related to the $\dot{V}O_2max$ ($v\dot{V}O_2max$), also known as the maximum aerobic speed (Zacca et al., 2019) and the critical speed (CS) method from multiple trials (Monod & Scherrer, 1965). These can be viewed as analogous physiological surrogates to the VO2max and MLSS, respectively (Burnley & Jones, 2007). The CS is a metabolic threshold that delineates the upper and lower boundaries of the heavy (sustainable) and severe (unsustainable) intensity domains, respectively. The distance capacity available above CS is known as distance prime or D' (Tsai & Thomas, 2017) which is analogous to the W´ used with other modalities (Burnley et al., 2006; Cheng et al., 2012). These two parameters together can help predicting the tolerable duration of exercise above the CS (Poole et al., 2016).

Recently, a three-minute all-out swimming test (3MT) was validated and assessed for reliability to determine the CS and D' from a single trial (Piatrikova et al., 2019; Tsai &Thomas, 2017). Originally, the CS was measured as the average power or speed of the last 30 s of the test in various modalities (Burnley et al., 2006; Cheng et al., 2012; Pettitt et al., 2012) including swimming (Courtwright et al., 2016; Mitchell et al., 2017; Piatrikova, Sousa, Willsmer et al., 2018; Piatrikova, Sousa, Gonzalez et al., 2019; Piatrikova, Willsmer et al., 2020). However, different methods to derive CS from the 3MT have been used rendering conflicting results. Some studies measured the average velocity of the last 30 s without consideration for the swimmers position in the pool (Courtwright et al., 2016; Piatrikova et al., 2019) and others used split times in 25 m (Tsai & Thomas, 2017) and 50 m pools (Piatrikova et al., 2020). Despite different methodologies, no comparisons were made between them. In addition, D’ has been shown to be lower in a 3MT when compared to conventional multiple trial methods (Piatrikova et al., 2019). Moreover, some studies have used the 3MT using various strokes, but to the author’s knowledge, no comparisons have been made between strokes within individuals. Another aspect that may affect performance during this test is body anthropometrics (Aksit et al., 2017; Pla et al., 2019). Additionally, the effects of resistance training may impact swimming performance as this is a crucial portion of improving the physical capabilities of a swimmer (Mujika & Crowley, 2019).

The purpose of this dissertation is to assess the applicability of the 3MT in collegiate swimmers. The primary purpose is to evaluate the differences of deriving the 3MT variables through the time-speed interval method and the lap-time splits method. A secondary purpose is to investigate the relationships between body anthropometrics, upper body power measured through a medicine ball pulldown throw (MBT), a traditional Bavg swimming test, and the variables derived from the 3MT in freestyle during pre- and post-season testing periods. Furthermore, the seasonal changes in body composition, MBT, and 3MT variables will be explored. A tertiary purpose is to assess the rate of speed drop-offs between the freestyle and secondary stroke 3MT. The evidence gathered from investigating the use of a 3MT in swimming can help coaches in better understanding individual athletic performance profiles, prescribe individualized training and manage training load distributions properly throughout the season.

Chapter 2. Comprehensive Review of the Literature

Collegiate swimming is comprised of 36 total events (18 for each sex) with distances ranging from the 50 yards to the mile (45.7 m to 1508.8 m, respectively). Event durations range from ~ 18 s (elite males) to ~ 16 minutes (elite females). Although most events are swum in ≤ 5 minutes, there are several events lasting ≥ 90 s. Events are contested in four distinct swimming strokes in which athletes may have to swim one or all in a single event (i.e., 200 & 400 individual medley). It is common knowledge that for shorter distances (50 & 100 m) a high anaerobic energy provision is required, while aerobic power becomes increasingly important with longer race durations (Rodríguez & Mader, 2011). Nonetheless, researchers have shown that aerobic development may still benefit performance in events such as the 100 m in swimming (Hellard et al., 2018) due to the increasing aerobic energy contributions at the 1-minute mark (Ogita, 2006).

In track sprint running, practitioners have purported the benefits from a contrasting lower intensity stimulus to the high intensity activities they are exposed to allowing for continuous rehearsal of sprinting mechanics without the neuromuscular straining demands from maximum sprinting speed (MSS) (DeWeese et al., 2019). Since competitive swimmers constantly must repeat high effort swims during practice and rely on proper recovery between multiple qualifying and final rounds during competition, some have proposed an increased focus on maximizing the principle of training specificity with race-paced training velocities in practice, such as the “Ultra Race Pace Sprint Training (USRPT) system” (Rushall, 2016). However, researchers have criticized and cautioned about some of these philosophies due to lack of research and since its deemphasis on low intensity training seem to counter current evidence of elite level athletes exceeding about 70% of their training loads at these intensities (Nugent et al., 2019). Nonetheless, developing adequate aerobic fitness has also been shown to increase heart rate variability (Piatrikova et al., 2021) and attenuate resting muscle sympathetic nervous activity coupled with larger muscle sympathetic nervous responses to physiological stress (Raymond, 2012), which is prosperous for a sprinter's high intensity training response. While MSS is paramount for sprinters, athletes competing in longer events may also benefit from development of the anaerobic speed reserve (ASR) (Sandford & Stellingwerff, 2019; Sanford et al., 2021).

Gauging athletic performance through sport specific swimming assessments has intrigued sports scientists and coaches for decades. Research into physiological performance markers, such as, maximum oxygen consumption ($\dot{V}O_{2max}$), threshold parameters, and heart rate have provided substantial advancement for understanding the underlying mechanisms of sport performance. Nevertheless, monitoring swimming performance has evolved from controlled settings to more practical time-efficient methods in the past half century (Pelayo & Alberty, 2011).

This literature review is an examination of the physiological determinants of swimming performance and traditional testing protocols used to measure them. An overview of field tests used to assess swimming performance will be briefly discussed in lieu of the more technical evaluations that inhibit ecological validity. Then, the methods of deriving the mechanical metrics, such as, the critical swimming speed (CS) and distance capacity above CSS (D') will be detailed to understand how the novel three-minute all-out swimming test (3MT) may be a convenient testing protocol for practitioners.

Maximum Oxygen Consumption ($\dot{V}O_{2max}$)

Maximal oxygen consumption ($\dot{V}O_{2max}$) is a quantitative measure of a person's maximum aerobic power or the ability to resynthesize adenosine triphosphate (ATP) through aerobic energy pathways (McArdle et al., 2015). Since the Nobel Prize winning work by A.V. Hill (Hill & Lupton, 1923), the study of the $\dot{V}O_{2max}$ in sports has been at the forefront of the agendas of sport scientists seeking to understand how to improve athletic performance and cardiorespiratory fitness (Bassett, 2002). Hill was revered as a pioneer and a leading expert on applied physiology in relation to sport, who first demonstrated the plateauing of the $\dot{V}O_{2max}$, and that cardiac output as the limiting factor in $\dot{V}O_{2max}$ tests. However, others have criticized this idea and offered other explanations, such as, the central motor commands in the brain being the limiting factor in maximal exercise (i.e., central governor) (Noakes, 2008a; Noakes, 2008b). Nonetheless, Hill's work paved the path to apply physiology in sport that allowed for the recognition of a new scientific discipline in exercise physiology triggering the advancements in sports performance today (Hale, 2008).

$\dot{V}O_{2max}$ Testing

Various methods and modalities have been used to measure $\dot{V}O_{2max}$ in swimmers, such as, running on treadmills, tethered swimming, free swimming, swim flumes, cycling and arm ergometry (Bonen et al., 1980; Corry & Powers, 1982; Lavoie et al., 1985; Magel & Faulkner, 1967; Saltin & Astrand, 1967). An athlete's $\dot{V}O_{2max}$ can be expressed in absolute terms (L/min) and relative to body mass (ml.kg.min^{-1}). Very large correlations and no significant differences in $\dot{V}O_{2max}$ have been shown between running and tethered swimming despite lower maximal heart rates in the latter (Magel & Faulkner, 1967). Lower maximal heart rates are expected in swimming due to greater venous blood return caused by the horizontal body position along with the effects of hydrostatic pressure from submergence in water leading to an elevated stroke volume allowing the athlete to still reach maximal cardiac outputs. While measuring $\dot{V}O_{2max}$ using different modalities may render similar results, performing such tests in exercises other than swimming lacks practicality and transferability to direct programming design.

Using a "Douglas bag" which entraps a subject's expired air within a neoprene bag for later analysis was originally considered the "Gold Standard" protocol for the measurement of the $\dot{V}O_{2max}$ (Hill & Lupton, 1923). Although studies have used this method in swimming (Magel & Faulkner, 1967) and technological advancements have relieved some burdens (Baldari et al., 2012; Rodríguez et al., 2003), the aquatic constraints place offers challenges for $\dot{V}O_2$ measurement. Another method used to extrapolate the $\dot{V}O_{2max}$ in swimming has been the backward extrapolation method in which $\dot{V}O_{2max}$ is extrapolated from the O_2 recovery curve through a series of gas collections post-exercise (Montpetit et al., 1981). Besides it not being a direct measure, it has been shown to add measurement error (Chaverri et al., 2016).

Despite the importance of measuring the $\dot{V}O_{2max}$ and the insightful information about a swimmer's aerobic power (Jorgić et al., 2011), multiple issues arise from different protocols. For example, the high costs and limited availability of a swim flume along with other equipment make it rare that coaches use it to test their athletes. Also, water flow from the swim flume device and the nature of tethered swimming itself may alter technique, change stroke mechanics, and slightly affect $\dot{V}O_2$ values (Sousa et al., 2014). Its practicality may fall short of giving coaches value that is applicable to performance prescriptions. Nonetheless, researchers indicate that the competitive performance, which has the highest level of ecological validity, should be the first level of evaluation (Smith et al., 2002).

Physiological Threshold Parameters in Swimming Performance

While measuring $\dot{V}O_{2max}$ has been the most common aerobic physiological performance variable studied, its fractional parameters have been shown more interest from researchers when attempting to predict performance (DiMenna & Jones, 2019; Poole et al., 2021). Some of these physiological performance markers, such as, the lactate threshold (LT) (Farrell et al., 1979), maximum lactate steady state (MLSS) (Billat et al., 2003) and the critical speed/power method (Monod & Scherrer, 1965) have shown better correlations with endurance performance, particularly among advanced and elite swimmers (Farrell et al., 1979). Scientists have also described other physiological mechanisms that can be used to gauge performance similarly, like the gas exchange threshold (GET) and the respiratory compensation point (RCP) that can reduce the invasiveness and risks associated with bloodborne pathogens from lactate measurements (Beaver et al., 1986; Poole et al., 2021). However, lactate related assessment protocols have been the most common method used in swimming (Anderson et al., 2006; Olbrecht, 2013; Sousa et al., 2014; Zarzeczny et al., 2013).

Blood lactate levels have been measured in athletes to help understand muscle metabolism during performance. Initially, the Lactate Threshold (LT) was referred to as the anaerobic threshold as it was believed that an increased production was caused by the depletion of O_2 in muscle (Wasserman et al., 1973). This belief would eventually be questioned as later evidence indicated that increases in blood lactate did not necessarily correspond to changes in anaerobiosis, but rather an increased rate of lactate production due to factors including, motor unit recruitment order (i.e. recruitment of type II fibers), limited oxygen supply, and exceeding lactate clearance rates (Brooks, 1985; Walsh & Bannister, 1988). The Maximum Lactate Steady Sate (MLSS) has been defined as the highest blood lactate concentration and workload that can be maintained over time without continuous blood lactate accumulation (Billat et al., 2003). A range of lactate concentrations have been associated with the MLSS (2 – 8 mMol/L) and it is estimated that continuous exercise duration at this metabolic rate should be around 30 – 60 mins (Billat et al., 2003). While the MLSS can better individualized training for athletes, the invasiveness, and long single and multiple duration protocols are time consuming and can be quite fatiguing.

While the use and study of lactate parameters have greatly advanced the understanding of the metabolic processes that distinguish aerobic and anaerobic exercise, practicality in many scenarios is still an issue and underlying factors can still influence its values (Poole et al., 2021). Poole and colleagues (2021) purported that the critical power (CP) method is the only measure that can closely predict the tolerable duration of high intensity exercise alongside a second metric known as the work accomplished above CP (W'; pronounced W-prime). The CP is defined as the asymptote of the power-time curve, which is the upper boundary for sustained exercise intensities, while the W' is the constant work that can be done above CP (Burnley et al., 2006; Jones & Vanhatalo, 2017). In the sport of swimming, mechanical metrics analogous to the CP and the W' are used, these are termed the Critical Swim Speed (CSS) and the distance capacity above CSS (D') (Courtwright et al., 2016; Piatrikova et al., 2019). Interestingly, the speed-time hyperbolic relationship has been shown to occur in all species (i.e., horses, salamanders, rodents, and others) (Poole et al., 2021) and is evident when plotting results of all the world records against their respective event distances in all sports as first done by A.V. Hill in 1925 (Hill D. , 1993). While some researchers have shown a positive relationship of the CSS with the MLSS in swimming (Wakayoshi et al., 1993) others have observed it to be slightly higher in speed despite the high correlation to aerobic variables (Espada & Alves, 2010;

Machado et al., 2018). The theoretical CP concept was described by Monod & Scherer (Monod & Scherrer, 1965) and later expanded by Moritani and others (Moritani et al., 1981). Based primarily on running efforts, CP typically is obtained by performing three to five time-trials between 2 to 15 minutes (Bergstrom et al., 2021; Hill D. , 1993). However, researchers have demonstrated that CSS using multiple distance combinations can result in differing values increasing chances for error (Galbraith et al., 2014; Mattioni-Maturana et al., 2018; Norouzi et al., 2021; Zacca & Castro, 2010).

Maximal Sprinting Speed

Maximum sprinting speed (MSS) is a maximal effort bout that produces the highest velocity that can be attained during any whole-body locomotor activity. Typically, MSS can be sustained for about 7 s, at which a decline in speed primarily results from the depletion of substrates from the phosphagen system (i.e., ATP-CP) (Mougios, 2006). Although the Newtonian laws still apply, due to the constraints that swimmers are subjected to in their sport, gravitational forces are relatively insignificant compared to running (Hall & Murphy, 2020). Performance determining factors, such as, drag forces, effective propulsive forces, propelling efficiency, and power output influence the swimming velocity that a swimmer can attain (Toussaint & Beek, 1992). The highest velocities during a swimming event (in pool only) occur after the dive from the blocks and coming off each wall from the flip turn as these are the only moments that ground reaction forces are consequential (Fig, 2010).

Methods of measuring the MSS have varied from using the average speed over short distances ranging from 10 – 50 m (Espada et al., 2016; Marinho et al., 2011; Marinho et al., 2012; Ramos-Veliz et al., 2014). Hall of fame and legendary Olympic swimmer, Dr. Gary Hall, Sr. has touted the use of the Speed RT velocity meter (APLab, Italy) in his coaching at the world famous “The Race Club” (Hall & Murphy, 2020). The device is composed of a small winch with an encoder that can be placed on the starting block post, an electronic acquisition unit, and a special software program to visualize data on a computer. However, scarce research has been performed using such devices. Although the shortest competitive event is the 50 m freestyle, the study of MSS in swimming pertaining durations ranging from 5 – 35 s has been limited. However, scientists have used distances of these durations, such as the 20 m sprint (Ramos-Veliz et al., 2014) to study other aspects of swimming performance (Espada et al., 2016; Marinho et al., 2012).

The importance of the MSS within the CSS concept was not fully appreciated until recently. Sanford and Stellingwerff (2019) described how the MSS alongside typical aerobic parameters can enhance the understanding of the complexities that eluded sports scientists within middle-distance running research. The MSS can allow practitioners to assess the anaerobic speed reserve (ASR), which is the difference between the MSS and maximum aerobic speed (MAS). Thus, ASR can help in understanding the tolerance of speeds within such ranges, as well as athlete profiles (i.e., fiber typology), and to modulate the prescription of high-intensity interval training (HIIT) (Sanford et al., 2021). The only study to the authors’ knowledge, in which ASR was measured and analyzed in swimming, calculated it from the results of the 50 m and 400 m swimming trials (Dalamitros et al., 2015). They found that the ASR showed strong negative and positive correlations with CSS and D’, respectively, which could be used as an indicator of training induced changes. Given that prediction of tolerance above the CSS has been well explained compared to the MAS parameter due to its demarcation of sustainable (< CSS) and unsustainable (> CSS) intensities (Burnley & Jones, 2007; Jones &

Vanhatalo, 2017), it seems more appropriate to define the ASR as the difference between MSS and CSS instead.

Anaerobic Work Capacity Measures

Anaerobic capacity (AC) can be defined as the maximum amount of ATP resynthesized via anaerobic metabolism during short-duration maximal exercise (Green, 1995). The phosphagen (alactic) and glycolytic systems (lactic) are the energy systems providing ATP reconstitution that fit the model of anaerobic capacity (Green & Dawson, 1993; Mougios, 2006). However, it is important to not confuse the term anaerobic capacity and anaerobic work capacity (AWC), although related they are not interchangeable. The former is the composition of biochemical energy provision through non-oxidative sources, while the latter is the produced mechanical power output maintained over time – which also involves aerobic energy provision (Green & Dawson, 1993; Green, 1995).

Many methods have been described attempting to estimate the AC, such as the maximal accumulated oxygen deficit in swimmers (Reis, Marinho, Barbosa et al., 2010; Reis, Marinho, Policarpo et al., 2010) . Yet other researchers have presented flaws with the multitude of methods and protocols used to estimate AC (Noordhof et al., 2010). Similar measurement issues are found within the swimming context. These problems have been shown to be the intensity of the bout, the differing durations, and number of bouts used to perform such a test. Another method used to estimate AC was measuring a swimmer’s performance during a 30 s all-out tethered swimming test and estimating work capacity above critical force (i.e., anaerobic impulse capacity) (Papoti et al., 2011). They measured the anaerobic impulse capacity by using multiple swimming bouts above critical force at various intensities. They found statistically significant correlations with the anaerobic impulse capacity and swimming performance in the

100, 200 and 400 m freestyle swims (r = 0.76, 0.66, and 0.59, respectively). They also found statistically significant correlations with the 30 s anaerobic fitness test and swimming performance in all the trials (r = 0.86, 0.78, and 0.71, respectively). Despite the associations with performance, equipment for measuring force may not be readily available and this limits the practicality of translating such information to training prescription. Researchers have also investigated MSS of various short distances to estimate the "anaerobic critical velocity" as a surrogate of functional anaerobic capacity for training and assessing anaerobic performance (Espada et al., 2016; Marinho et al., 2011; Marinho et al., 2012; Neiva et al., 2010). However, traditionally measuring the MSS in swimming has consisted of separate testing that takes up valuable time, which is scarce in time-regulated collegiate settings.

While scientists have attempted to measure the AWC of athletes, D', which is a second parameter obtained from the CS method, initially was erroneously considered its surrogate (Green, 1995; Green & Dawson, 1993). Due to the elegant work by a group of authors (Jones & Vanhatalo, 2017; Poole & Jones, 2012; Poole et al., 2016) it has been demonstrated that due to the O_2 kinetics (Burnley & Jones, 2007) and how D' can be affected by exposure to hyperoxia (Vanhatalo et al., 2010) that the W' (akin to D') *"may not represent a fixed 'anaerobic' substrate store, but rather a mechanical work capacity which can be performed whilst the* VO_2 *and [PCr] kinetics project towards their respective maximal and nadir values"*. Nonetheless, the D' alongside the CSS can provide an estimation of the tolerable duration of speeds within the severe-intensity domains (> CSS).

Field Tests Measuring Swimming Performance

Practical field tests have been proposed and used to evaluate elite level swimmers (Olbrecht, 2013; Pyne et al., 2000; Sousa et al., 2014). These tests have included time trials

(Olbrecht, 2013), incremental step tests (Fernandes et al., 2011), CSS methods of multiple (Wakayoshi et al., 1992; Hill D. , 1993), and single trials (i.e., 3MT) (Mitchell et al., 2017; Piatrikova et al., 2019; Tsai & Thomas, 2017). Despite the apparent validity of these tests, many swimming coaches elect to pursue “traditional testing” sets for performance assessments. One such “traditional” method employed by Hall of Fame Coach Jon Urbanchek has been the use of a “best average” swimming test (Bavg).

Best Average Swimming Test (Bavg)

Originally, the Bavg method was based after completing a set of repeated 400 m swims (i.e., 5 x 400 m) as fast as possible with a one-minute rest interval between each. The subsequent average speed from all repetitions was used to calculate the resulting training zones for “The Color System”, which was an intensity zone system that identified higher numbers with higher intensity (i.e., Zone 1 = white, Zone 2 = pink, Zone 3 = red, Zone 4 = blue, Zone 5 = purple). Across many swimming programs and throughout the years, coaches have modified the Bavg method to adjust to “their team’s contextual fit”. Instead of repeated 400 m swims, intervals of 100 and 200 m swims have been performed to obtain a Bavg pace.

The 10 x 100 m Bavg test variation, when compared to the original in total volume, repetition distance, swimming pace, and the rest intervals have marked differences. Variations in work to rest ratio durations and intensity may represent differing physiological and performance responses due to the variations of cardiovascular work, anaerobic glycolytic energy contribution, acute neuromuscular strain, with no exceptions during swimming (Buchheit & Luarsen, 2013; Libicz et al., 2005). Moreover, the total duration of such a testing protocol is very time consuming. Elite level collegiate athletes performing a 10 x 100 m Bavg test would take about 12 - 13 minutes, given that each repetition is completed at about 60 s with

15 s rest intervals. Hence, slower swimmers and a full team roster size will increase the time burden constraints which could increase total testing time to around 60 – 75 minutes (32 athletes). In addition, using this method still requires coaches to measure MSS which takes up more time. Given the limited training time that collegiate swimming programs have, this does not seem very efficient.

Three-Minute All-Out Swimming Test (3MT)

The 3MT can be performed with minimal equipment and with many athletes at once making it relatively time efficient. A video recording device is used to capture footage for post-analysis and calculation of metrics. The variables that can be determined from the 3MT are the MSS, CSS, D', fatigue index percentage (FI%), ASR, speed reserve ratio (SRR) (Sandford & Stellingwerff, 2019), $v\dot{V}O_{2max}$ estimated from the average speed at 90 s of the test (Pettitt et al., 2012), and in swimming the LT has also been estimated as ~90% of CSS (Piatrikova et al., 2018). Considering the time efficiency of the 3MT against other protocols (i.e., 3MT = 3 mins vs Bavg = ≥60 mins per individual) and the informational value stemming from such a test, it might be an important addition to a coaches' toolbox, especially when time constraints are an issue.

The 3MT was originated by Burnley and associates (2006) with habitually active subjects in cycling. They showed that the measurement of $\dot{V}O_{2peak}$ between the 3MT and the ramp test were not statistically different. Also, the subjects were able to maintain CP for 30 minutes with stable blood lactate concentrations. The end power of the 3MT (last 30 seconds) did not differ from the CP measured from conventional multiple time trials and had nearly perfect correlation (r = 0.99) (Vanhatalo et al., 2007). In this study they also showed very large correlations (r = 0.84) for the W' between both methods. The 3MT has also been conducted in female distance runners on a track using a Global Positioning Systems (GPS) to track velocity metrics and CS, which were reported to not be statistically different from the speed at the GET, while the $\dot{V}O_2$ uptake at the 50%Δ from LT did not differ from lab measurements during an incremental treadmill test (Pettitt et al., 2012). Interestingly, racers with higher D' were able to maintain higher speeds above the CS than those with lower D'. Another modality in which the 3MT has been implemented was using a rowing ergometer, in which very large correlations with no statistical differences were found between end power from 3MT and CP from the conventional method of multiple trials (Cheng et al., 2012). However, no correlations were found between W', and it was found to be statistically greater than that of the conventional method. This discrepancy was explained by the movement patterns observed in rowing allowing for a recovery phase in which muscles relax before and after a drive phase which could confound the values in the 3MT. The 3MT has also been used with team sport athletes (i.e., soccer) to prescribe HIIT with an individualized approach of percentage expenditure of the D' within each interval (Clark et al., 2013).

Tsai and Thomas (2017) were the first to validate the 3MT in the modality of swimming. They showed near perfect correlations for CSS between all method calculations ($r > 0.95$), while no correlations for the D' and higher variability with lower values for the 3MT were observed. While that study was performed with average trained athletes, Piatrikova and colleagues validated the use of the 3MT with national and international level swimmers observing very high test-retest repeatability for the CSS ($r = 0.97$, CV = 0.9%) with no significant differences compared to the conventional method, however, although D' in the 3MT did have a very large correlation to the conventional method, it was statistically lower with higher variability ($r = 0.87$; CV = 9.1%).

Interestingly, Piatrikova and others (2018) estimated exercise intensity boundaries in swimmers using a 3MT showing very large to near perfect correlations for LT (89% of CSS), lactate turnpoint (98.5% of CSS), and maximum aerobic speed (103.5% of CSS) compared to an assessment with a typical step test, with no statistically significant differences. These estimated thresholds could potentially demarcate intensity domains with peculiar physiological profiles based on the $\dot{V}O_2$ response and acid-base status elicited during the exercise activity (Burnley & Jones, 2007; Poole & Jones, 2012). Although the use of these results should be taken carefully, since these may not be generalized to a wider population of swimmers, a consistent distinction with intensity domains seem evident and future research for this aspect may be warranted. These four domains are known as the moderate, heavy, severe, and extreme intensity domains, separating each by the LT, CSS, and the highest intensity in which fatigue is reached prior to attaining $\dot{V}O_{2max}$, respectively. The 3MT has also been utilized throughout a competitive season to prescribe individualized HIIT using a percentage of depletion of the D' for intervals (60 or 80%) in which improvements of CSS were shown despite a reduction in training volume of > 25%, but this improvement was at the expense of reductions in D' possibly due to interval intensities not being sufficiently high enough to induce anaerobic adaptations (i.e., > extreme intensity domain) (Piatrikova et al., 2020). This effect could also be explained by improvements in the $\dot{V}O_2$ kinetics, since D' has been shown to be correlated to the $\dot{V}O_2$ slow component (Vanhatalo et al., 2016).

One issue with 3MT studies in swimming has been the fact that researchers have used an exact calculations for the CSS as done with studies using other modalities (Courtwright et al., 2016; Piatrikova E. , Sousa, Gonzalez et al., 2019; Piatrikova E. , Sousa, Willsmer et al., 2018; Tsai & Thomas, 2017), such as cycling (Burnley et al., 2006), running (Pettitt et al., 2012), and rowing (Cheng et al., 2012) by calculating the average speed of the final 30 s of the test. Cones at each 10 m distance have also been used to easily track the swimmer's average speed throughout the test. The problems arising from these methods in swimming are the fact that the latter three modalities have a continuous cyclical display of mechanical work, while swimming in a pool involves flip turns that intermittently discontinues the repetitive motions as the swimmer tumbles over near a wall to push themselves off generating higher forces and speeds than in any other moment throughout the test (Bishop et al., 2013). Also, a swimmer's location during a certain time interval may be different, affecting the interpretation of that average speed time. For example, one swimmer may be coming into the wall while another is coming out of it. The former swimmer comes into the wall with less acceleration while the latter is greatly accelerated by the push-off. Piatrikova and colleagues (2020) ran into another problem as they observed swimmers in which speeds were so slow at the end of the test, they were not able to complete a flip turn within the last 30 seconds. This would drastically lower the average speed and CSS due to the missing flip turn. Nonetheless, they included these athletes within the analysis and no comparisons by taking the average speed of the last lap performed during the test with no comparisons made between calculation methods. Precise calculations of metrics within a test are an important tenant in sports science data collection and this distinction between calculations must be evaluated.

Other Factors to Consider in Swimming Performance

Anthropometrics

Swimming performance can be influenced by morphological characteristics that can determine potential success for different event distances (Pla et al., 2019; Siders et al., 1993). Successful swimmers tend to be tall and long-limbed (Yarar et al., 2021) with distance specialists showing lower body masses than sprinters (Pla et al., 2019). The higher body mass in sprint swimmers could signify greater muscle mass that enables the necessary power generation to overcome the increasing drag forces encountered when swimming at faster speeds (Siders et al., 1993; Toussaint, 2002). However, higher forces do not always equal to faster speeds as better swimming technique can also influences reduction in drag forces (Toussaint et al., 1988; Tsunokawa et al., 2019) and increased accelerations (Leblanc et al., 2007). Thus, it appears that higher forces coupled with excellent technique should produce faster times. Anthropometrical factors have been shown to explain 45.8% of performance in 100 m freestyle swimming (Latt et al., 2010) and while almost impossible to change these characteristics, growth spurts can have impact on swimming trial results over time (Zacca et al., 2020). Swimmers with a particular anthropometric profile may be more advantaged than others when swimming specific stroke techniques (Nevill et al., 2020). However, some of these relationships seem to diminish with aging as children approach adult size (Strzala et al., 2019). Despite the reduced association of anthropometric measurements with swimming, longitudinal changes in body composition for elite level swimmers may still influence performance (Anderson et al., 2006), but performance could more definitively be dictated by stroke parameters (Barbosa et al., 2008; Zacca et al., 2020).

The only study to the authors' knowledge to compare CSS to any anthropometrical variables in the sport of swimming was carried out with younger athletes (Aksit et al., 2017). The researchers found statistically significant correlations with CSS and multiple anthropometrical characteristics and somatotype components ($r = 0.34 – 0.66$). Although the D' was not measured, the estimated propulsive force was reported and showed a strong association with flexed arm circumference ($r = 0.87$) and thoracic girth in males ($r = 0.90$). The problems stemming from these associations are, that they may diminish over time with maturation and with training experience (Strzala et al., 2019). On the other hand, in a study performed using a cycle-ergometer, healthy male subjects performed the CP test using four-time trials to exhaustion (Miura et al., 2002). The authors found statistically significant correlations between the cross-sectional area of the thigh, W' (r = 0.59), and the peak accumulated O_2-deficit (r = 0.54) concluding that the cross-sectional area of the muscle was related to anaerobic work capacity, which they had considered to be the derived W' from the power-duration curve. However, W' has been shown not to be linked to fixed "anaerobic" substrate stores or the anaerobic work capacity (Vanhatalo et al., 2010). Nonetheless, given that competitive swimmers tend to partake in resistance training programs to improve performance (Mujika & Crowley, 2019) and successful sprint swimmers have greater body mass than distance swimmers (Pla et al., 2019), research concerning the associations between anthropometric variables and the speed-duration curve parameters (CSS & D') seem warranted.

Resistance training

The objective of competitive swimming is to be fast enough to finish the race before your opponents. However, swimmers will encounter higher drag forces with higher swimming speeds (Toussaint, 2002), signaling an important role of increasing strength and power for improved performance (Mujika & Crowley, 2019). Strength and conditioning coaches working with elite swimmers tend to prescribe resistance training programs seeking to increase power, robustness, and durability that allows athletes to withstand the rigors of competition and reduce injury risk (Crowley et al., 2018). Due to the nature of the sport, various methods have been used to apply strength training that ranges from in-water specific exercises, dry-land mimicking exercises, and traditional resistance training protocols, all showing positive results when concurrent with swimming training (Fone & van den Tillar, 2022). The importance of quantifying tethered forces in swimming has previously been shown to be a reasonable method to assess performance within specific environments (Morouco et al., 2014; Toubekis et al., 2010). However, equipment to conduct such tests are not easily available. Other methods have been used to estimate the upper body strength, explosive strength, and power of athletes with simple medicine ball throws of different loads (Palao & Valdés, 2013). Statistically significant relationships have been observed with weighted pull-ups, back squat barbell velocity, non-countermovement jumps and 50 y sprint swim performance in Division I collegiate swimmers (Kao et al., 2018). Statistically significant correlations were also found between sprint swimming performance, including the flip turn, and strength and power metrics featuring bench press (free weight & Smith Machine), squat (free weight & Smith Machine), countermovement jump, and medicine ball chest throw (Keiner et al., 2019; Lopes et al., 2019;).

In a systematic review of “dry-land” strength and conditioning, it was concluded that recommendations for resistance training programs should be based on increasing maximal strength with about 2 – 4 sessions per week and each session involving 2 – 3 sets of 3 – 5 repetitions at 80 – 90 % of the one repetition maximum (1RM) (Amaro et al., 2018). However, this approach does not consider the nuances of training variation associated with the competitions calendar, the need for proper recovery, training, and tapering before major competitions, appropriate integration with other training aspects, etc. Indeed, consistently training with higher volumes, particularly when carried to failure prolongs recovery (Morán-Navarro et al., 2017; Pareja-Blanco et al., 2020). The prolonged recovery is especially important for athletes as it may affect adaptation to other conditioning aspects as well as the resistance training. Also, periodization approaches, when properly programmed, have been shown to produce superior results when compared to a variety of other methods (Stone et al. 2021), including consistent training to failure (Carroll et al., 2018; Painter et al., 2012;). Furthermore, both traditional and block periodization, and programming protocols have been shown to produce excellent swimming results (González-Ravé et al., 2021; Hellard et al., 2019; Hermosilla et al., 2021; Stone et al., 2021).

In addition, a focus on reducing the shoulder girdle imbalances stemming from repetitive concentric arm actions would help in reducing the likelihood of overuse injuries (Batalha et al., 2015). However, there is scarcity of research focused on the use of resistance training protocols to invoke changes in the power-duration curve parameters (i.e., CS, D' and their analogs), especially none to the author's knowledge involving swimming. There have been inconsistent results when considering the performance effects on the power-duration parameters after engaging in resistance training protocols. In healthy untrained males, six weeks of a resistance training program only brought about improvements in the y-intercept (analogous to D') without changes in CP, time to exhaustion, or VO_{2peak} (Bishop & Jenkins, 1996). Interestingly, they observed a negative correlation with changes in CP and y-intercept following resistance training. Although some insight can be highlighted concerning the influence of the curvature constant variable or y-intercept (W'/D') on performance separate from endurance training, it is important to note that these were untrained individuals and the same cannot necessarily be expected for trained athletes. In a study performed with distance runners, six weeks of resistance training resulted in 5 km performance improvements with no change in CV (analogous to CSS), and despite decreases in anaerobic running distance (analogous to D') (Karsten et al., 2014). Moreover, when resistance training was eliminated in the following six weeks, performance in the endurance only group returned to near baseline levels. In a study with cyclists, although resistance training did not elicit change in CP, W' improved substantially and resistance training adaptations (strength, power, etc.) were positively correlated with improvements in time to exhaustion (Sawyer et al., 2014).

In a review that cited the effects of resistance training on CS and CP, the authors concluded that the use of a set-repetition scheme of 4 x 8 at 80% of 1RM focusing on hypertrophy would be beneficial to enhance W' (Hurd et al., 2022). However, it is important to elucidate that each resistance training protocol had unique outcomes possibly due to the distinct set-repetition schemes. In Karsten and associates (2014), a low repetition high intensity protocol was used (4 x 4 at 80% of 1RM), which is shown to improve strength by eliciting higher neuromuscular recruitment (Bazyler et al., 2015; Stone et al., 2007). On the other hand, Sawyer, and colleagues (2014), used a higher repetition scheme of 3 x 8 repetitions maximum, which induces more metabolic by-products that perturb pH balance in muscle causing peripheral fatigue (Edge et al., 2006). Higher repetition schemes (4 x 12±3 reps) may help improve characteristics related to anaerobic work capacity (Painter, Rodriguez-Castellano, & Stone, 2020). Due to each protocol possibly inducing benefits through differing mechanisms it is important to consider how each can fit within a sequential periodized plan, such as done in the block periodization method (Haff, 2019; Hellard et al., 2019; Issurin, 2008; Stone et al., 2021).

Stroke Types

World record swims at similar distances show faster times for freestyle, butterfly, backstroke, and breaststroke in that order. Of the four competitive swimming strokes, freestyle is the most economical followed by backstroke, butterfly, and breaststroke (Barbosa et al., 2006). The discontinuous nature of the latter two strokes (butterfly & breaststroke) explains the higher performance decrements in the latter portions of a 100 m event (Neiva et al., 2010). This observation appears to be correct even at longer race durations, especially when considering the 100 m event may still require a relatively high aerobic energy provision (Hellard et al., 2018). Swimming events involving strokes other than freestyle are contested up to the 200 m distance, but the 400 m individual medley, which can last upwards of four minutes, splits each stroke style in equal distances of 100 m for butterfly, backstroke, breaststroke, and freestyle in that order. Given that the current world record for the 200 m freestyle stands at 1:42:00 mm:ss (as of July 17, 2022) the energetic requirements for such an event are predominantly aerobic, but still with a substantial contribution from the anaerobic energy system (Rodríguez & Mader, 2011). Since other strokes will take longer to finish a certain distance (Neiva et al., 2010) more reliance on aerobic energy is to be expected (Hellard et al., 2018; Rodríguez & Mader, 2011). This is an important detail to understand for athletes and coaches as training sets must respect the "S.A.I.D." principle (Specific Adaptations to Imposed Demands) to obtain expected performance outcomes.

Most studies reporting the CSS and D' or conducting tests that derive these variables in swimming (i.e., single or multiple trial) have measured such metrics using only freestyle (Greenshields et al., 2018; Piatrikova et al., 2018; Tsai & Thomas, 2017) or the swimmer's best stroke (Mitchell et al., 2017; Piatrikova et al., 2020), which have been averaged as a whole group and not compared within each other. The only study to the authors' knowledge that has been conducted to assess the reliability and feasibility of the CSS protocol in all four strokes was performed by national-level swimmers (Scott et al., 2020). They used the 200 m and 400 m swimming trial performances and found that CSS was reliable (TE $\leq$ 0.04 m.s.; CV% $<$ 4 % for all strokes). However, swimmers only used their best strokes and did not perform all strokes that would have allowed for between stroke comparisons within individuals. They also found very high variability for the D’ (TE = 4 – 9 m; CV% 13 – 45%). The swimmers were asked follow-up questions post testing to inquire on their perception on being able and willing to perform an 800 m swimming trial in the respective strokes performed during the study. Not surprisingly, the butterfly group, which requires a relatively high energy output, had the lowest percentage of perceived capability of finishing such distance in such stroke. Given the increasing error rates of the two-trial protocol and no within-subject stroke comparisons of CSS were made, it would be important to ascertain whether the hyperbolic relationship drop-off patterns are similar per stroke within the same individuals. This would be important for swimmers that may use all four strokes during competition (i.e., individual medley swimmers).

Summary

Swimming events are varied by stroke and distance, thus the underlying bioenergetic and metabolic mechanisms also vary. Two factors that are quite important for most swimming events is critical power (CP) and work reserve (work potentially performed above the CP; D’). Critical power is not easily measured, particularly in swimming. Several mechanical estimates of critical power have been developed (critical swimming speed; CSS). It is obvious that more research is necessary to elucidate how CP might be best estimated for swimming.

References

Aksit, T., Ozkol, M., Vural, F., Penkunlu, E., Aydinoglu, R., & Varol, R. (2017). Contribution of anthropometric characteristics to critical swimming velocity and estimated propulsive force. *Journal of Physical Education and Sport*, 17(1): 212-218.

Amaro, N., Morouco, P., Marques, M., Batalha, N., Neiva, H., & Marinho, D. (2018). A systematic review on dry-land strength and conditioning training on swimming performance. *Science & Sports*, 34(1): e1-e14.

Anderson, M., Hopkins, W., Roberts, A., & Pyne, D. (2006). Monitoring seasonal and long-term changes in test performance in elite swimmers. *European Journal of Sports Science*, 6(3): 145-154.

Baldari, C., Fernandes, R., Meucci, M., Ribeiro, J., Vilas-Boas, J., & Guidetti, L. (2012). Is the New AquaTrainer Snorkel Valid for VO2 Assessment in Swimming? *International Journal of Sports Medicine*, 34(4): 336-344.

Barbosa, T., Fernandes, R., Keskinen, K., & Vilas-Boas, J. (2008). The influence of stroke mechanics into energy cost of elite swimmers. *European Journal of Applies Physiology*, 130(2): 139-149.

Barbosa, T., Fernandes, R., Keskinen, K., Colaco, P., Cardoso, C., Silva, J., & Vilas-Boas, J. (2006). Evaluation of the Energy Expenditure in Competitive Swimming Strokes. *International Journal of Sports Medicine*, 27(11): 894-899.

Bassett, D. (2002). Scientific contributions of A.V. Hill: exercise physiology pioneer. *Journal of Applied Physiology*, 93: 1567-1582.

Batalha, N., Raimundo, A., Tomas-Carus, P., Paulo, J., Simao, R., & Silva, A. (2015). Does a land-based compensatory strength-training programme influences the rotator cuff balance of young competitive swimmers? *European Journal of Sports Science*, 15(8): 764-772.

Bazyler, C., Abbott, H., Bellon, C., Taber, C., & Stone, M. (2015). Strength for Endurance Athletes: Theory to Practice. *Journal of Strength and Conditioning*, 37(2): 1-12.

Beaver, W., Wasserman, K., & Whipp, B. (1986). A new method for detecting anaerobic threshold by gas exchange. *Journal of Applied Physiology*, 60(6): 2020-2027.

Bergstrom, H., Dinyer, T., Succi, P., Voskuil, C., & Housh, T. (2021). Applications of the Critical Power Model to Dynamic Constant External Resistance Exercise: A Brief Review of the Critical Load Test. *Sports*, 9(2): 1-15.

Billat, V., Sirvent, P., Py, G., Koralsztein, J., & Mercier, J. (2003). The Concept of Maximal Lactate Steady State. *Sports Medicine*, 33(6): 407-426.

Bishop, C., Cree, J., Read, P., Chavda, S., Edwards, M., & Turner, A. (2013). Strength and Conditioning for Sprint Swimming. *Strength and Conditioning Journal*, 35(6): 1-6.

Bishop, D., & Jenkins, D. (1996). The Influence of Resistance Training on the Critical Power Function & Time to Fatigue at Critical Power. *The Australian Journal of Science and Medicine in Sport*, 28(4): 101-105.

Bonen, A., Wilson, B., Yarkony, M., & Belcastro, A. (1980). Maximal oxygen uptake during free, tethered, and swim flume swimming. *Journal of Applied Physiology*, 48(2): 232-235.

Brooks, G. (1985). Anaerobic threshold: review of the concept and directions for future research. *Medicine and Science in Sport and Exercise*, 17(1): 22-31.

Buchheit, M., & Luarsen, P. (2013). High-Intensity Interval Training, Solutions to the Programming Puzzle - Part I: Cardiopulmonary Emphasis. *Sports Medicine*, 43(5): 313-338.

Burnley, M., & Jones, A. (2007). Oxygen uptake kinetics as a determinant of sports performance. *European Journal of Sports Science*, 7(2): 63-79.

Burnley, M., Doust, J., & Vanhatalo, A. (2006). A 3-min All-out Test to Determine Peak Oxygen Uptake and the Maximal Steady State. *Medicine and Science in Sport and Science*, 38(11): 1995-2003.

Carroll, K., Bernards, J., Bazyler, C., Taber, C., Stuart, C., DeWeese, B., . . . Stone, M. (2018). Divergent Performance Outcomes Following Resistance Training Using Repetition Maximums or Relative Intensity. *International Journal of Sports Physiology and Performance*, 14(1): 1-28.

Chaverri, D., Schuller, T., Iglesias, X., Hoffman, U., & Rodriguez, F. (2016). A New Model for Estimating Peak Oxygen Uptake Based on Postexercise Measurements in Swimming. *International Journal of Sports Physiology and Performance*, 11(4): 419-424.

Cheng, C., Yang, Y., Lin, H., Lee, C., & Wang, C. (2012). Determination of critical power in trained rowers using a three-minute all-out rowing test. *European Journal of Applied Physiology*, 112: 1251-1260.

Clark, I., West, B., Reynolds, S., Murray, S., & Pettitt, R. (2013). Applying the Critical Velocity Model for an Off-Season High Intensity Interval Training Program. *Journal of Strength and Conditioning Research*, 27(12): 3335-3341.

Corry, I., & Powers, N. (1982). Maximal Aerobic Power Measurement in Runners and Swimmers. *British Journal of Sports Medicine*, 16(3): 154-160.

Courtwright, S., Williams, J., Clark, I., Pettitt, R., & Dicks, N. (2016). Monitoring Interval-Training Responses for Swimming using the 3-min All-out Exercise Test. *International Journal of Exercise Science*, 9(5): 545-553.

Crowley, E., Harrison, A., & Lyons, M. (2018). Dry-Land Resistance Training Practices of Elite Swimming Strength and Conditioning Coaches. *Journal of Strength and Conditioning Research*, 32(9): 2592-2600.

Dalamitros, A., Fernandes, R., Toubekis, A., Manou, V., Loupos, D., & Kellis, S. (2015). Is speed reserve related to critical speed and anaerobic distance capacity in swimming? *Journal of Strength and Conditioning Research*, 29(7): 1830-1836.

DeWeese, B., Wagle, J., & Bingham, G. (2019). Let the rhythm hit them: Adjusting the tempo to skillfully surf the intensity curve. . *Techniques Magazine*, 10(4): 52-59.

DiMenna, F., & Jones, A. (2019). Aerobic performance assessment. In P. Comfort, P. Jones, & J. McMahon, *Performance Assessment in Strength and Conditioning* (pp. 212-239). Abingdon, Oxon: Routledge.

Edge, J., Hill-Haas, S., Goodman, C., & Bishop, D. (2006). Effects of resistance training on H+ regulation, buffer capacity, and repeated sprints. *Medicine and Science in Sports and Exercise*, 38(11): 2004-2011.

Espada, M., & Alves, F. (2010). Critical Velocity and the Velocity at Maximal Lactate Steady State in Swimming. *Biomechanics and Medicine in Swimming XI* (pp. 194-196). Oslo: Norwegian School of Sports Science.

Espada, M., Costa, A., Louro, H., Conceiao, A., Filho, D., & Pereira, A. (2016). Anaerobic Critical Velocity and Sprint Swimming Performance in Masters Swimmers. *International Journal of Sports Science*, 6(1A): 31-35.

Farrell, P., Wilmore, J., Coyle, E., Billing, J., & Costill, D. (1979). Plasma lactate accumulation and distance running performance. *Medicine and Sciennce in Sports and Exercise*, 25(10): 1089-1090.

Fernandes, R., Sousa, M., Machado, L., & Vilas-Boas, J. (2011). Step Length and Individual Anaerobic Threshold Assessment in Swimming. *International Journal of Sports Medicine*, 32(12): 940-946.

Fig, G. (2010). Why Competitive Swimmers Need Explosive Power. *Strength and Conditioning Journal*, 32(4): 84-86.

Fone, L., & van den Tillar, R. (2022). Effects of Different Types of Strength Training on Swimming Performance in Competitive Swimmers: A Systematic Review. *Sports Medicine*, 8(1): 1-26.

Galbraith, A., Hopker, J., Lelliot, S., Diddams, L., & Passfield, L. (2014). A Single-Visit Field Test of Critical Speed. *International Journal of Sports Physiology and Performance*, 9(6): 931-935.

González-Ravé, J., Pyne, D., Castillo, J., González-Mohíno, F., & Stone, M. (2021). Training periodization for a world-class 400 meters individual medley swimmer. *Biology of Sport*, 39(4): 883-888.

Green, S. (1995). Measuring of Anaerobic Work Capacities in Humans. *Sports Medicine*, 19(1): 32-42.

Green, S., & Dawson, B. (1993). Measurment of Anaerobic Capacities in Humans: Definitions, Limitations, and Unsolved Problems. *Sports Medicine*, 15(5): 312-327.

Greenshields, J., Goss, C., & Stager, J. (2018). Variation in Critical Speed and Finite Distance Capacity of Elite Swimmers. *Annual Meeting of the American College of Sports Medicine* (p. 50(5S): 525). Minneapolis: Medicine and Science in Sports and Exercise.

Haff, G. (2019). The essentials of periodization. In I. Jeffreys, & J. Moody, *Strength and Conditioning for Sports Performance* (pp. 404-448). Abingdon, London: Routledge.

Hale, T. (2008). History of developments in sport and exercise physiology: A.V. Hill, maximal oxygen uptake, and oxygen debt. *Journal of Sports Sciences*, 26(4): 365-400.

Hall, G., & Murphy, D. (2020). *Fundamentals of Fast Swimming: How to Improve Your Swimming Technique.* Islamorada, FL: The Race Club.

Hellard, P., Avalos-Fernandes, M., Lefort, G., Pla, R., Mujika, I., Toussaint, J., & Pyne, D. (2019). Elite swimmers' training patterns in the 25 weeks prior to their season's best performances: insights into periodization from a 20-years cohort. *Frontiers in Physiology*, 10(363): 1-16.

Hellard, P., Pla, R., Rodríguez, F., Simbana, D., & Pyne, D. (2018). Dynamics of the metabolic response during a competitive 100-m freestyle in elite male swimmers. *International Journal of Sports Physiology and Performance*, 13(10): 1011-1020.

Hermosilla, F., González-Ravé, J., Del Castillo, J., & Pyne, D. (2021). Periodization and programming for individual 400 m medley swimmers. *International Journal of Environmental Research and Public Health*, 18(12): 6474.

Hill, A., & Lupton, H. (1923). Muscular Exercise, Lactic Acid, and the Supply and Utilization of Oxygen. *International Journal of Medicine*, 16(62): 135-171.

Hill, D. (1993). The critical power concept. A review. . *Sports Medicine*, 16(4): 237-254.

Hurd, K., Surges, M., & Farell, J. (2022). Use of Exercise Training to Enhance the Power-Duration Curve: A Systematic Review. *Journal of Strength and Conditioning Research*, XX(X): 000-000.

Issurin, V. (2008). Block periodization versus traditional training theory: a review. *Journal of Sports Medicine and Physical Fitness*, 48(1): 65-75.

Jones, A., & Vanhatalo, A. (2017). The 'Critical Power' Concept: Applications to Sports Performance with a Focus on Intermittent High-Intensity Exercise. *Sports Medicine*, 47(1): S65-S78.

Jorgić, B., Puletić, M., Okičić, T., & Meškovska, N. (2011). Importance of Maximal Oxygen Consumption During Swimming. *Physical Education and Sport*, 9(2): 183-191.

Kao, S., Ishida, A., & Ainsworth, B. (2018). The Correlation Between Strength and Power Measures with Sprint Freestyle Performance in Division 1 Collegiate Swimmers. *Journal of Swimming Research*, 26(1): 22-31.

Karsten, B., Stevens, L., Colpus, M., Larumbe-Zabala, E., & Naclerio, F. (2014). The Effects of Sport-Specific Maximal Strength and Conditioning Training on Critical Velocity, Anaerobic Running Distance, and 5-km Race Performance. *International Journal of Sports Physiology and Performance*, 11(1): 80-85.

Keiner, M., Wirth, K., Fuhrmann, S., Kunz, M., Hartmann, H., & Haff, G. (2019). The Influence of Upper- and Lower-Body Maximum Strength on Swim Block Start, Turn, and Overall Swim Performance in Sprint Swimming. *Journal of Strength and Conditioning Research*, 35(10): 2839-2845.

Latt, E., Jurimae, J., Maestu, J., Purge, P., Ramson, R., Haljaste, K., . . . Jurimae, T. (2010). Physiological, biomechanical, and anthropometrical predictors of sprint swimming performance in adolescent swimmers. *Journal of Sport Sciences and Medicine*, 9(1): 398-404.

Lavoie, J., Lèger, L., Leone, M., & Provencher, P. (1985). A Maximal Multistage Swim Test to Determine the Functional and Maximal Aerobic Power of Competitive Swimmers. *Journal of Swimming Research*, 1(2): 17-22.

Leblanc, H., Seifert, L., Tourny-Chollet, C., & Chollet, D. (2007). Intra-cyclic Distance per Stroke Phase, Velocity Fluctuations and Acceleration Time Ratio of a Breastroker's Hip: A Comparison between Elite and Nonelite Swimmers at Different Race Paces. *International Journal of Sports Medicine*, 28(2): 140-147.

Libicz, S., Roels, B., & Millet, G. (2005). VO2 Responses to Intermittent Swimming Sets at Velocity Associated to VO2max. *Canadian Journal of Applied Physiology*, 30(5): 543-553.

Lopes, T., Goncalves, C., Graca, C., Neiva, H., & Marinho, D. (2019). The Relationship between Front Crawl Swimming Performance and Strength Variables in College Swimmers. *Ergonomics International Journal*, 3(2): 1-9.

Machado, M., Borges, J., Galdino, I., Cunha, L., Souza-Sá Filho, A., Soares, D., & Junior, I. (2018). Does critical velocity represent the maximal lactate steady state in youth swimmers? *Science & Sport*, 34(3): 1-7.

Magel, J., & Faulkner, J. (1967). Maximum oxygen uptakes of college swimmers. *Journal of Applied Physiology*, 22(5): 929-938.

Marinho, D., Amorim, R., Costa, A., Marques, M., Pérez-Turpin, J., & Neiva, H. (2011). "Anaerobic" critical velocity and swimming performance in young swimmers. *Journal of Human Sport and Exercise*, 6(1): 80-86.

Marinho, D., Barbosa, T., Silva, A., & Neiva, H. (2012). Applying Anaerobic Critical Velocity in Non-Elite Swimmers. *International Journal of Swimming Kinetics*, 1(1): 33-50.

Mattioni-Maturana, F., Fontana, F., Pogliaghi, S., Passfield, L., & Murias, J. (2018). Critical power: How different protocols and models affect its determination. *Journal of Science and Medicine in Sport*, 21(7): 742-747.

McArdle, W., Katch, F., & Katch, V. (2015). *Exercise Physiology: Nutrition, Energy, and Human Performance.* Baltimore, MD: Wolters-Kluwers.

Mitchell, L., Pyne, D., Saunders, P., & Rattray, B. (2017). Reliability and validity of a modified 3-minute all-out swimming test in elite swimmers. *European Journal of Sports Science*, 18(3): 307-314.

Miura, A., Endo, M., Sato, H., Sato, H., Barstow, T., & Fukuba, Y. (2002). Relationship between the curvature constant parameter of the power-duration curve and muscle cross-sectional area of the thigh for cycle ergometry in humans. *European Journal of Applied Physiology*, 87(3): 238-244.

Monod, H., & Scherrer, J. (1965). The work capacity of a synergic muscular group. *Ergonomics*, 8: 329-338.

Montpetit, R., Léger, L., Lavoie, J., & Cazorla, G. (1981). V̇02 Peak During Free Swimming Using the Backward Extrapolation of the O2 Recovery Curve. *European Journal of Applied Physiology*, 47(4): 385-391.

Morán-Navarro, R., Pérez, C., Mora-Rodríguez, R., de la Cruz-Sánchez, E., González-Badillo, J., Sánchez-Medina, L., & Pallarés, J. (2017). Time course of recovery following resistance training leading or not to failure. . *European Journal of Applied Physiology*, 117(12): 2387-2399.

Moritani, T., Nagata, A., DeVries, H., & Muro, M. (1981). Critical power as measure of physical work capacity and anaerobic threshold. *Ergonomics*, 24(5): 339-350.

Morouco, P., Marinho, D., Keskinen, K., Badillo, J., & Marques, M. (2014). Thethered Swimming Can Be Used to Evaluate Force Contribution for Short-Distance Swimming Performance. *Journal of Strength and Conditioning Research*, 28(11): 3093-3099.

Mougios, V. (2006). *Exercise Biochemistry*. Champaign, Ill. : Human Kinetics.

Mujika, I., & Crowley, E. (2019). Strength Training for Swimmers. In M. Schumann, & B. Ronnestad, *Concurrent Aerobic and Strength Training: Scientific Basics and Practical Applications* (pp. 369-386). Switzerland: Springer International Publishing AG.

Neiva, H., Fernandes, R., & Vilas-Boas, J. (2010). Anaerobic Critical Velocity in Four Swimming Techniques. *International Journal of Sports Medicine*, 32(1): 195-198.

Nevill, A., Negra, Y., Myers, T., Sammoud, S., & Chaabene, H. (2020). Key somatic variables associated with, and differences between the 4 swimming strokes. *Journal of Sports Sciences*, 38(7): 787-794.

Noakes, T. (2008a). How did AV Hill understand the V̇O2max and the "plateau phenomenon"? Still no clarity? *British Journal of Sports Medicine*, 42: 574-580.

Noakes, T. (2008b). Testing for maximum oxygen consumption has produced a brainless mode of human exercise performance. *British Journal of Sports Medicine*, 42(7): 551-555.

Noordhof, D., Koning, J., & Foster, C. (2010). The Maximal Accumulated Oxygen Deficit Method. *Sports Medicine*, 40(4): 285-302.

Norouzi, M., Cabuk, R., Balki, G., As, H., & Ozkaya, O. (2021). The Effect of Using Different Exhaustion Intervals and Mathematical Models on Critical Power Estimations. *Hacettepe Journal of Sports Sciences*, 32(3): 151-166.

Nugent, F., Comyns, T., Kearney, P., & Warrington, G. (2019). Ultra-Short Race-Pace Training (USRPT) In Swimming: Current Perspectives. *Open Access Journal of Sports Medicine*, 10(1): 133-144.

Ogita, F. (2006). Energetics in competitive swimming and its applications for training. . *International Symposium on Biomechanics and Medicine in Swimming* (pp. 6(2): 117-121). Porto Faculdade de Desporto da Universidade do Porto.

Olbrecht, J. (2013). *The Science of Winning: Planning, Periodizing and Optimizing Swim Training.* Antwerp, Belgium: F&G Partners.

Painter, K., Haff, G., Ramsey, M., McBride, J., Triplett, T., Sands, W., . . . Stone, M. (2012). Strength gains: block versus daily undulating periodization weight training among track and field athletes. *International Journal of Sports Physiology and Performance*, 7(2): 161-169.

Painter, K., Rodriguez-Castellano, L., & Stone, M. (2020). High Volume Resistance Training and its Effects on Anaerobic Work Capacity Over Time: A Review. *The Sport Journal*, 3(1): 1-17.

Palao, J., & Valdés, D. (2013). Testing protocol for monitoring upper-body strength using medicine balls. *Journal of Human Sport & Exercise*, 8(2): 334-341.

Papoti, M., da Silva, A., Araujo, G., Santiago, V., Martins, L., Cunha, S., & Gobatto, C. (2011). Aerobic and Anaerobic Performances in Tethered Swimming. *International Journal of Sports Medicine*, 34(8): 712-719.

Pareja-Blanco, F., Rodríguez-Rosell, D., Aagaard, P., Sánchesz-Medina, L., Ribas-Serna, J., Mora-Custodio, R., . . . González-Badillo, J. (2020). Time Course of Recovery From Resistance Exercise With Different Set Configurations. *Journal of Strength and Conditioning Research*, 34(10): 2867-2876.

Pelayo, P., & Alberty, M. (2011). The History of Swimming Research. In L. Seifert, D. Chollet, & I. Mujika, *World Book of Swimming: From Science to Performance* (pp. ix - xxvi). Hauppauge, New York: Nova Science Publishers, Inc.

Pettitt, R., Jamnick, N., & Clark, E. (2012). 3-min All-out Exercise Test for Running. *International Journal of Sports Medicine*, 33: 426-431.

Piatrikova, E., Sousa, A., Gonzalez, J., & Williams, S. (2019). Validity and reliability of the 3-minute all-out test in national and international competitive swimmers. *International Journal of Sports Physiology and Performance*, 13(9): 1190-1198.

Piatrikova, E., Sousa, A., Willsmer, N., Gonzalez, J., & Williams, S. (2018). Demarcating exercise intensity domains in freestyle swimming: is there and alternative to incremental step test and beats below HRmax method? . *Journal of Strength and Conditioning Research*, 34(9): 2575-2584.

Piatrikova, E., Willsmer, N., Altini, M., Mladen, J., Lachlan, M., Gonzalez, J., . . . Williams, S. (2021). Monitoring the heart rate variability responses to training loads in competitive swimmers using a smartphone application and the Banister Impulse-Response model. *International Journal of Sports Physiology and Performance*, 16(6):787-795.

Piatrikova, E., Willsmer, N., Sousa, A., Gonzalez, J., & S, W. (2020). Individualizing training in swimming; is there a place for the application of the critical speed and critical stroke rate concepts? *International Journal of Sports Physiology and Performance*, 15(5): 1-8.

Pla, R., Leroy, A., Massal, R., Bellami, M., Kaillani, F., Hellard, P., . . . Sedeaud, A. (2019). Bayesian approach to quantify morphological impact on performance in international elite freestyle swimming. *BMJ Open Sport & Exercise Medicine*, 5: 1-7.

Poole, D., & Jones, A. (2012). Oxygen Uptake Kinetics. *Comprehensive Physiology*, 2(2): 933-996.

Poole, D., Burnley, M., Vanhatalo, H., Rossiter, B., & Jones, A. (2016). Critical Power: An Important Fatigue Threshold in Exercise Physiology. *Medicine and Science in Sports and Exercise*, 48(11): 2320-2334.

Poole, D., Rossiter, H., Brooks, G., & Gladden, L. (2021). The Anaerobic Threshold: 50+ Years of Controversy. *The Journal of Physiology*, 599(3): 737-767.

Pyne, D., Maw, G., & Goldsmith, W. (2000). Protocols for the Physiological Assessment of Swimmers. In A. S. Commission, *Physiological Tests for Elite Athletes* (pp. 372-382). Champaign, Ill: Human Kinetics.

Ramos-Veliz, R., Requena, B., Suarez-Arrones, L., Newton, R., & Sáez de Villareal, E. (2014). Effects of 18-week in-season heavy resistance and power training on throwing velocity, strength, jumping, and maximal sprint swim performance of elite male water polo players. *Journal of Strength and Conditioning Research*, 28(4): 1007-1014.

Raymond, D. (2012). The effect of aerobic fitness on the cardiovascular and sympathetic nervous system response to physiological stress at rest and during dynamic exercise. *Thesis*.

Reis, V., Marinho, D., Barbosa, F., Reis, A., Guidetti, L., & Silva, A. (2010). Examining the Accumulated Oxygen Deficit Method in Breaststroke Swimming. *European Journal of Applied Physiology*, 109(6): 1129-1135.

Reis, V., Marinho, D., Policarpo, F., Carneiro, A., Baldari, C., & Silva, A. (2010). Examining the Accumulated Oxygen Deficit Method in Front Crawl Swimming. *International Journal of Sports Medicine*, 31(6): 421-427.

Rodríguez, F., & Mader, A. (2011). Energy Systems in Swimming. In L. Seifert, D. Chollet, & I. Mujika, *World Book of Swimming: From Science to Performance* (pp. 225-240). New York: Nova Science.

Rodríguez, F., Keskinen, K., Keskinen, O., & Malvela, M. (2003). Oxygen uptake kinetics during free swimming: a pilot study. *In: Chartard, JC, Biomechanics and Medicine in Swimming IX*, 379-384.

Rushall, B. (2016, March 14). *USRPT Defined: After Two Years USRPT Comes of Age.* Retrieved from Swimming Science Bulletin #49: https://coachsci.sdsu.edu/swim/bullets/49DEFINED.pdf

Saltin, B., & Astrand, P. (1967). Maximal oxygen uptake in athletes. *Journal of Applied Physiology*, 23(3): 353-358.

Sandford, G., & Stellingwerff, T. (2019). "Questioning Your Categories": the Misunderstood Complexity of Middle-Distance Running Profiles With Implications for Research Methods and Application. *Frontiers in Sports and Active Living*, 1(28): 1-8.

Sanford, G., Laursen, P., & Buchheit, M. (2021). Anaerobic Speed/Power Reserve and Sport Performance: Scientific Basis, Current Applications and Future Directions. *Sports Medicine*, 51(10): 2017-2028.

Sawyer, B., Stokes, D., Womack, C., Hugh, M., Weltman, A., & Gaesser, G. (2014). Strength Training Increases Endurance Time to Exhaustion During High-Intensity Exercise Despite No Change in Critical Power. *Journal of Strength and Conditioning Research*, 28(3): 601-609.

Scott, B., Burden, R., & Dekerle, J. (2020). Critical speed, D' and pacing in swimming: reliability of a popular critical speed protocol applied to all four strokes. *Research Square*, 10.21203/rs.3.rs-77508/v1.

Siders, W., Lukaski, H., & Bolonchuk, W. (1993). Relationship among swimming performance, body composition and somatotype in competitive collegiate swimmers. *Journal of Sports Medicine and Physical Fitness*, 33(2): 166-171.

Smith, D., Norris, S., & Hogg, J. (2002). Performance Evaluation of Swimmers: Scientific Tools. *Sports Medicine*, 32(9): 539-554.

Sousa, A., Figueiredo, P., Pendergast, D., Kjendlie, P., Vilas-Boas, J., & Fernandes, R. (2014). Critical Evaluation of Oxygen-Uptake Assessment in Swimming. *International Journal of Sports Physiology and Performance*, 9(2): 190-202.

Stone, M., Hornsby, W., Haff, G., Fry, A., Suárez, D., Liu, J., . . . Pierce, K. (2021). Periodization and Block Periodization in Sports: Emphasis on Strength-Power Training- A Provocative and Challenging Narrative. *Journal of Strength and Conditioning Research*, 35(8): 2351-2371.

Stone, M., Stone, M., & Sands, W. (2007). *Principles and Practices of Resistance Training.* Champaign, Ill.: Human Kinetics.

Strzala, M., Stanula, A., Krezalek, P., Ostrowski, A., Kaca, M., & Glab, G. (2019). Influence of Morphology and Strength on Front Crawl Swimming Speed in Junior and Youth Age-Group Swimmers. *Journal of Strength and Conditioning Research*, 33(10): 2836-2845.

Toubekis, A., Gourgoulis, V., & Tokmakidis, S. (2010). Tethered Swimming as an Evaluation Tool of Single Arm-Stroke Force. *XIth International Symposium for Biomechanics and Medicine in Swimming.* Oslo, Norway: Norwegian School of Sports Sciences .

Toussaint, H. (2002). Biomechanics of Propulsion and Drag in Front Crawl Swimming. *Applied proceedings - XXth International Symposium on Biomechanics in Sports. University of Extremadura*, (pp. 11-22). Caceres, Spain.

Toussaint, H., & Beek, P. (1992). Biomechanics of Competitive Front Crawl Swimming. *Sports Medicine*, 13(1): 8-24.

Toussaint, H., Beelen, A., Rodenburg, A., Sargeant, A., de Groot, G., Hollander, A., & van Ingen Schenau, G. (1988). Propelling efficiency of front-crawl swimming. *Journal of Applied Physiology*, 65(6): 2506-2512.

Tsai, M., & Thomas, S. (2017). 3-Min All-Out in Swimming. . *International Journal of Sports Physiology and Performance*, 12(1): 1-17.

Tsunokawa, T., Kadi, T., Mankyu, H., & Ogita, F. (2019). Estimation of hand propulsion forces at four swimming techniques using pressure measurement and underwater motion capture. *24th Annual Congress of the European College of Sport Science* (p. Abstract). Prague, Czech Republic: European College of Sports Science.

Vanhatalo, A., Black, M., DiMenna, F., Blackwell, J., Schmidt, J., Thompson, C., . . . Jones, A. (2016). The mechanistic bases of the power-time relationship: muscle metabolic responses and relationship to muscle fiber type. *Journal of Physiology*, 594(15): 4407-4423.

Vanhatalo, A., Doust, J., & Burnley, M. (2007). Determination of Critical Power Using a 3-min All-out Cycling Test. *Medicine and Science in Sports and Exercise*, 39(3): 548-555.

Vanhatalo, A., Fulford, J., DiMenna, F., & Jones, A. (2010). Influence of hyperoxia on muscle metabolic responses and the power-duration relationship during severe-intensity exercise in humans: a 31P magnetic resonance spectroscopy study. *Experimental Physiology*, 95(4): 528-540.

Wakayoshi, K., Ikuta, K., Yoshida, T., Udo, M., Moritani, T., Mutoh, Y., & Miyashita, M. (1992). Determination and validity of critical velocity as an index of swimming performance in the competitive swimmer. . *European Journal of Physiology and Occupational Physiology*, 64(2): 153-157.

Wakayoshi, K., Yoshida, T., Udo, M., Harada, T., Moritani, T., Mutoh, Y., & Miyashita, M. (1993). Does critical swimming velocity represent exercise intensity at maximal lactate steady state? *European Journal of Applied Physiology and Ocuppational Physiology*, 66(1): 90-95.

Walsh, M., & Bannister, E. (1988). Possible Mechanisms of the Anaerobic Threshold. *Sports Medicine*, 5(5): 269-302.

Wasserman, K., Whipp, B., Koyal, S., & Beaver, W. (1973). Anaerobic threshold and respiratory gas exchange during exercise. *Journal of Applied Physiology*, 35(2): 236-243.

Yarar, H., Barug, D., Bostan, A., Kaya, A., & Aydin, E. (2021). Influence of Physical Anthropometric Properties on Sprint Swimming Performance. *Pakistan Journal of Medical & Health Sciences*, 15(2): 814-818.

Zacca, R., & Castro, F. (2010). Critical Swimming Speed Obtained by the 200-400 Meters Model in Young Swimmers. *Biomechanics and Medicine in Swimming XI* (pp. 307-309). Oslo, Norway: Norwegian School of Sport Sciences.

Zacca, R., Azevedo, R., Chainok, P., Vilas-Boas, J., Castro, F., Pyne, D., & Fernandes, R. (2020). Monitoring Ag-Group Swimmers Over a Training Macrocycle: Energetics, Technique, and Anthropometrics. *Journal of Strength and Conditioning Research*, 34(3): 818-827.

Zarzeczny, R., Kuberski, M., Deska, A., Zarzeczna, D., & Rydz, K. (2013). The Evaluation of Critical Swimming Speed in 12-Year-Old Boys. *Human Movement*, 14(1): 35-40.

Chapter 3. Evaluating and Comparing the Critical Speed Calculation Methods from the 3-Minute All-Out Swimming Test and Its Relationship to the Best Average Swimming Test

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Introduction

For years, practitioners have used different testing protocols to measure swimming specific performance which is paramount to inform coaches, athletes and sport scientists about the individual training response and progress to a prescribed program (Anderson et al., 2006; Pyne et al., 2000). These have included incremental swimming (Lavoie et al., 1985) or 400 m time trials to determine maximum aerobic power (Espada & Alves, 2010; Zacca et al., 2019), and maximum lactate steady state (MLSS) or critical speed (CS) determined through single or multiple trials to identify physiological performance thresholds (Courtwright et al., 2016; Dekerle et al., 2002; Piatrikova et al., 2019; Tsai & Thomas, 2017; Wakayoshi et al., 1992; Zacca & Castro, 2010; Zacca et al., 2016). Anaerobic performance testing has ranged from maximal sprinting speed (MSS) using various distances (Ramos et al., 2014) to specific swimming force testing protocols (Papoti et al., 2013). For many of these testing protocols the requirement of invasive blood analyses may also be necessary.

Despite the efforts, environmental constraints, costs, invasiveness, limited time, and lack of expertise render many of these testing protocols impractical and/or challenging for coaches to implement – especially in college settings. Hence, coaches gravitate towards traditional methods with limited theoretical evidence to demarcate training zones based on "best average swimming (Bavg) testing sets". One valid method used to delineate between moderate, heavy and severe intensities (Burnley & Jones, 2007) has been the critical speed (CS) method (Monod & Scherrer, 1965; Pettitt, 2016). This has been successfully applied to swimming using various methods to derive the CS and the finite capacity of available work above the CS (D'; pronounced D-prime) (Dalamitros et al., 2015; Piatrikova et al., 2019; Shiyoyama et al., 2010; Tsai & Thomas, 2017; Wakayoshi et al., 1992). Moreover, some researchers have also mentioned that body anthropometrics can help in predicting CS (Aksit et al., 2017).

The three-minute all-out test (3MT) originated by Burnley and associates (2006) for cycling, has recently been validated and shown to be a reliable protocol for determining CS and the finite distance capacity available above CS (*D'*; pronounced D-prime) in swimming (Piatrikova et al., 2018; Tsai & Thomas, 2017). Typically, the CS is obtained as the average pace of the final 30 s of the 3MT. However, in a recent study by Piatrikova and colleagues (2020), an additional method was used to derive the CS which was also included in their analysis. They calculated CS as the average pace of the last completed lap when athletes did not complete a full lap within the final 30 s of the 3MT. Since the last 30 s section of the test excluded flip turns in such cases, an underestimation of the CS would ensue, as flip turns usually increase swimmer speed due to the wall push-off. The use of both these methods as interchangeable might confound results because CS differences may be influenced by the flip turns performed within the last 30 seconds or lap completion that occurred earlier than this time frame. There also was also no mention of any comparison between both methods. Furthermore, this might unintentionally modify other variables used to assess individual athletic performance profiles, such as, D’, fatigue index (FI), the anaerobic speed reserve (ASR) (Dalamitros et al., 2015), the speed reserve ratio (SRR) (Sandford et al., 2018; Sandford & Stellingwerff, 2019), and would blur the “thresholds boundaries” for other training zones that could be identified with such a test (Piatrikova et al., 2018). This is particularly true if a coach decides to use a different method for measuring maximum sprint speed (MSS) (Dalamitros et al., 2015; Mitchell et al., 2017; Neiva et al., 2011; Tsai & Thomas, 2017).

However, if both CS methods were to result in non-significantly different values, then experienced coaches can save more time by taking time splits with a stopwatch as it has been shown to be a reliable, convenient, and inexpensive method for taking time splits (Mann et al., 2015), including the first (MSS) and the average of the last two laps of the 3MT (CSS) which could aid in profiling by identifying the ASR. Evaluating CS with this method should be possible as most studies using the 3MT in swimming have shown a stabilization of the speed at about 60 to 90 s of the test duration in recreationally trained (Tsai & Thomas, 2017) to elite level athletes (Piatrikova et al., 2019). While the 3MT can be an efficient way to monitor swimming performance and to individualize HIIT prescription (Courtwright et al., 2016) throughout a competitive season (Piatrikova et al., 2020), consistent methods of quantifying these variables are necessary for data consistency. Also, this could relieve coaches of losing valuable training time with a more efficient testing protocol.

The first purpose of this study was to compare the CS and *D’* values using two different calculation methods, the average of the last 30 s and the average speed of the last two laps using split times from a single 3MT in freestyle swimming. The inter-rater reliability between two researchers will be evaluated to test the agreement between both testers for the distances at 150 and 180 seconds and the split times from the 3MT. The second purpose of this study was to compare the resulting variables of a 3MT to the results of a Bavg test composed of a 10 x 100 m swum as fast as possible with about 10 – 20 s rest between intervals – both tests to be performed in freestyle. A comparison of the effect sizes of each test will be analyzed pre- and post- 6 weeks of concurrent training.

Methods

Athletes

All athletes (n = 28; males = 15 & females = 13, performance level = 80.7 ± 3.86% [71.3% - 88.8%] of world record for 25 m short course) were apparently healthy (as assessed by preseason sports medicine screening), ≥ 18 years of age, and currently participating with a local National Athletics Intercollegiate Association (NAIA) swimming team.

Study Design

The study was performed during the beginning of the Fall semester of the swimming season after summer break. The Bavg and the 3MT were performed during practice times prior to and after six weeks of concurrent swimming and resistance training (accumulation block). Prior to data collection, athletes signed a written informed consent approved by the University Institutional Review Board (IRB) in the spirit of the Helsinki Declaration, to store their data for further analysis. Data was collected as part of an on-going athlete monitoring program and was later stored in the East Tennessee State University Sports Science Research Repository (ETSU-SSRR). Due to the COVID-19 pandemic, which limited face to face contact, additional approval by the IRB was sought to use an online video conference call with all athletes. Athletes were explained about the details of how their data from the ETSU-SSRR was going to be used. After the conference call, each athlete was individually contacted to via cellphone to seek their verbal consent.

The 3-minute All-out Swimming Test

Tests were held at regularly scheduled practices times to comply with NAIA regulations. Athletes performed a mixed standardized 1,100 m warm-up like what they performed prior to competition (Balilionis et al., 2012). Swimmers rested 10 minutes between warm-up and the swimming tests to allow recovery from warm-up (Ferguson et al., 2010) and reduce the negative effects on D' (Vanhatalo & Jones, 2009). Swimmers were instructed to swim as fast as possible from the first whistle until they heard the second whistle signifying the end (180 s) and were strictly warned about not pacing themselves throughout the entire duration of the test. Strong verbal encouragement was given to ensure a maximum effort. Video footage was captured using a digital video camera (CANON EOS 700D, Australia) at a sample rate of 30 FPS similar to other studies (Clark et al., 2013; Courtwright et al., 2016). The camera was set up at one end of the pool towards one corner at 2.0 m above the ground and all lane line markers were visible.

The Best Average Swimming Test

The Bavg test was performed during the beginning of the season (1st practice session) after pre-season testing. Prior to performing the Bavg test a similar warm up as performed prior to the 3MT was used. The Bavg test consisted of swimming 10 repetitions of 100 m at the best possible pace (i.e., best average) with 90 or 100 s send-out intervals to allow athletes about 10 – 20 seconds minimum rest. For example, if the athlete arrived at 72 s, the athlete would have 18 s left with a send-out of 90 s. If the athlete arrived at ≥80 s, then the send-out would be 100 s. One swimmer per lane performed the set (6 in total at once), while an assistant wrote down their times per repetition. At the end, these times were averaged to obtain their Bavg pace.

Data Analysis & Statistics

Windows Media Player 12 (Windows 10 Microsoft 2021, Washington, USA) was used to analyze video footage and measure all lap splits by two researchers (LRC & IFA) using a stopwatch (3X300 Memory Stopwatch, FINIS Australia) (Tsai & Thomas, 2017). Splits were taken upon the athlete's feet touching the wall for a push off after each flip turn. Maximum sprint speed was measured as the average speed of the first 25 m (Equation 1). A free open-source sports video analysis software (Kinovea 0.8.15) was used to measure the distance covered by each athlete at every 15 s interval using equally distributed lane line markers as reference (31.75 cm each). The swimmer's head position was used as guidance for the distance covered. Critical speed was determined by two methods, 1) the interval method, which is the average speed of the last 30 s of the 3MT using (Equation 2), 2) and the lap method, which is the average of the last 2 laps completed by the athlete before the end of the test (Equation 3). The results were annotated on a custom-made spreadsheet on Microsoft Excel® (Microsoft 365 MSO, Washington, USA) automatically calculating all variables once completed.

Equation 1. MSS ($m.s^{-1}$) = Lap Distance (25 m) /Time in seconds to complete 1st Lap

Equation 2. CS_{30} ($m.s^{-1}$) = (D180 – D150)/30

Equation 3. CS_L ($m.s^{-1}$) = Distance of Last 2 Laps (50 m) /Time (s) to complete last 2 laps where D150 and D180 are the distances covered by the athlete at 150 and 180 s, respectively.

Previously, Piatrikova and associates (2018) used cones parallel to the pool deck at every 5 m to measure these variables from video analysis by using a stopwatch at each interval. The data from their study showed that the CS derived from a single 3MT was not significantly different from the CS derived from a conventional method using multiple trials (i.e. 200, 400, 600, and 800 m), while showing excellent reliability (r = 0.97) and low variability (CV = 0.9%). However, they showed that D' from the 3MT was lower compared to a speed-time model and distance-time model obtained from the multiple swimming trials used in the conventional method, while still showing good test-retest reliability (r = 0.87) and low variability (CV = 9.1%). Lane lines at our pool were equally marked for distance at every 5 m from the wall and every 0.32 meters between the 5 m flag markings. Hence, the videos could be visually analyzed to measure the distance covered at all time interval time points using the head of the athlete as reference instead of the farthest point reached as done by Piatrikova and colleagues (2018).

Both D150 and D180 were analyzed from video and used to calculate the finite capacity of work available above CS for the interval method (D'_{30}) using Equation 4. For the lap method, the sum of the differences in speed between each lap split and the resulting CS_L from the 3MT were used to calculate D-prime (D'_L) using Equation 5.

Equation 4. D'_{30} (m) = $[(D150/150)-CS_{30}] \times 150$

Equation 5. D'_L (m) = $\sum_i (SSi - CS) \times 25$

where, SS_i is each lap split speed and CS is used from the lap method (CS_L).

For the lap method, a criterion was used to ensure all athletes performed the test with all-out maximal effort and if they did not meet the criteria, then that athlete's 3MT data was discarded from analysis. The criterion was that if the average speed of the last two laps performed (CS_L) were faster than the combined average speed at 100 and 125 m, then that athlete's data would be flagged as it would be evidence of submaximal effort during and acceleration towards the end of the 3MT. The distances of 100 and 125 m were selected because the athletes in our study averaged around 68 to 78 s for those distances during the 3MT, respectively. This is approximately where the aerobic energy pathway becomes the predominant energy source (Mougios, 2006), and if the athlete gave a maximal all-out effort, the evident time-dependent speed drop-off would have been caused by an accumulation of metabolic by-products resulting from anaerobic metabolism which would inhibit maximal muscle fiber recruitment for accelerations (Bundle & Weyand, 2012).

Statistical analysis was performed using JASP (Version 0.14.1). Intraclass correlation coefficients (ICC) were used to assess the inter-rater reliability of the measured splits taken for each lap performed (lap method) and the distances covered at 150 and 180 s of the 3MT (interval method) between two researchers (LRC & IA) using a two-way mixed effect model for absolute agreement and multiple raters (Hopkins, 2015; Koo & Li, 2016). One-way repeated measures analysis of variance (RMANOVA) was used to compare the sequential average speeds of the 15 s interval method to verify for the stabilization of speed during the 3MT (Mitchell et al., 2017; Piatrikova et al., 2019). Bland-Altman plots were created to observe the behavior of the differences within the 3MT variables (CS & D'). Pearson's correlation coefficient (on normally distributed data) and Spearman's ranked correlations (on non-normally distributed data) were also used to evaluate the relationship between Bavg and 3MT variables

(MSS, CS, D' & ASR) collected 72 hours apart during the transition from pre-season to in-season. Paired samples T-tests were used to assess the difference between Bavg and 3MT variables (CS & D') at 3MT1 and 3MT3. Independent *t*-tests were performed to test the mean difference between the CS, and the D' from both calculation methods (interval method vs lap method). The ICC's will be rated as poor, moderate, good, or excellent on the respective ICC values: less than 0.50, between 0.50 – 0.75, between 0.75 – 0.90, and greater than 0.90, respectively. The relationship between variables will be rated as trivial, small, moderate, large, very large, nearly perfect, or perfect based on the respective r values: 0.00-0.10, 0.1 - 0.30, 0.30 - 0.50, 0.50 - 0.70, 0.70 - 0.90, 0.90 - 1.00. Cohen's *d* effect size differences were also calculated and interpreted with magnitude thresholds of 0-0.20, 0.21-0.60, 0.61-1.20, 1.21-2.00 and 2.00 and above as trivial, small, moderate, large, and very large (Hopkins et al., 2009). The level of significance was set at $p \leq 0.05$. Data are reported as mean ± SD.

Results

Inter-rater Reliability of Distance and Split Times

All data was shown to be normally distributed and homoscedastic. Intra-rater reliability between LRC and IFA for the measured distances (D150 and D180) and all lap split times for all swimmers during the 3MT had excellent reliability (ICC[3,2] = 0.999 and ICC[3,2] = 0.987, respectively).

Mean Speed-Time Profile of the 3MT

Mauchly's test of sphericity was violated for which Greenhouse-Geisser correction was used ($p < 0.001$). Repeated measures analysis of variance showed a within subject effects, $F= 512.08(1.33, 35.80)$, $p < 0.001$. Planned comparison analysis showed that all ($p < 0.01$) but the last two sequential 15-s intervals (p = 0.08 and 0.06, for 150 vs 160 s and 165 vs 180 s intervals, respectively) were significantly different when compared to the previous one (Figure 3.1).

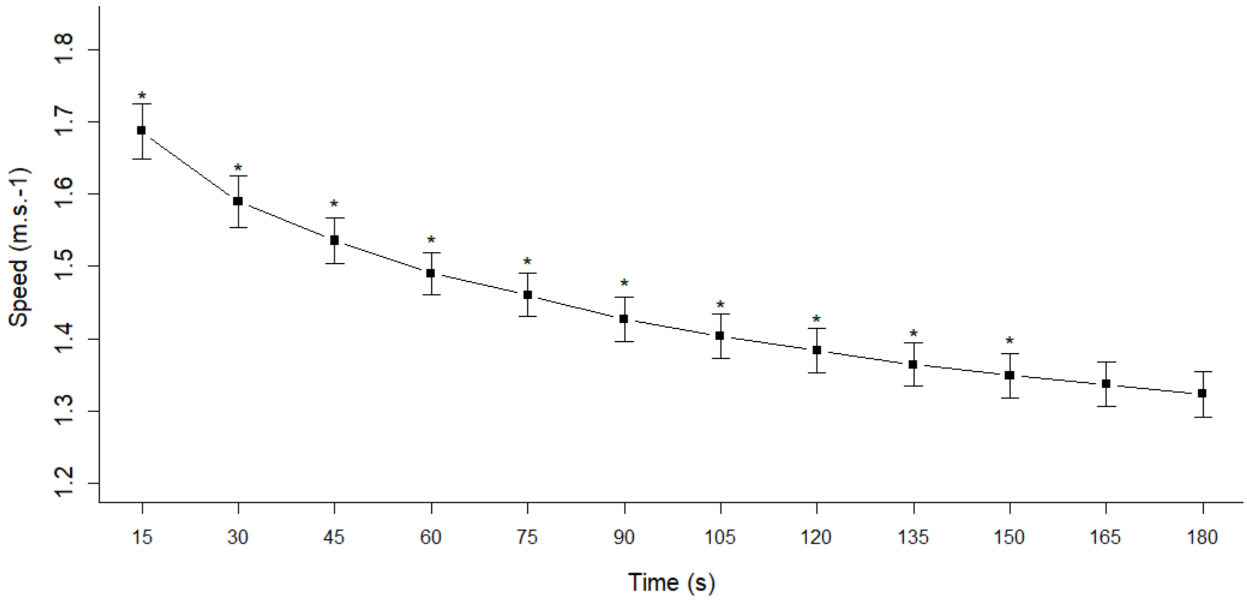

Figure 3.1 The group mean speed profile of the 3-minute all-out swimming test.
**p*<0.01 when comparing to the previous 15 s speed interval beginning from the last interval shown after post-hoc analysis, n = 28.

Comparing Methods to Derive 3MT Variables

Bland-Altman plots for CS showed that data did not present remarkable behavior (Figure 3.2A), while there seemed to be a bias or systematic error for D' with a mean difference of -8.03 m for D'_{30} compared to D'_{L} (Figure 3.2B).

Table 3.1 shows the descriptive 3MT performance variables for each method. Critical speed was not shown to be significantly different between methods, $t(54) = -0.21$, $p = 0.83$, $d = -0.06$. However, D'_{L} was significantly higher than D'_{30} and had a moderate effect size, $t(54) = -2.61$, $p = 0.01$, $d = -0.70$. Figure 3.3 shows the 3MT average speed profiles calculated using the interval and lap split methods for one athlete. Despite no significant statistical differences in CS between methods for the group means, some athletes presented with overestimated or underestimated results for CSL. Figure 3.4 shows the average speed profile for four athletes of different performance levels, yet a similar speed decay at all performance levels (Figure 3.4).

Table 3.1. Comparison of interval and lap split methods to derive 3MT swimming performance variables, n = 28.

	Group	**Mean ± SD**	**SE**	***t*(df = 54)**	***p***	**Cohen's *d***
Critical Speed (m.s.$^{-1}$)	CS_{30}	1.20 ± 0.12	0.02			
	CS_L	1.20 ± 0.11	0.02	-0.21	0.83	-0.06
D-prime (m)	D'_{30}	22.59 ± 9.28	1.75			
	D'_L	30.62 ± 9.90	1.87	-3.13	0.003	-0.84

Table 3.2. Pairwise correlation table for Bavg and 3MT performance variables during the pre-season (n = 28).

			Test		
Bavg	-	MSS	Pearson's	0.78	***
Bavg	-	CS_L	Pearson's	0.81	***
Bavg	-	D'_L	Pearson's	0.15	
Bavg	-	ASR	Pearson's	-0.03	

* p < .05, ** p < .01, *** p < .001

Shapiro-Wilkes bivariate normality test showed that all data between the Bavg and 3MT performance variables were normally distributed. Table 3.2 contains the correlation results for the Bavg and 3MT performance variables. Best average speed showed very large correlations to MSS (r = 0.78, p = 0.001) and CS_L (r = 0.81, p = 0.001).

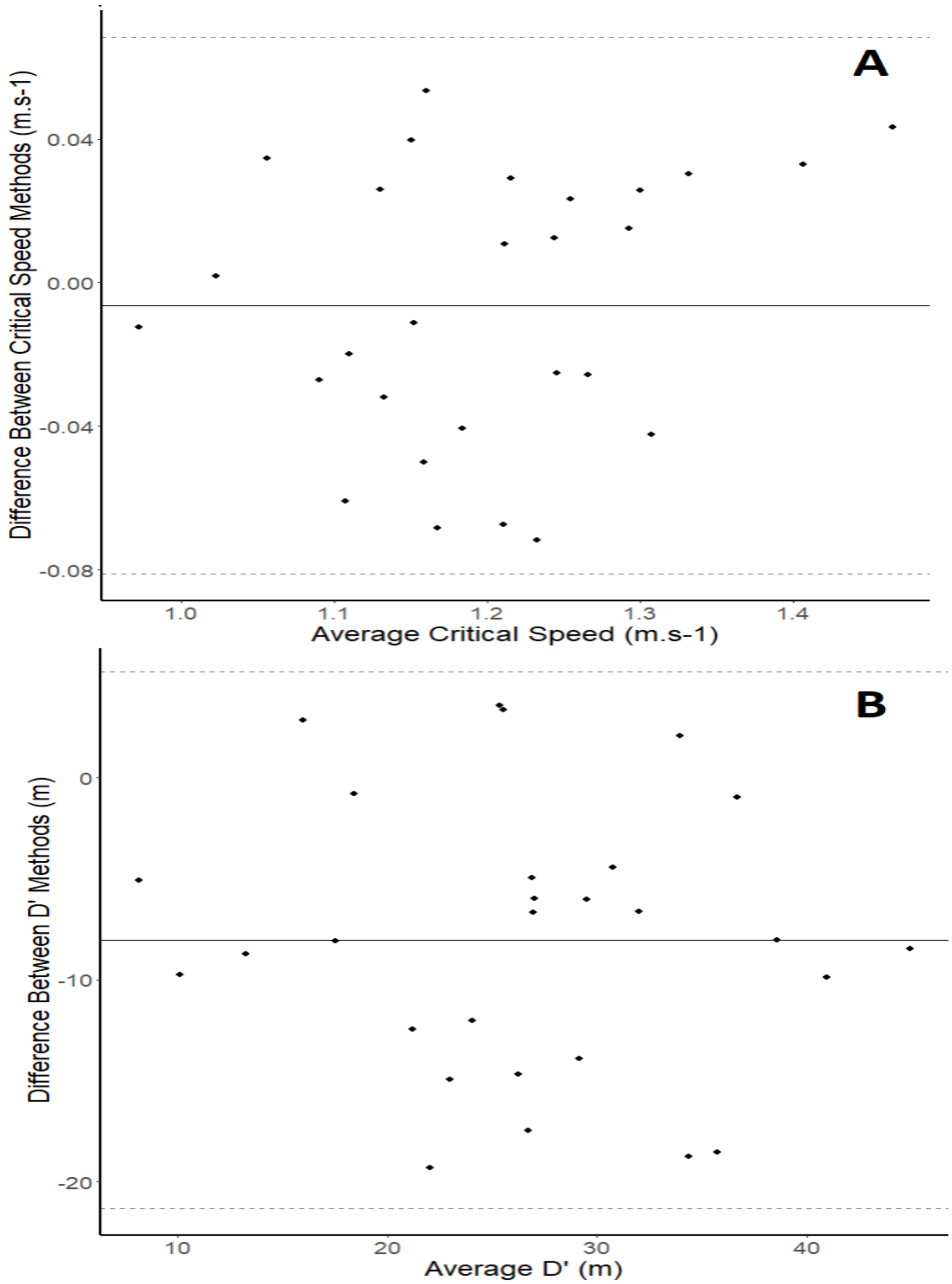

Figure 3.2. Bland-Altman analysis for differences in methods to derive CS (A) and D' (B) performance variables from the 3MT. In the panels, the solid horizontal lines represent the mean difference between CS_{30} and CS_{L} (A), and D_{30} and D'_{L} (B), respectively. The dashed lines represent the 95% limits of agreement; n = 28.
Note: CS_{30} = critical speed using the interval method, CS_{L} = critical speed using the lap method, D'_{30} = distance capacity above CS using the interval method, D'_{L} = distance capacity above CS using the lap method, 3MT = three-minute all-out swimming test.

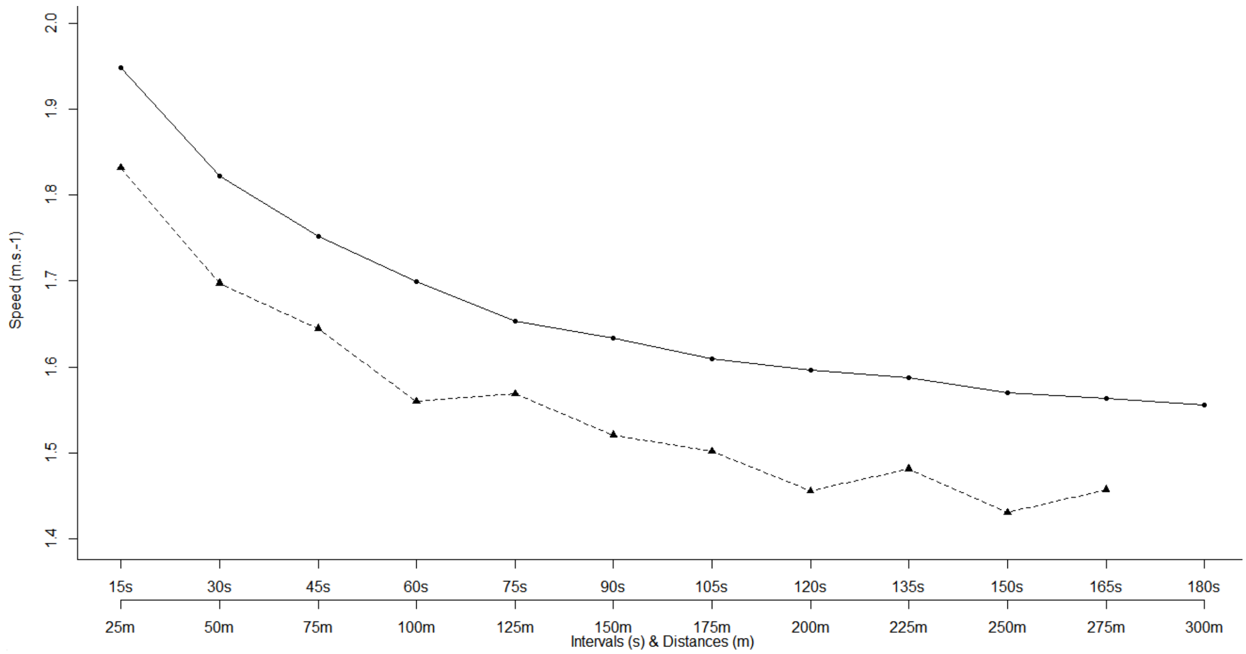

Figure 3.3. Three-minute all-out swimming test average speed profile calculated by the interval and lap split methods for one athlete.

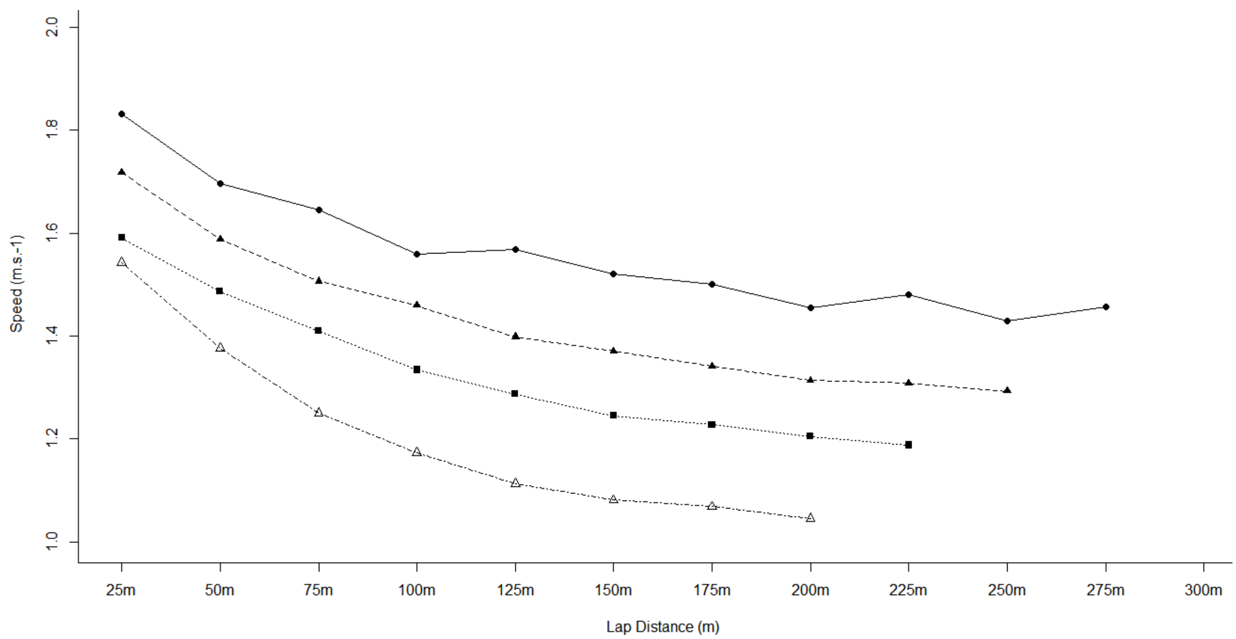

Figure 3.4. Three-minute all-out swimming test average lap split speed profile for four athletes of different performance levels. Note: Bavg = best average swimming test, 3MT = three-minute all-out swimming test, MSS = maximum sprint speed, CS_L = critical speed using the lap split method, D'_L = distance capacity of available work above critical speed using the lap split method, ASR = anaerobic speed reserve using the lap split method.

Comparing 3MT vs Bavg

Considering the nature of the Bavg and the 3MT, visual illustrations were created to compare and understand how each physiological threshold surrogate would fair against each other (Figure 3.5 & 3.6).

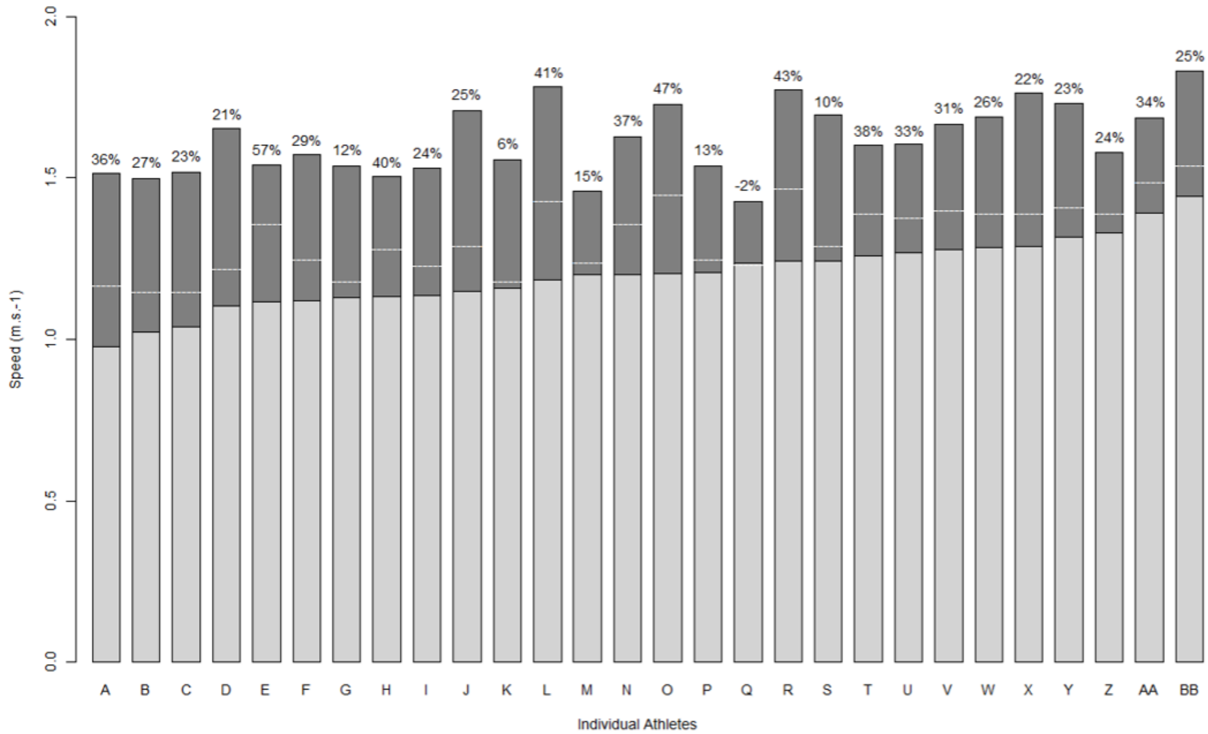

Figure 3.5. Variability of the percentage of anaerobic speed reserve (dark grey shaded area) at which best average swimming test is expressed (white dashed line).

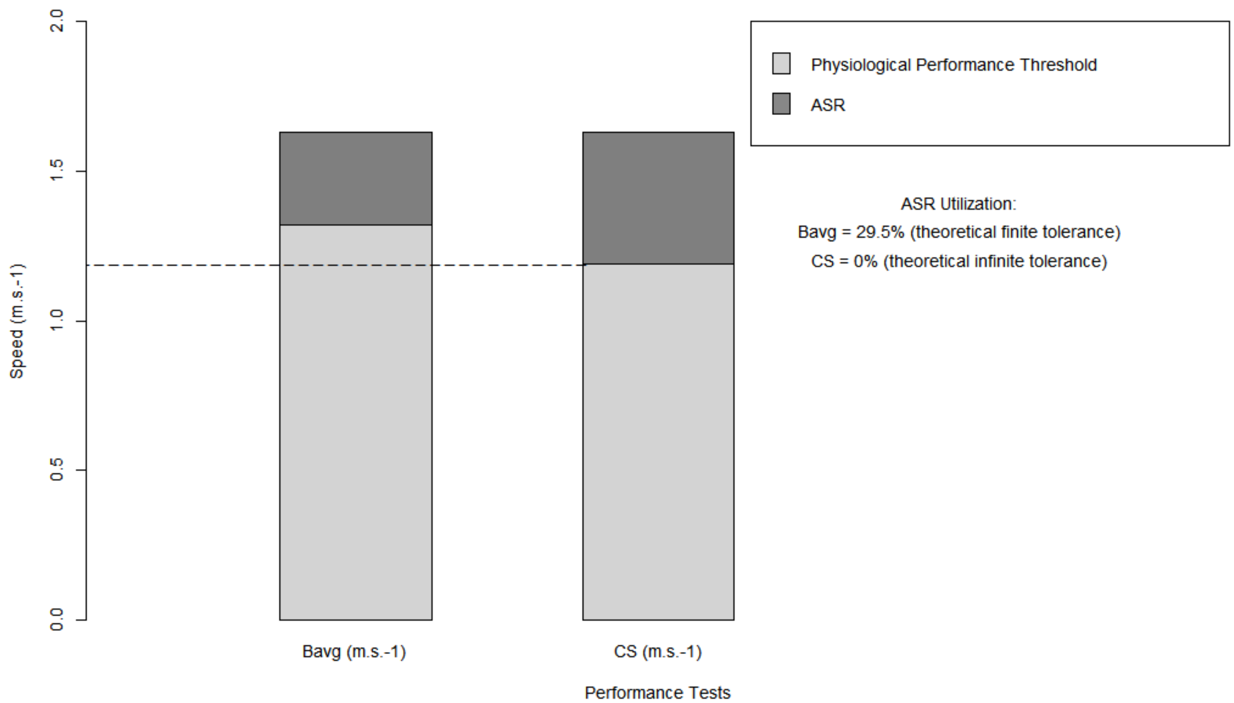

Figure 3.6. Comparison of the average theoretical anaerobic speed reserves using differing physiological performance thresholds in a single athlete. Swimming at the Bavg pace automatically subjects the athlete to be at 29.5% of their ASR, which would have a finite capacity, contrary to when swimming at CS.
Note: ASR = anaerobic speed reserve, Bavg = best average swimming test pace, CS = critical speed from the three-minute all-out swimming test.

For the Bavg pace, one missing data point from the post-testing period was imputed by calculating the average change from pre- to post-training (0.04 $m.s.^{-1}$) and adding this to the pre-training value of the corresponding post-training missing data point. Table 3.3 displays the changes that occurred from the beginning of the season and 8-weeks after at mid-season. A moderate increase in Bavg speed was observed, $Z = 29.00$, $p < 0.001$.

Table 3.3. Bavg (n = 28) and 3MT (n = 25) performance changes from baseline (3MT1) to 6-weeks after concurrent swimming and strength training (3MT3).

Variable	**3MT1**	**3MT3**	**SE (pre/post)**	**Statistic**	**Effect Size (*d*)**
Bavg ***	1.32 ± 0.11	1.36 ± 0.12	0.02/0.02	29.00[a]	-0.85
MSS	1.62 ± 0.11	1.62 ± 0.11	0.02/0.02	180.00 [a]	-0.11
CS_L ***	1.20 ± 0.10	1.30 ± 0.10	0.02/0.02	-8.38	-1.68
D'_L ***	31.80 ± 9.56	21.62 ± 7.76	1.91/1.55	6.80	1.36

****p* < 0.001; [a] Wilcoxon test was used for analysis.
Note. For Wilcoxon test, effect size is given by the matched rank biserial correlation. Bavg = best average swimming test, CS = critical swimming speed, D' = distance capacity above critical speed, 3MT1 = baseline testing, 3MT3 = testing after 6 weeks of concurrent swimming and resistance training, SE = standard error.

Discussion

Comparing 3MT Variable Calculation Methods

The first purpose of this study was to compare the calculation methods used to derive the CS and D' from a 3MT in swimming. First, our data showed a hyperbolic relationship for the speed decay of the 3MT and was statistically significant for all intervals when comparing them each to their prior respective interval except for the last two. This goes in line with previous research that attempted to objectively justify a speed stabilization or asymptote during the 3MT (Mitchell, Pyne, Saunders, & Rattray, 2017; Tsai & Thomas, 2017; Piatrikova E. , Sousa, Gonzalez, & Williams, 2019). Statistical comparisons of the average interval speeds were previously tested by performing t-tests with Bonferroni correction (Courtwright, Williams, Clark, Pettitt, & Dicks, 2016; Mitchell, Pyne, Saunders, & Rattray, 2017; Tsai & Thomas, 2017; Piatrikova E. , Sousa, Gonzalez, & Williams, 2019). However, this method of repeated measurements seemed inappropriate as repeated sequential testing would reduce the statistical power for which in the current study a one-way repeated measures ANOVA with planned comparisons was used. Hence, the speed-time profile in our study appeared to stabilize and reach an asymptote as expected.

There was no statistically significant difference between calculation methods for CS (CS_L vs CS_{30}). However, D'_{30} was statistically significantly lower than D'_L with evidence of systematic error or bias in its measurement (Figure 3.2). This validates the results of previous research that had used both methods to calculate CS within their analysis when athletes did not complete a full 50 m lap in the last 30 s of the 3MT (Piatrikova, Willsmer, Sousa, Gonzalez, & S, 2020). Average swimming speed that does not involve a flip turn will underestimate the pace an athlete will be prescribed for short and long interval HIIT, since ground reaction forces from the wall push-off will increase the athlete's average speed (Bishop et al., 2013). Our pool was 25 m in length and during the 3MT all our athletes completed at least 200 m of full lap swims. The time spent to complete the last two laps ranged from 35 – 49 s within our group of athletes. It is important to note that when testing the 3MT in swimmers, data results will correspond to the pool dimensions it was performed in, since 25 m will involve more wall push-offs, hence faster speeds, so any prescriptions must take this into account.

However, the same cannot be said for the D'_L. Prior literature has shown that D' was about 50 – 75% lower than D' when measured through conventional methods of multiple time-trials (Tsai & Thomas, 2017). Although Tsai and Thomas (2017) used split times to record average speed at every 25 m, they calculated CS as the average speed of the last 30 s, and hence the D' was also shown to be significantly lower compared to the conventional methods. A similar pattern was observed by Piatrikova and others (2019) as they showed that D' from the 3MT (D'_{30} method) was consistently lower when compared to linear regression calculation methods. Our data is consistent with these results showing that calculating D' from a 3MT as originally done with cyclists (last 30 s of the 3MT) will significantly reduce its value (Burnley, Doust, & Vanhatalo, 2006). The D'30 presented with high variability (CV% = 41.1%) while D'L although still high was lower (CV% = 32.3%). The variability of D'30 presented in our results seem to look the same as other studies that tested healthy average trained swimmers and triathletes (CV% = 43.1%) (Tsai & Thomas, 2017), NCAA DI female swimmers (CV% = 43.5 – 62.5%) (Courtwright, Williams, Clark, Pettitt, & Dicks, 2016), highly trained swimmers (CV% = 33.5 – 54.4%) (Piatrikova, Willsmer, Sousa, Gonzalez, & S, 2020), but higher than a modified 3MT (CV% = 5.7%) (Mitchell, Pyne, Saunders, & Rattray, 2017). The low variability of the D' for the modified 3MT could be due to the nature of how the test was performed. A series of all-out 25 sprints with 5 s intervals were performed until the total accumulation of time surpassed 180 s total. So, then an integration of a Speed-Time Model was used to calculate the D'. This would not be adequate for comparison since even a brief rest of 5 s could be sufficient to influence of the central nervous response inevitably affecting the speed drop-off result. There were also inconsistent differences in the results between the D' calculations methods in our study. Differences between the methods ranged between 2 – 53% higher in D'_L when compared to D'_{30}. The two athletes with the lowest differences in D' (2 and 4%) were also the athletes that covered less total distance and had the slowest CS of the group, while those that covered the most distance and had higher CS showed the highest differences (47% & 53%). Meanwhile the rest of the group were above 15% minimum difference. These data indicate that D'L incurs in less, but still high variability at least in collegiate athletes.

One glaring fact during the analysis was that averaging interval speed at different time intervals would have athletes at different locations in the pool. For example, an athlete that is coming out of the wall push-off will present with a faster average speed while those coming into the wall would have slowed down from crossing the pool. This will indeed affect speed estimates as athletes would not be under the same circumstances due to their position within the pool. The alternative D' calculation used in the current study was suggested from a conversation sustained with Dr. Eva Piatrikova. Calculating the sum of the differences between each average split speed and the resulting CS multiplied by the lap distance (i.e., 25 m) would give an estimate of the area under the curve (distance capacity above CS; Equation 5). Since the D' from conventional methods was higher than D' from a 3MT, Piatrikova mentioned that D' values with this calculation were comparable to conventional methods and resolved the disparity (unpublished data). Judging by the increased value of D'_L in our study, this speculation seems logical, yet further research is needed to assess the veracity of this claim. Nonetheless, the D'_L represented 12.9% ± 4.1% of the total distance swum by the athletes during the 3MT, while D'_{30} was equivalent to 9.7 ± 3.5%. This seems comparable to Courtwright et al. (2016) who showed that D' represented 9% of the total distance. Considering that Courtwright and associates also used the original 3MT method of deriving D' (D'_{30}) it is possible that equivalent values would be observed if the lap split method would have been used. In the study by Tsai and Thomas (2017) they found that average 3MT D' values were 60% and 51% of the D' values calculated from a linear total distance regression and a non-linear time to speed method, respectively. In the Piatrikova and others validation study they found that D' from 3MT was 84% and 88% of the distance-time model and the speed-1/time model, respectively. Our data showed that the average D'_{30} values were 78% of the average D'_L values which is slightly higher and slightly lower than the former and latter studies, respectively. The discrepancies from the Tsai & Thomas study could be explained by differences in age (35.2 ± 10.5 years) and performance levels since they had a mix of swimmers and triathletes that only required a minimum of two years' experience competing in swimming. When comparing against the Piatrikova study, the sample used were international and national level athletes with performances ranging from 70% - 80% of world record in the 50 m pool event distances versus our athlete sample of 71 – 89% of world record in the 25 m event distances. It seems as the higher the level of the athlete the less the differences of D' between methods, yet the higher variability explained in the above text must be considered.

Given the excellent inter-rater reliability of split times taken during the lap split method (ICC[3,2] = 0.987), coaches and practitioners can confidently use a stopwatch to track split times. This has been shown to be a valid method compared to electronic measurements (Mann, Ivey, Brechue, & Mayhew, 2015). It is suggested that a video camera be used to record all athletes that are performing the test with a view of the entire pool that can allow to track all lap splits from the participants and later analyze the 3MT performance afterwards as done in this study. This can ensure time-efficiency by obviating the set-up of cones or the use of any robust sports video analysis software for average interval time speed which takes considerable time to track and measure. Furthermore, athletes of differing performance levels express similar speed decay patterns even when total distances covered during the test were varied (Figure 3.4). Coaches should ensure that athletes perform tests with all-out effort and athletes should not be aware of remaining time to avoid pacing strategies. Nonetheless, a criterion to ensure that athletes performed the test with maximal effort was introduced in our analysis. This criterion was based on the physiological assumption that around 60 – 75 s of maximal effort aerobic energy production becomes the predominant energy source as anaerobic energy is hindered due to the metabolic influence of elevated hydrogen ions (Mougios, 2006; Ogita, 2006). In our group, this corresponds to distances of 100 and 125 m approximately, since our group averaged

68 and 78 s, respectively. The second assumption is that at maximal efforts the athlete should expend all anaerobic energy reserves around the 90 – 120 s time frame, hence, given these assumptions, faster speeds during the last two laps should not occur. In this study, no athlete violated the criteria in the baseline test (3MT1), but three violated it during the post-6-week training block for which they were excluded from the pre-post-training analysis.

Comparing 3MT vs Bavg

To the author's knowledge, the Bavg test has no scientific evidence to support its use, nor has it been validated against any other published method, yet collegiate coaches widely use it as a threshold parameter to derive training zones for prescription, such as, the color code system. So, for the second purpose of the current study, we sought to compare the Bavg as a threshold parameter compared to CS derived from the 3MT. It is understood that maximal all-out efforts with longer rest intervals will allow athletes to maintain a higher level of performance than continuous efforts minimizing performance decrement (Billat V. , 2001). Although the Bavg pace is yet to be well understood, in our study it had a significant very large correlation to MSS ($r = .78$) and CS_L ($r = .81$). This shows that it may very well have an aerobic fitness component, yet it is also dependent on an athlete's MSS capability. However, the lack of correlation of the Bavg to D' and ASR are an interesting phenomenon that increases the obscurity of the interval nature of the Bavg test, especially when rest intervals may vary per person (i.e., 10 – 20 s). These factors may influence the results of the Bavg speed dependent on an athlete's ability to recover within the allotted rest interval and may represent varying relative intensities in respect to the ASR (Sanford, Laursen, & Buchheit, 2021). This also makes less clear how to manage athletes according to how much of the D' may be targeted to be used within a HIIT.

In the current investigation, we calculated the ASR as the difference between the MSS and the CS_L. This defers from other researchers who have previously identified the ASR to be the difference between MSS and maximum aerobic speed or the velocity associated to $\dot{V}O_{2max}$ (Sandford, Kilding, Ross, & Luarsen, 2018; Sandford & Stellingwerff, 2019; Sanford, Laursen, & Buchheit, 2021). The justification for this distinction comes from the unique physiological responses of the $\dot{V}O_2$ kinetics within the heavy and severe intensity domains (Burnley & Jones, 2007; Poole & Jones, 2012; Poole, Burnley, Vanhatalo, Rossiter, & Jones, 2016). Once intensity of exercise surpasses the CS threshold, the intensity is high enough to subject the athlete's physiology to an incremental $\dot{V}O_2$ slow component which in the case of swimming would reduce the available D' – a finite capacity that allows to sustain such intensity for a limited time – until the intensity is forced down to CS intensity (Burnley & Jones, 2007; Poole & Jones, 2012; Poole, Burnley, Vanhatalo, Rossiter, & Jones, 2016).

The great majority of athletes showed that Bavg speed was higher than CS, but with varying relative intensities in respect to their ASR (Figure 3.5). Bavg speed varied from -2% to 57% of the ASR. Athlete "Q" who was the only athlete to show a Bavg pace below CS_L had the smallest ASR of the group and this difference (0.002 $m.s.^{-1}$) was lower than the SE of 0.02 $m.s.^{-1}$. This is possibly the quintessential example that justifies the use of CS_L as the lower boundary of the ASR, as it could have been possible that during the Bavg test D'_L was theoretically used up almost entirely bringing the intensity to CS levels (Figure 3.5). Nonetheless, this hypothesis needs to be investigated in future research as this was not measured in our study. One possible reason for the variability of where the Bavg pace is relatively expressed at could be the differing rest intervals taken by each athlete during such test (i.e., 10 – 20 s) as the intervals are performed on differing send-out times for everyone (i.e., 90 – 100 s). Another reason could be the differing glycolytic hormonal profiles between athletes that are sprinter or endurance types that can dictate the rate of anaerobic glycolysis, anaerobic energy use and recoverability within rest intervals during the Bavg test (Vucetic, Mozek, & Rakovac, 2015). A descriptive comparison between threshold surrogates (CS_L & Bavg) as if each were identifying their respective lower boundaries of the ASR was made to demonstrate an example of one athlete (Figure 3.6). If an athlete were to swim at the Bavg pace, the swimming intensity would have a finite tolerance (29.5% of ASR), which if kept until fatigue would drive intensity down to CS_L where it would stabilize, as shown by athlete "Q" (Figure 3.5).

When comparing the training effects changes after a 6-week period of concurrent swimming and resistance training (strength-endurance and basic strength block), the Bavg pace had moderate (ES = -.85) significant difference. Meanwhile, both the CS_L and D'_L had large (ES = -1.68 and 1.36, respectively) significant differences within the same time frame. Since there were no significant differences between MSS (ES = -.11; during 3MT), it seems that improvements in Bavg swimming test were mainly driven by the changes in the CS_L and D'_L. However, deeper analysis into the correlations between the changes for the Bavg and the 3MT variables were trivial (r = -.12 and .16, for CS_L and D'_L, respectively). Albeit the 3MT was more time-efficient compared to the Bavg test in testing the same group of 28 athletes (Bavg = 100 minutes vs 3MT = 25 minutes, approximately for both). Due to the nature of the Bavg swimming pace, both the CS and MSS simultaneously influence its results, and this coupled with the varied rest intervals taken by the athletes between each 100 m swim would make it a cumbersome task to discern which physiological improvements have occurred.

Conclusion

The 3MT appears to be a suitable test for determining the CS and D’ for collegiate swimmers and can be used for individualized prescription. Coaches can use a simple stopwatch and record videos of the test for later analysis of split times making this a time-efficient protocol for the time-restricted setting in collegiate sports. The lap split method is a more appropriate and practical calculation method to measure CS and D’ then compared to the original interval methods. Both variables in conjunction can help in understanding the tolerable duration of high-intensity intervals above the CS. The Bavg test has much variability in terms of its relative individual intensity and may not be as sensitive to physiological changes as the variables derived from the 3MT.

References

Aksit, T., Ozkol, M., Vural, F., Penkunlu, E., Aydinoglu, R., & Varol, R. (2017). Contribution of anthropometric characteristics to critical swimming velocity and estimated propulsive force. *Journal of Physical Education and Sport*, 17(1): 212-218.

Amaro, N., Morouco, P., Marques, M., Batalha, N., Neiva, H., & Marinho, D. (2018). A systematic review on dry-land strength and conditioning training on swimming performance. *Science & Sports*, 34(1): e1-e14.

Anderson, M., Hopkins, W., Roberts, A., & Pyne, D. (2006). Monitoring seasonal and long-term changes in test performance in elite swimmers. *European Journal of Sports Science*, 6(3): 145-154.

Baldari, C., Fernandes, R., Meucci, M., Ribeiro, J., Vilas-Boas, J., & Guidetti, L. (2012). Is the New AquaTrainer Snorkel Valid for VO2 Assessment in Swimming? *International Journal of Sports Medicine*, 34(4): 336-344.

Balilionis, G., Nepocatych, S., Ellis, C., Richardson, M., Neggers, Y., & Bishop, P. (2012). Effects of Different Types of Warm-Up on Swimming Performance, Reaction Time, and Dive Distance. *Journal of Strength and Conditioning Research*, 26(12): 3297-3303.

Barbosa, T., Fernandes, R., Keskinen, K., & Vilas-Boas, J. (2008). The influence of stroke mechanics into energy cost of elite swimmers. *European Journal of Applies Physiology*, 130(2): 139-149.

Barbosa, T., Fernandes, R., Keskinen, K., Colaco, P., Cardoso, C., Silva, J., & Vilas-Boas, J. (2006). Evaluation of the Energy Expenditure in Competitive Swimming Strokes. *International Journal of Sports Medicine*, 27(11): 894-899.

Bassett, D. (2002). Scientific contributions of A.V. Hill: exercise physiology pioneer. *Journal of Applied Physiology*, 93: 1567-1582.

Batalha, N., Raimundo, A., Tomas-Carus, P., Paulo, J., Simao, R., & Silva, A. (2015). Does a land-based compensatory strength-training programme influences the rotator cuff balance of young competitive swimmers? *European Journal of Sports Science*, 15(8): 764-772.

Bazyler, C., Abbott, H., Bellon, C., Taber, C., & Stone, M. (2015). Strength for Endurance Athletes: Theory to Practice. *Journal of Strength and Conditioning*, 37(2): 1-12.

Beaver, W., Wasserman, K., & Whipp, B. (1986). A new method for detecting anaerobic threshold by gas exchange. *Journal of Applied Physiology*, 60(6): 2020-2027.

Bergstrom, H., Dinyer, T., Succi, P., Voskuil, C., & Housh, T. (2021). Applications of the Critical Power Model to Dynamic Constant External Resistance Exercise: A Brief Review of the Critical Load Test. *Sports*, 9(2): 1-15.

Billat, V. (2001). Interval Training for Performance: A Scientific and Empirical Practice. Special Recommendations for Middle- and Long-Distance Running. Part II: Anaerobic Interval Training. *Sports Medicine*, 31(2): 75-90.

Billat, V., Sirvent, P., Py, G., Koralsztein, J., & Mercier, J. (2003). The Concept of Maximal Lactate Steady State. *Sports Medicine*, 33(6): 407-426.

Bishop, C., Cree, J., Read, P., Chavda, S., Edwards, M., & Turner, A. (2013). Strength and Conditioning for Sprint Swimming. *Strength and Conditioning Journal*, 35(6): 1-6.

Bishop, D., & Jenkins, D. (1996). The Influence of Resistance Training on the Critical Power Function & Time to Fatigue at Critical Power. *The Australian Journal of Science and Medicine in Sport*, 28(4): 101-105.

Bonen, A., Wilson, B., Yarkony, M., & Belcastro, A. (1980). Maximal oxygen uptake during free, tethered, and swim flume swimming. *Journal of Applied Physiology*, 48(2): 232-235.

Brooks, G. (1985). Anaerobic threshold: review of the concept and directions for future research. *Medicine and Science in Sport and Exercise*, 17(1): 22-31.

Buchheit, M., & Luarsen, P. (2013). High-Intensity Interval Training, Solutions to the Programming Puzzle - Part I: Cardiopulmonary Emphasis. *Sports Medicine*, 43(5): 313-338.

Bundle, M., & Weyand, P. (2012). Sprint Exercise Performance: Does Metabolic Power Matter? *Exercise and Sports Science Reviews*, 40(3): 174-182.

Burnley, M., & Jones, A. (2007). Oxygen uptake kinetics as a determinant of sports performance. *European Journal of Sports Science*, 7(2): 63-79.

Burnley, M., Doust, J., & Vanhatalo, A. (2006). A 3-min All-out Test to Determine Peak Oxygen Uptake and the Maximal Steady State. *Medicine and Science in Sport and Science*, 38(11): 1995-2003.

Carroll, K., Bernards, J., Bazyler, C., Taber, C., Stuart, C., DeWeese, B., . . . Stone, M. (2018). Divergent Performance Outcomes Following Resistance Training Using Repetition

Maximums or Relative Intensity. *International Journal of Sports Physiology and Performance*, 14(1): 1-28.

Chaverri, D., Schuller, T., Iglesias, X., Hoffman, U., & Rodriguez, F. (2016). A New Model for Estimating Peak Oxygen Uptake Based on Postexercise Measurements in Swimming. *International Journal of Sports Physiology and Performance*, 11(4): 419-424.

Cheng, C., Yang, Y., Lin, H., Lee, C., & Wang, C. (2012). Determination of critical power in trained rowers using a three-minute all-out rowing test. *European Journal of Applied Physiology*, 112: 1251-1260.

Clark, I., West, B., Reynolds, S., Murray, S., & Pettitt, R. (2013). Applying the Critical Velocity Model for an Off-Season High Intensity Interval Training Program. *Journal of Strength and Conditioning Research*, 27(12): 3335-3341.

Clark, I., West, B., Reynolds, S., Murray, S., & Pettitt, R. (2013). Applying the Critical Velocity Model for an Off-Season Interval Training Program. *Journal of Strength and Conditioning Research*, 27(12): 3335-3341.

Corry, I., & Powers, N. (1982). Maximal Aerobic Power Measurement in Runners and Swimmers. *British Journal of Sports Medicine*, 16(3): 154-160.

Courtwright, S., Williams, J., Clark, I., Pettitt, R., & Dicks, N. (2016). Monitoring Interval-traininf Responses for Swimming using the 3-min All-out Exercise Test. *International Journal of Exercise Science*, 9(5): 545-553.

Courtwright, S., Williams, J., Clark, I., Pettitt, R., & Dicks, N. (2016). Monitoring Interval-Training Responses for Swimming using the 3-min All-out Exercise Test. *International Journal of Exercise Science*, 9(5): 545-553.

Crowley, E., Harrison, A., & Lyons, M. (2018). Dry-Land Resistance Training Practices of Elite Swimming Strength and Conditioning Coaches. *Journal of Strength and Conditioning Research*, 32(9): 2592-2600.

Dalamitros, A., Fernandes, R., Toubekis, A., Manou, V., Loupos, D., & Kellis, S. (2015). Is speed reserve related to critical speed and anaerobic distance capacity in swimming? *Journal of Strength and Conditioning Research*, 29(7): 1830-1836.

Dalamitros, A., Fernandes, R., Toubekis, A., Manou, V., Loupos, D., & Kellis, S. (2015). Is Speed Reserve Related to Critical Speed and Anaerobic Distance Capacity in Swimming? *Journal of Strength and Conditioning Research*, 29(7): 1830-1836.

Dekerle, J., Sidney, M., Hespel, J., & Pelayo, P. (2002). Validity and Reliability of Critical Speed, Critical Stroke Rate, and Anaerobic Capacity in Relation to Front Crawl Swimming Performances. *International Journal of Sports Medicine*, 23: 93-98.

DeWeese, B., Wagle, J., & Bingham, G. (2019). Let the rhythm hit them: Adjusting the tempo to skilffully surf the intensity curve. . *Techniques Magazine*, 10(4): 52-59.

DiMenna, F., & Jones, A. (2019). Aerobic performance assessment. In P. Comfort, P. Jones, & J. McMahon, *Performance Assessment in Strength and Conditioning* (pp. 212-239). Abingdon, Oxon: Routledge.

Edge, J., Hill-Haas, S., Goodman, C., & Bishop, D. (2006). Effects of resistance training on H+ regulation, buffer capacity, and repeated sprints. *Medicine and Science in Sports and Exercise*, 38(11): 2004-2011.

Espada, M., & Alves, F. (2010). Critical Velocity and the Velocity at Maximal Lactate Steady State in Swimming. *Biomechanics and Medicine in Swimming XI* (pp. 194-196). Oslo: Norwegian School of Sports Science.

Espada, M., Costa, A., Louro, H., Conceiao, A., Filho, D., & Pereira, A. (2016). Anaerobic Critical Velocity and Sprint Swimming Performance in Masters Swimmers. *International Journal of Sports Science*, 6(1A): 31-35.

Farrell, P., Wilmore, J., Coyle, E., Billing, J., & Costill, D. (1979). Plasma lactate accumulation and distance running performance. *Medicine and Sciennce in Sports and Exercise*, 25(10): 1089-1090.

Ferguson, C., Rossiter, H., Whipp, B., Cathcart, A., Murgatroyd, S., & Ward, S. (2010). Effect of recovery duration from prior exhaustive exercise on the parameters of the power-duration relationship. *Journal of Applied Physiology*, 108(4): 866-874.

Fernandes, R., Sousa, M., Machado, L., & Vilas-Boas, J. (2011). Step Length and Individual Anaerobic Threshold Assessment in Swimming. *International Journal of Sports Medicine*, 32(12): 940-946.

Fig, G. (2010). Why Competitive Swimmers Need Explosive Power. *Strength and Conditioning Journal*, 32(4): 84-86.

Fone, L., & van den Tillar, R. (2022). Effects of Different Types of Strength Training on Swimming Performance in Competitive Swimmers: A Systematic Review. *Sports Medicine*, 8(1): 1-26.

Galbraith, A., Hopker, J., Lelliot, S., Diddams, L., & Passfield, L. (2014). A Single-Visit Field Test of Critical Speed. *International Journal of Sports Physiology and Performance*, 9(6): 931-935.

González-Ravé, J., Pyne, D., Castillo, J., González-Mohíno, F., & Stone, M. (2021). Training periodization for a world-class 400 meters individual medley swimmer. *Biology of Sport*, 39(4): 883-888.

Green, S. (1995). Measuring of Anaerobic Work Capacities in Humans. *Sports Medicine*, 19(1): 32-42.

Green, S., & Dawson, B. (1993). Measurment of Anaerobic Capacities in Humans: Definitions, Limitations, and Unsolved Problems. *Sports Medicine*, 15(5): 312-327.

Greenshields, J., Goss, C., & Stager, J. (2018). Variation in Critical Speed and Finite Distance Capacity of Elite Swimmers. *Annual Meeting of the American College of Sports Medicine* (p. 50(5S): 525). Minneapolis: Medicine and Science in Sports and Exercise.

Haff, G. (2019). The essentials of periodization. In I. Jeffreys, & J. Moody, *Strength and Conditioning for Sports Performance* (pp. 404-448). Abingdon, London: Routledge.

Hale, T. (2008). History of developments in sport and exercise physiology: A.V. Hill, maximal oxygen uptake, and oxygen debt. *Journal of Sports Sciences*, 26(4): 365-400.

Hall, G., & Murphy, D. (2020). *Fundamentals of Fast Swimming: How to Improve Your Swimming Technique.* Islamorada, FL: The Race Club.

Hellard, P., Avalos-Fernandes, M., Lefort, G., Pla, R., Mujika, I., Toussaint, J., & Pyne, D. (2019). Elite swimmers' training patterns in the 25 weeks prior to their season's best performances: insights into periodization from a 20-years cohort. *Frontiers in Physiology*, 10(363): 1-16.

Hellard, P., Pla, R., Rodríguez, F., Simbana, D., & Pyne, D. (2018). Dynamics of the metabolic response during a competitive 100-m freestyle in elite male swimmers. *International Journal of Sports Physiology and Performance*, 13(10): 1011-1020.

Hermosilla, F., González-Ravé, J., Del Castillo, J., & Pyne, D. (2021). Periodization and programming for individual 400 m medley swimmers. *International Journal of Environmental Research and Public Health*, 18(12): 6474.

Hill, A., & Lupton, H. (1923). Muscular Exercise, Lactic Acid, and the Supply and Utilization of Oxygen. *International Journal of Medicine*, 16(62): 135-171.

Hill, D. (1993). The critical power concept. A review. . *Sports Medicine*, 16(4): 237-254.

Hopkins, W. (2015). *Spreadsheets for analysis of validity and reliability. Sportscience 19, 36-42*. Retrieved from Sportscience: sportsci.org/2015/ValidRely.htm

Hopkins, W., Marshall, S., Batterham, A., & Hanin, J. (2009). Progressive Statistics for Studies in Sports Medicine and Exercise Science. *Medicine & Science in Sports & Exercise*, 41(1): 3-12.

Hurd, K., Surges, M., & Farell, J. (2022). Use of Exercise Training to Enhance the Power-Duration Curve: A Systematic Review. *Journal of Strength and Conditioning Research*, XX(X): 000-000.

Issurin, V. (2008). Block periodization versus traditional training theory: a review. *Journal of Sports Medicine and Physical Fitness*, 48(1): 65-75.

Jones, A., & Vanhatalo, A. (2017). The 'Critical Power' Concept: Applications to Sports Performance with a Focus on Intermittent High-Intensity Exercise. *Sports Medicine*, 47(1): S65-S78.

Jorgić, B., Puletić, M., Okičić, T., & Meškovska, N. (2011). Importance of Maximal Oxygen Consumption During Swimming. *Physical Education and Sport*, 9(2): 183-191.

Kao, S., Ishida, A., & Ainsworth, B. (2018). The Correlation Between Strength and Power Measures with Sprint Freestyle Performance in Division 1 Collegiate Swimmers. *Journal of Swimming Research*, 26(1): 22-31.

Karsten, B., Stevens, L., Colpus, M., Larumbe-Zabala, E., & Naclerio, F. (2014). The Effects of Sport-Specific Maximal Strength and Conditioning Training on Critical Velocity, Anaerobic Running Distance, and 5-km Race Performance. *International Journal of Sports Physiology and Performance*, 11(1): 80-85.

Keiner, M., Wirth, K., Fuhrmann, S., Kunz, M., Hartmann, H., & Haff, G. (2019). The Influence of Upper- and Lower-Body Maximum Strength on Swim Block Start, Turn, and Overall Swim Performance in Sprint Swimming. *Journal of Strength and Conditioning Research*, 35(10): 2839-2845.

Koo, T., & Li, M. (2016). A Guideline of Selecting and Reporting Intraclass Correlation Coefficients for Reliability Research. *Journal of Chiropractic Medicine*, 15: 155-163.

Latt, E., Jurimae, J., Maestu, J., Purge, P., Ramson, R., Haljaste, K., . . . Jurimae, T. (2010). Physiological, biomechanical, and anthropometrical predictors of sprint swimming performance in adolescent swimmers. *Journal of Sport Sciences and Medicine*, 9(1): 398-404.

Lavoie, J., Lèger, L., Leone, M., & Provencher, P. (1985). A Maximal Multistage Swim Test to Determine the Functional and Maximal Aerobic Power of Competitive Swimmers. *Journal of Swimming Research*, 1(2): 17-22.

Leblanc, H., Seifert, L., Tourny-Chollet, C., & Chollet, D. (2007). Intra-cyclic Distance per Stroke Phase, Velocity Fluctuations and Acceleration Time Ratio of a Breastroker's Hip: A Comparison between Elite and Nonelite Swimmers at Different Race Paces. *International Journal of Sports Medicine*, 28(2): 140-147.

Libicz, S., Roels, B., & Millet, G. (2005). VO2 Responses to Intermittent Swimming Sets at Velocity Associated to VO2max. *Canadian Journal of Applied Physiology*, 30(5): 543-553.

Lopes, T., Goncalves, C., Graca, C., Neiva, H., & Marinho, D. (2019). The Relationship between Front Crawl Swimming Performance and Strength Variables in College Swimmers. *Ergonomics International Journal*, 3(2): 1-9.

Machado, M., Borges, J., Galdino, I., Cunha, L., Souza-Sá Filho, A., Soares, D., & Junior, I. (2018). Does critical velocity represent the maximal lactate steady state in youth swimmers? *Science & Sport*, 34(3): 1-7.

Magel, J., & Faulkner, J. (1967). Maximum oxygen uptakes of college swimmers. *Journal of Applied Physiology*, 22(5): 929-938.

Mann, B., Ivey, P., Brechue, W., & Mayhew, J. (2015). Validity and Reliability of Hand and Electronic Timing for 40-yd Sprint in College Football Players. *Journal of Strength and Conditioning Research*, 29(6): 1509-1514.

Marinho, D., Amorim, R., Costa, A., Marques, M., Pérez-Turpin, J., & Neiva, H. (2011). "Anaerobic" critical velocity and swimming performance in young swimmers. *Journal of Human Sport and Exercise*, 6(1): 80-86.

Marinho, D., Barbosa, T., Silva, A., & Neiva, H. (2012). Applying Anaerobic Critical Velocity in Non-Elite Swimmers. *International Journal of Swimming Kinetics*, 1(1): 33-50.

Mattioni-Maturana, F., Fontana, F., Pogliaghi, S., Passfield, L., & Murias, J. (2018). Critical power: How different protocols and models affect its determination. *Journal of Science and Medicine in Sport*, 21(7): 742-747.

McArdle, W., Katch, F., & Katch, V. (2015). *Exercise Physiology: Nutrition, Energy, and Human Performance.* Baltimore, MD: Wolters-Kluwers.

Mitchell, L., Pyne, D., Saunders, P., & Rattray, B. (2017). Reliability and validity of a modified 3-minute all-out swimming test in elite swimmers. *European Journal of Sports Science,* 18(3): 307-314.

Mitchell, L., Pyne, D., Saunders, P., & Rattray, B. (2017). Reliability and validity of a modified 3-minute all-out swimming test in elite swimmers. *European Journal of Sports Science,* 18(3): 307-314.

Miura, A., Endo, M., Sato, H., Sato, H., Barstow, T., & Fukuba, Y. (2002). Relationship between the curvature constant parameter of the power-duration curve and muscle cross-sectional area of the thigh for cycle ergometry in humans. *European Journal of Applied Physiology*, 87(3): 238-244.

Monod, H., & Scherrer, J. (1965). The work capacity of a synergic muscular group. *Ergonomics*, 8: 329-338.

Montpetit, R., Léger, L., Lavoie, J., & Cazorla, G. (1981). V̇02 Peak During Free Swimming Using the Backward Extrapolation of the O2 Recovery Curve. *European Journal of Applied Physiology*, 47(4): 385-391.

Morán-Navarro, R., Pérez, C., Mora-Rodríguez, R., de la Cruz-Sánchez, E., González-Badillo, J., Sánchez-Medina, L., & Pallarés, J. (2017). Time course of recovery following resistance training leading or not to failure. . *European Journal of Applied Physiology*, 117(12): 2387-2399.

Moritani, T., Nagata, A., DeVries, H., & Muro, M. (1981). Critical power as measure of physical work capacity and anaerobic threshold. *Ergonomics*, 24(5): 339-350.

Morouco, P., Marinho, D., Keskinen, K., Badillo, J., & Marques, M. (2014). Thethered Swimming Can Be Used to Evaluate Force Contribution for Short-Distance Swimming Performance. *Journal of Strength and Conditioning Research*, 28(11): 3093-3099.

Mougios, V. (2006). *Exercise Biochemistry.* Champaign, Ill. : Human Kinetics.

Mougios, V. (2006). *Exercise Biochemistry.* Champaign, Ill.: Human Kinetics.

Mujika, I., & Crowley, E. (2019). Strength Training for Swimmers. In M. Schumann, & B. Ronnestad, *Concurrent Aerobic and Strength Training: Scientific Basics and Practical Applications* (pp. 369-386). Switzerland: Springer International Publishing AG.

Neiva, H., Fernandes, R., & Vilas-Boas, J. (2010). Anaerobic Critical Velocity in Four Swimming Techniques. *International Journal of Sports Medicine*, 32(1): 195-198.

Neiva, H., Fernandes, R., & Vilas-Boas, J. (2011). Anaerobic Critical Velocity in Four Swimming Techniques. *International Journal of Sports Medicine*, 32: 195-198.

Nevill, A., Negra, Y., Myers, T., Sammoud, S., & Chaabene, H. (2020). Key somatic variables associated with, and differences between the 4 swimming strokes. *Journal of Sports Sciences*, 38(7): 787-794.

Noakes, T. (2008a). How did AV Hill understand the V̇O2max and the "plateau phenomenon"? Still no clarity? *British Journal of Sports Medicine*, 42: 574-580.

Noakes, T. (2008b). Testing for maximum oxygen consumption has produced a brainless mode of human exercise performance. *British Journal of Sports Medicine*, 42(7): 551-555.

Noordhof, D., Koning, J., & Foster, C. (2010). The Maximal Accumulated Oxygen Deficit Method. *Sports Medicine*, 40(4): 285-302.

Norouzi, M., Cabuk, R., Balki, G., As, H., & Ozkaya, O. (2021). The Effect of Using Different Exhaustion Intervals and Mathematical Models on Critical Power Estimations. *Hacettepe Journal of Sports Sciences*, 32(3): 151-166.

Nugent, F., Comyns, T., Kearney, P., & Warrington, G. (2019). Ultra-Short Race-Pace Training (USRPT) In Swimming: Current Perspectives. *Open Access Journal of Sports Medicine*, 10(1): 133-144.

Ogita, F. (2006). Energetics in competitive swimming and its applications for training. . *International Symposium on Biomechanics and Medicine in Swimming* (pp. 6(2): 117-121). Porto Faculdade de Desporto da Universidade do Porto.

Olbrecht, J. (2013). *The Science of Winning: Planning, Periodizing and Optimizing Swim Training.* Antwerp, Belgium: F&G Partners.

Painter, K., Haff, G., Ramsey, M., McBride, J., Triplett, T., Sands, W., . . . Stone, M. (2012). Strength gains: block versus daily undulating periodization weight training among track and field athletes. *International Journal of Sports Physiology and Performance*, 7(2): 161-169.

Painter, K., Rodriguez-Castellano, L., & Stone, M. (2020). High Volume Resistance Training and its Effects on Anaerobic Work Capacity Over Time: A Review. *The Sport Journal*, 3(1): 1-17.

Palao, J., & Valdés, D. (2013). Testing protocol for monitoring upper-body strength using medicine balls. *Journal of Human Sport & Exercise*, 8(2): 334-341.

Papoti, M., da Silva, A., Araujo, G., Santiago, V., Martins, L., Cunha, C., & Gobatto, C. (2013). Aerobic and Anaerobic Performances in Tethered Swimming. *International Journal of Sports Medicine*, 34: 712-719.

Papoti, M., da Silva, A., Araujo, G., Santiago, V., Martins, L., Cunha, S., & Gobatto, C. (2011). Aerobic and Anaerobic Performances in Tethered Swimming. *International Journal of Sports Medicine*, 34(8): 712-719.

Pareja-Blanco, F., Rodríguez-Rosell, D., Aagaard, P., Sánchesz-Medina, L., Ribas-Serna, J., Mora-Custodio, R., . . . González-Badillo, J. (2020). Time Course of Recovery From Resistance Exercise With Different Set Configurations. *Journal of Strength and Conditioning Research*, 34(10): 2867-2876.

Pelayo, P., & Alberty, M. (2011). The History of Swimming Research. In L. Seifert, D. Chollet, & I. Mujika, *World Book of Swimming: From Science to Performance* (pp. ix - xxvi). Hauppauge, New York: Nova Science Publishers, Inc.

Pettitt, R. (2016). Applying the Critical Speed Concept to Racing Strategy and Interval Training Prescription. *International Journal for Sports Physiology and Performance*, 11(7): 842-847.

Pettitt, R., Jamnick, N., & Clark, E. (2012). 3-min All-out Exercise Test for Running. *International Journal of Sports Medicine*, 33: 426-431.

Piatrikova, E., Sousa, A., Gonzalez, J., & Williams, S. (2019). Validity and reliability of the 3-minute all-out test in national and international competitive swimmers. *International Journal of Sports Physiology and Performance*, 13(9): 1190-1198.

Piatrikova, E., Sousa, A., Willsmer, N., Gonzalez, J., & Williams, S. (2018). Demarcating exercise intensity domains in freestyle swimming: is there and alternative to incremental step test and beats below HRmax method? . *Journal of Strength and Conditioning Research*, 34(9): 2575-2584.

Piatrikova, E., Willsmer, N., Altini, M., Mladen, J., Lachlan, M., Gonzalez, J., . . . Williams, S. (2021). Monitoring the heart rate variability responses to training loads in competitive swimmers using a smartphone application and the Banister Impulse-Response model. *International Journal of Sports Physiology and Performance*, 16(6):787-795.

Piatrikova, E., Willsmer, N., Sousa, A., Gonzalez, J., & S, W. (2020). Individualizing training in swimming; is there a place for the application of the critical speed and critical stroke rate concepts? *International Journal of Sports Physiology and Performance*, 15(5): 1-8.

Pla, R., Leroy, A., Massal, R., Bellami, M., Kaillani, F., Hellard, P., . . . Sedeaud, A. (2019). Bayesian approach to quantify morphological impact on performance in international elite freestyle swimming. *BMJ Open Sport & Exercise Medicine*, 5: 1-7.

Poole, D., & Jones, A. (2012). Oxygen Uptake Kinetics. *Comprehensive Physiology*, 2(2): 933-996.

Poole, D., Burnley, M., Vanhatalo, H., Rossiter, B., & Jones, A. (2016). Critical Power: An Important Fatigue Threshold in Exercise Physiology. *Medicine and Science in Sports and Exercise*, 48(11): 2320-2334.

Poole, D., Rossiter, H., Brooks, G., & Gladden, L. (2021). The Anaerobic Threshold: 50+ Years of Controversy. *The Journal of Physiology*, 599(3): 737-767.

Pyne, D., Maw, G., & Goldsmith, W. (2000). Protocols for the Physiological Assessment of Swimmers. In A. S. Commission, *Physiological Tests for Elite Athletes* (pp. 372-382). Champaign, Ill: Human Kinetics.

Ramos, R., Requena, B., Suarez-Arrones, L., Newton, R., & Sáez de Villareal, E. (2014). Effects of 18-Week In-Season Heavy-Resistance and Power Training on Throwing Velocity, Strength, Jumping, and Maximal Sprint Swim Performance of Elite Male Water Polo Players. *Journal of Strength and Conditioning Research*, 28(4): 1007-1014.

Ramos-Veliz, R., Requena, B., Suarez-Arrones, L., Newton, R., & Sáez de Villareal, E. (2014). Effects of 18-week in-season heavy resistance and power training on throwing velocity, strength, jumping, and maximal sprint swim performance of elite male water polo players. *Journal of Strength and Conditioning Research*, 28(4): 1007-1014.

Raymond, D. (2012). The effect of aerobic fitness on the cardiovascular and sympathetic nervous system response to physiological stress at rest and during dynamic exercise. *Thesis*.

Reis, V., Marinho, D., Barbosa, F., Reis, A., Guidetti, L., & Silva, A. (2010b). Examining the Accumulated Oxygen Deficit Method in Breaststroke Swimming. *European Journal of Applied Physiology*, 109(6): 1129-1135.

Reis, V., Marinho, D., Policarpo, F., Carneiro, A., Baldari, C., & Silva, A. (2010a). Examining the Accumulated Oxygen Deficit Method in Front Crawl Swimming. *International Journal of Sports Medicine*, 31(6): 421-427.

Rodríguez, F., & Mader, A. (2011). Energy Systems in Swimming. In L. Seifert, D. Chollet, & I. Mujika, *World Book of Swimming: From Science to Performance* (pp. 225-240). New York: Nova Science.

Rodríguez, F., Keskinen, K., Keskinen, O., & Malvela, M. (2003). Oxygen uptake kinetics during free swimming: a pilot study. *In: Chartard, JC, Biomechanics and Medicine in Swimming IX*, 379-384.

Rushall, B. (2016, March 14). *USRPT Defined: After Two Years USRPT Comes of Age.* Retrieved from Swimming Science Bulletin #49: https://coachsci.sdsu.edu/swim/bullets/49DEFINED.pdf

Saltin, B., & Astrand, P. (1967). Maximal oxygen uptake in athletes. *Journal of Applied Physiology*, 23(3): 353-358.

Sandford, G., & Stellingwerff, T. (2019). "Questioning Your Categories": the Misunderstood Complexity of Middle-Distance Running Profiles With Implications for Research Methods and Application. *Frontiers in Sports and Active Living*, 1(28): 1-8.

Sandford, G., Kilding, A., Ross, A., & Luarsen, P. (2018). Maximal Sprint Speed and the Anaerobic Speed Reserve Domain: The Untapped Tools that Differentiate the World's Best 800 m Runners. *Sports Medicine*, 49(6): 843-852.

Sanford, G., Laursen, P., & Buchheit, M. (2021). Anaerobic Speed/Power Reserve and Sport Performance: Scientific Basis, Current Applications and Future Directions. *Sports Medicine*, 51(10): 2017-2028.

Sanford, G., Laursen, P., & Buchheit, M. (2021). Anaerobic Speed/Power Reserve and Sport Performance: Scientific Basis, Current Applications and Future Directions. . *Sports Medicine*, 51(10): 2017-2028.

Sawyer, B., Stokes, D., Womack, C., Hugh, M., Weltman, A., & Gaesser, G. (2014). Strength Training Increases Endurance Time to Exhaustion During High-Intensity Exercise Despite No Change in Critical Power. *Journal of Strength and Conditioning Research*, 28(3): 601-609.

Scott, B., Burden, R., & Dekerle, J. (2020). Critical speed, D' and pacing in swimming: reliability of a popular critical speed protocol applied to all four strokes. *Research Square*, 10.21203/rs.3.rs-77508/v1.

Shiyoyama, Y., Okita, K., Baba, Y., & Sato, D. (2010). Does the Y-Intercept of a Regression Line in the Critical Velocity Concept Represent the Index for Evaluating Anaerobic Capacity? *Biomechanics and Medicine in Swimming XI* (pp. 288-290). Oslo: Nordbergtrykk as.

Siders, W., Lukaski, H., & Bolonchuk, W. (1993). Relationship among swimming performance, body composition and somatotype in competitive collegiate swimmers. *Journal of Sports Medicine and Physical Fitness*, 33(2): 166-171.

Smith, D., Norris, S., & Hogg, J. (2002). Performance Evaluation of Swimmers: Scientific Tools. *Sports Medicine*, 32(9): 539-554.

Sousa, A., Figueiredo, P., Pendergast, D., Kjendlie, P., Vilas-Boas, J., & Fernandes, R. (2014). Critical Evaluation of Oxygen-Uptake Assessment in Swimming. *International Journal of Sports Physiology and Performance*, 9(2): 190-202.

Stone, M., Hornsby, W., Haff, G., Fry, A., Suárez, D., Liu, J., . . . Pierce, K. (2021). Periodization and Block Periodization in Sports: Emphasis on Strength-Power Training-

A Provocative and Challenging Narrative. *Journal of Strength and Conditioning Research*, 35(8): 2351-2371.

Stone, M., Stone, M., & Sands, W. (2007). *Principles and Practices of Resistance Training.* Champaign, Ill.: Human Kinetics.

Strzala, M., Stanula, A., Krezalek, P., Ostrowski, A., Kaca, M., & Glab, G. (2019). Influence of Morphology and Strength on Front Crawl Swimming Speed in Junior and Youth Age-Group Swimmers. *Journal of Strength and Conditioning Research*, 33(10): 2836-2845.

Toubekis, A., Gourgoulis, V., & Tokmakidis, S. (2010). Tethered Swimming as an Evaluation Tool of Single Arm-Stroke Force. *XIth International Symposium for Biomechanics and Medicine in Swimming.* Oslo, Norway: Norwegian School of Sports Sciences .

Toussaint, H. (2002). Biomechanics of Propulsion and Drag in Front Crawl Swimming. *Applied proceedings - XXth International Symposium on Biomechanics in Sports. University of Extremadura*, (pp. 11-22). Caceres, Spain.

Toussaint, H., & Beek, P. (1992). Biomechanics of Competitive Front Crawl Swimming. *Sports Medicine*, 13(1): 8-24.

Toussaint, H., Beelen, A., Rodenburg, A., Sargeant, A., de Groot, G., Hollander, A., & van Ingen Schenau, G. (1988). Propelling efficiency of front-crawl swimming. *Journal of Applied Physiology*, 65(6): 2506-2512.

Tsai, M., & Thomas, S. (2017). 3-Min All-Out in Swimming. . *International Journal of Sports Physiology and Performance*, 12(1): 1-17.

Tsunokawa, T., Kadi, T., Mankyu, H., & Ogita, F. (2019). Estimation of hand propulsion forces at four swimming techniques using pressure measurement and underwater motion capture. *24th Annual Congress of the European College of Sport Science* (p. Abstract). Prague, Czech Republic: European College of Sports Science.

Vanhatalo, A., & Jones, A. (2009). Influence of prior sprint exercise on the parameters of the 'all-out critical power test' in men. *Experimental Physiology*, 94(2): 255-263.

Vanhatalo, A., Black, M., DiMenna, F., Blackwell, J., Schmidt, J., Thompson, C., . . . Jones, A. (2016). The mechanistic bases of the power-time relationship: muscle metabolic responses and relationship to muscle fiber type. *Journal of Physiology*, 594(15): 4407-4423.

Vanhatalo, A., Doust, J., & Burnley, M. (2007). Determination of Critical Power Using a 3-min All-out Cycling Test. *Medicine and Science in Sports and Exercise*, 39(3): 548-555.

Vanhatalo, A., Fulford, J., DiMenna, F., & Jones, A. (2010). Influence of hyperoxia on muscle metabolic responses and the power-duration relationship during severe-intensity exercise in humans: a 31P magnetic resonance spectroscopy study. *Experimental Physiology,* 95(4): 528-540.

Vucetic, V., Mozek, M., & Rakovac, M. (2015). Peak Blood Lactate Parameters in Athletes of Different Running Events During Low-Intensity Recovery After Ramp-Type Protocol. *Journal of Strength and Conditioning Research*, 29(4): 1057-1063.

Wakayoshi, K., Ikuta, K., Yoshida, T., Udo, M., Moritani, T., Mutoh, Y., & Miyashita, M. (1992). Determination and validity of critical velocity as an index of swimming performance in the competitive swimmer. . *European Journal of Physiology and Occupational Physiology*, 64(2): 153-157.

Wakayoshi, K., Yoshida, T., Udo, M., Harada, T., Moritani, T., Mutoh, Y., & Miyashita, M. (1993). Does critical swimming velocity represent exercise intensity at maximal lactate steady state? *European Journal of Applied Physiology and Ocuppational Physiology*, 66(1): 90-95.

Walsh, M., & Bannister, E. (1988). Possible Mechanisms of the Anaerobic Threshold. *Sports Medicine*, 5(5): 269-302.

Wasserman, K., Whipp, B., Koyal, S., & Beaver, W. (1973). Anaerobic threshold and respiratory gas exchange during exercise. *Journal of Applied Physiology*, 35(2): 236-243.

Yarar, H., Barug, D., Bostan, A., Kaya, A., & Aydin, E. (2021). Influence of Physical Anthropometric Properties on Sprint Swimming Performance. *Pakistan Journal of Medical & Health Sciences*, 15(2): 814-818.

Zacca, R., & Castro, F. (2010). Critical Swimming Speed Obtained by the 200-400 Meters Model in Young Swimmers. *Biomechanics and Medicine in Swimming XI* (pp. 307-309). Oslo, Norway: Norwegian School of Sport Sciences.

Zacca, R., & Castro, F. (2010). Critical Swimming Speed Obtained by the 200-400 Meters Model in Young Swimmers. *Biomechanics and Medicine in Swimming XI* (pp. 307-309). Oslo: Norwegian School of Sports Science.

Zacca, R., Azevedo, R., Chainok, P., Vilas-Boas, J., Castro, F., Pyne, D., & Fernandes, R. (2020). Monitoring Ag-Group Swimmers Over a Training Macrocycle: Energetics, Technique, and Anthropometrics. *Journal of Strength and Conditioning Research*, 34(3): 818-827.

Zacca, R., Azevedo, R., Peterson-Silveira, R., Vilas-Boas, J., Pyne, D., Castro, F., & Fernandes, R. (2019). Comparison of Incremental Intermittent and Time Trial Testing in Age-Group Swimmers. *Journal of Strength and Conditioning Research*, 33(3): 801-810.

Zacca, R., Fernandes, R., Pyne, D., & de S Castro, F. (2016). Swimming Training Assessment: The Critical Velocity and the 400-m Test for Age-Group Swimmers. *Journal of Strength and Conditioning Research*, 30(5): 1365-1372.

Zarzeczny, R., Kuberski, M., Deska, A., Zarzeczna, D., & Rydz, K. (2013). The Evaluation of Critical Swimming Speed in 12-Year-Old Boys. *Human Movement*, 14(1): 35-40.

Chapter 4. The Relationship and Seasonal Changes Between Body Anthropometrics, Upper Body Explosive Power, Swimming Performance During a Three-Minute All-Out Swimming Test

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Introduction

Collegiate swimming involves a wide variety of events (38 total; 19 per sex), each requiring a unique blend of biomechanical and physiological traits coupled with specific individual strategies that enable performance success (Mauger et al., 2012). These events could range in duration from about 18 s (i.e., 45.7 m freestyle) in elite level males to about 16 minutes (i.e., 1509 m freestyle) in elite level females (± 95% of WR). Nonetheless, over 81% of these events are swum in ≤ 5 minutes.

Interestingly, body anthropometrics have shown to be related to sprint freestyle swimming performance in young (Peters et al., 2014), college aged (Yarar et al., 2021), and international level athletes (Pla et al., 2019). In the latter study, distance swimmers showed lower body mass than sprinters evidencing the importance of a larger muscle mass for the latter athlete to produce higher propulsive forces to counteract the increasing drag forces when moving through water at higher speeds (Toussaint, 2002). This observation suggests an important role for strength and power in swimmers, which has been supported by the literature (Lopes et al., 2019; Mujika & Crowley, 2019). In addition to this, energy system contribution varies on event duration and intensity. Higher anaerobic energy provision is required for shorter races (45.7 & 91.4 m), with increasing importance of aerobic capacity in events ≥ 200 m (Rodríguez & Mader, 2011). Some argue that high aerobic fitness can still modulate optimal performance for events as short as the 100 m in swimming (Hellard, 2018).

One method that has been shown to improve the prescription for high-intensity interval training (HIIT) is the critical speed method which considers the asymptote of the hyperbolic power/speed-time relationship and the curvature constant of maximal effort exercise (Monod & Scherrer, 1965). The critical speed (CS) has been purported to function as a "fatigue threshold" delineating sustainable and unsustainable exercise (Poole et al., 2016) separating the heavy and severe intensity domains (Burnley & Jones, 2007). Moreover, some researchers have also mentioned that body anthropometrics can help in predicting CS (Aksit et al., 2017). The three-minute all-out swimming test (3MT) has been validated and shown to be a reliable protocol for determining CS and D' (Piatrikova et al., 2018; Tsai & Thomas, 2017). The CS can be obtained as the average pace of the final two completed laps at the end of the 3MT. Maximal sprinting speed can be measured as the average speed of the first lap that the athlete completes in a 3MT. Other useful variables can be calculated to assess individual athletic performance profiles such as fatigue index percentage (FI) (Mitchell et al., 2017) and the anaerobic speed reserve (ASR) (Dalamitros et al., 2015; Sandford et al., 2018; Sandford & Stellingwerff, 2019; Sanford et al., 2021).

While the 3MT has been used to monitor swimming performance and to individualize HIIT prescription throughout a competitive season (Courtwright et al., 2016; Piatrikova et al., 2020), to the author's knowledge no study has assessed the relationships of body anthropometrics, upper body power and performance variables derived from a 3MT. Understanding these relationships could aid in the talent identification process of athletes and possibly help in predicting individual performances. For the first purpose of this study, we explored the relationships between body anthropometrics, medicine ball pulldown throws performance (MBT), and the resulting variables from the 3MT. For the second purpose, pre- and post-season changes for anthropometrics and MBT performance will be evaluated along with the assessment of the repeated 3MT tests throughout a concurrent swimming and resistance training program. Furthermore, the seasonal changes of the relationships from pre- to post-season will be analyzed.

Methods

Athletes

Athletes who were apparently healthy (according to preseason sports medicine screening) and that completed all testing procedures with proper execution were included. Data from a total of 28 athletes (n = 18; males = 12 & females = 6, performance level = 79.9 ± 3.73% [ranging from 71.3% - 85.3%] of world record) were collected during five different testing periods during pre-season (body anthropometrics & MBT), in-season, and post-season (3MT1 – 3MT4). All athletes were ≥18 years of age and were actively participating with a local National Athletics Intercollegiate Association (NAIA) swimming team.

Study Design

The present study was performed during the Fall semester of the swimming season after the summer break. Athletes were tested for body composition and medicine ball throw performance prior to beginning and after the mid-season meet (August – November). The 3MT was performed during practice times prior to the beginning of each resistance training block and at the end of the season except for the beginning of the tapering phase (Table 1). Body anthropometrics and medicine ball performance was performed prior to and after the whole training stage. Swim training was exclusively controlled by the head swimming coach using training zones prescribed based off Bavg test pace (traditional color zone method). Swimmers trained in the pool 6 days a week (3.4 ± 1.2 km per day) for which the first 3 weeks consisted of aerobic and general preparation work, followed by 9 weeks of a mix of aerobic, anaerobic and race pace work. Resistance training was performed 3 days a week (Table 1) using a push, pull and combined (push & pull) scheme (Table 2).

Table 4.1. Resistance Training Layout Including Anthropometric and Performance Tests.

	Week	Sets	Reps	Mon[a]	Tues[b]	Wed	Thur[c]	Fri
Pre-Season Tests	1					(BC, MB)		(3MT1)
Strength-Endurance	2	3	10	M	ML		VL	
	3	3	10	MH	M		L	
	4	3	10	H	MH		L	
Basic Strength 1	5	3	5	M(3MT2)	ML		VL	
	6	3	5	MH	M		L	
	7	3	5	H	MH		L	
Basic Strength 2	8	3	3	M(3MT3)	ML		VL	
	9	3	3	MH	M		L	
	10	3	3	H	MH		L	
Peaking/Taper	11	3	2	M	ML		VL	
	12	3	2	L	VL		VL	
Post-Season Tests	13			(BC, MB)	(3MT4)			

Note: a = push workout, b = pull workout, c = combination push/pull workout, BC = body composition and anthropometric testing, MB = medicine ball throw performance test, 3MT = three-minute all-out swimming tests (performed that day during the swimming session), VL = very light, L = light, ML = moderately light, M = moderate, MH = moderately heavy, H = heavy, VH = very heavy.

The study was performed during the beginning of the Fall semester of the swimming season after summer break. Prior to data collection, athletes signed a written informed consent approved by the University Institutional Review Board (IRB) in the spirit of the Helsinki Declaration, to store their data for further analysis. Data was collected as part of an on-going athlete monitoring program and was later stored in the East Tennessee State University Sports Science Research Repository (ETSU-SSRR). Due to the COVID-19 pandemic, which limited face to face contact, additional approval by the IRB was sought to use an online video conference call with all athletes. Athletes were explained about the details of how their data from the ETSU-SSRR was going to be used. After the conference call, each athlete was individually contacted to via cellphone to seek their verbal consent.

Body Anthropometrics

Anthropometric measurements, such as, height, wingspan, hand width, seated height, and foot length were taken only at the beginning of the season, while skinfolds and body mass were also performed at the end of the season one day before the 3MT. Skinfolds were taken using a Lange Skinfold Caliper (Seko, USA) by an ISAK Level 1 anthropometrist with at least 10 years of experience. Body mass measurements were collected using a digital scale (Health-o-meter Professional 498KL, Ill., USA) and was measured to the nearest 0.1 kilogram. Standing and sitting height, wingspan and hand width were measured to the nearest 0.1 centimeter using a measuring tape and a Health-o-meter Universal Wall Mounted Height Rod (MFI Medical, San Diego, CA).

Table 4.2. Resistance training blocks with exercises using a push (Monday), pull (Tuesday) and combination (Thursday) scheme.

Day	Block 1	Block 2	Block 3	Block 4
	Strength Endurance	**Basic Strength**	**Max Strength**	**Peaking/Taper**
Monday	BS DBOHP DBBP	BS PP FNP BP	BS PP SL	1/2SQ* DBJS*BJ PP*MBOHT
Tuesday	CP2K CGSS CGSLDL BOR	CPFK CGMTP CGSLDL CU	CGMTP CGSLDL PUP	PC*MBSUT SAPD*MBLPT
Thursday	BS CP2K DBOHP BOR	BS CPFK PP CU	BS CGMTP PP PUP	1/2SQ* DBJS*BJ PP*MBOHT

Note: BS = back squat, DBOHP = dumbell overhead press, DBBP = dumbell overhead press, CP2K = clean pull to knee, CGSS = clean grip shoulder shrugs, CGSLDL = clean grip stiff-legged deadlift, BOR = barbell overhand row, PP = push-press, FNP, front neck press, BP = bench press, CPFK = clean pull from the knee, CGMTP = clean grip mid-thigh pull, CU = chin up, SL = side lunge, PUP = pull ups, 1/2SQ* = 1 x3 set of half squat, DBJS*BJ = dumbell jump squat contrasted with box jumps, PP*MBOHT = push-press contrasted with medicine ball overhead throw, PC*MBSUT = power clean contrasted with medicine ball underhand throw, SAPD*MBLPT = straight-arm pull down contrasted with medicine ball pull down throw.

The Medicine Ball Pull-Down Throw Test

A dynamic 5-minute warm up was performed involving jumping jacks, arm circles, arm swings and submaximal throws. Athletes were instructed to align themselves on the mat with fingertips on the edge of the mat (0 m) when lying down, and to not lift their upper backs from the floor after throwing the medicine ball horizontally in relation to the floor similar in motion to the pulldown during the underwater breaststroke start. One warm-up throw was allowed prior to each load used (i.e., MBT_{low} = 2.7 kg, MBT_{med} = 4.6 kg, and MBT_{hi} = 6.8 kg). A concentric only motion was allowed without countermovement action before each throw (Palao & Valdés, 2013). The tester would place a cone at the point where the medicine ball first hit the ground marking the throw distance. The average of two throws was taken as the measurement and a third throw was allowed if the difference between throws was more than one meter.

The 3-minute All-out Swimming Test

Tests were held at regularly scheduled practices to comply with NAIA regulations. Athletes performed a mixed standardized 1,100 m warm-up as they performed prior to competition (Balilionis et al., 2012). Swimmers rested 10 minutes between warm-up and the swimming tests to recover from warm-up (Ferguson et al., 2010) and to reduce the negative effect on D’ (Vanhatalo & Jones, 2009). Swimmers were instructed to swim as fast as possible from the first whistle until they heard the second whistle signifying the end (180 s) and were strictly warned about not pacing themselves throughout the entire duration of the test. Strong verbal encouragement was given to ensure a maximum effort.

Video footage was captured using a digital video camera (CANON EOS 700D, Australia) at a sample rate of 30 FPS similar to other studies (Clark et al., 2013; Courtwright et al., 2016). The camera was set up at one end of the pool towards one corner at 2.0 m above the ground and all lane line markers were visible. Windows Media Player 12 (Windows 10 Microsoft 2021, Washington, USA) was used to analyze video footage for split times using a stopwatch (3X300 Memory Stopwatch, FINIS Australia) upon the athlete’s feet touching the wall after a flip turn (Tsai & Thomas, 2017).

Data Analysis & Statistics

A criterion was used to ensure all athletes performed the test with all-out maximal effort and if they did not meet the criteria, then that athlete’s 3MT data was discarded from analysis. The criterion was that if the average speed of the last two laps performed (CS; Equation 1) were faster than the combined average speed at 100 and 125 m, then that athlete's data would be flagged as it would be evidence of submaximal effort and acceleration towards the end of the 3MT. The distances of 100 and 125 m were selected because the athletes in our study averaged around 68 to 78 s for those distances during the 3MT, respectively. This is approximately where the aerobic energy pathway becomes the predominant energy source (Mougios, 2006), and if the athlete gave a maximal all-out effort, the evident time-dependent speed drop-off would have been caused by an accumulation of metabolic by-products resulting from anaerobic metabolism which would inhibit maximal muscle fiber recruitment for accelerations (Bundle & Weyand, 2012).

Maximum sprint speed was measured as the average speed of the first 25 m (Equation 2). To calculate the finite capacity of work available above CS (D') Equation 3 was used. The ASR was calculated using Equation 4.

Equation 1. CS ($m.s^{-1}$) = Distance of Last 2 Laps (50 m) /Time in Seconds to Complete Last 2 Laps

Equation 2. MSS ($m.s^{-1}$) = Lap Distance (25 m) /Time in seconds to complete 1st Lap

Equation 3. D' (m) = $\sum_i (SSi - \mathrm{CS})$

where, SS_i is each lap split speed.

Equation 4. ASR = MSS – CS

Statistical analysis was performed using JASP (Version 0.14.1). Two-way mixed effects intraclass correlation coefficients were used to measure the consistency between two trials of the MBT at each load and skinfold measurements during the pre- and post-season (3MT4) (Hopkins, 2015; Koo & Li, 2016). Pearson's correlation coefficient (on bivariate normally distributed data) and Spearman's ranked correlations (on bivariate non-normally distributed data) were used to assess the relationships between body anthropometrics, MBT, MSS, CS, D' and ASR collected from the 3MT during the pre-season and before winter break. Paired samples T-tests were used to assess the difference between MBT and body fat percentage at baseline (pre-season) and 3MT4 (post-season). Holm-Šidàk correction was used to control for familywise Type I error (Abdi, 2010). Three separate one-way analysis of variance (ANOVA) with repeated measures were performed to test the seasonal changes of MSS, CS and D'. The ICC's will be rated as poor, moderate, good, or excellent on the respective ICC values: less than 0.50, between 0.50 – 0.75, between 0.75 – 0.90, and greater than 0.90, respectively. The relationship between variables will be rated as trivial, small, moderate, large, very large, nearly perfect, or perfect based on the respective r values: 0.00-0.10, 0.10 - 0.30, 0.30 - 0.50, 0.50 - 0.70, 0.70 - 0.90, 0.90 - 1.00. Cohen's *d* effect size differences were also calculated and interpreted with magnitude thresholds of 0-0.20, 0.21-0.60, 0.61-1.20, 1.21-2.00 and 2.00 and above as trivial, small, moderate, large, and very large (Hopkins et al., 2009). The level of significance was set at $p \leq 0.05$. Data are reported as mean ± SD.

Results

From the initial selection pool of 28 athletes, six were excluded from correlation analysis involving pre- & post-tests of anthropometrics and MBT, as they did not meet the criteria to assure maximal all-out efforts during the 3MT (females = 3 & males = 3). Another athlete was eliminated from repeated measures ANOVA assessments involving 3MT analysis due to not completing the 3MT in all four testing periods (n = 1 female). Data from another athlete was discarded from all analyses involving pre- and post-testing due to health complications that arose towards the end of the season (n = 1 male). Sample sizes vary between analyses due to the issues previously mentioned.

Correlations for body anthropometrics and performance variables

Intraclass correlation coefficient for both the skinfold (ICC[3,1] = 0.997) and MBT (ICC[3,1] = 0.978) measurements showed excellent reliability during pre- and post-testing. Shapiro-Wilkes bivariate normality tests showed that some data violated normality assumptions for correlation analyses. Those that violated the assumptions were analyzed using Spearman's ranked correlation and are presented accordingly in Table 4.1. Despite slight improvements or diminishes, correlations did not significantly change from pre- to post-season when using published online calculations to test for the differences between pre- and post-season correlations, t(21) = -1.59 – 0.61, p = 0.08 – 0.60 (Steiger, 1980).

Table 4.3. Pairwise correlation table for body anthropometrics, medicine ball pulldown throw, and 3MT performance variables from pre- (3MT1) and post-testing (3MT4) (n = 21).

			Pre-season (3MT1)		**Post-season (3MT4)**	
Comparisons			**Pearson r**	**Spearman rho**	**Pearson r**	**Spearman rho**
Height	-	MSS	0.63 **			
Height	-	CS	0.43 *			
Height	-	D'	0.41			
Height	-	ASR	0.25			
Height	-	MBT_L		.61 **		
Height	-	MBT_M		.58 **		
Height	-	MBT_H		.55 **		
Sit Height	-	MSS	0.71 ***			
Sit Height	-	CS	0.37			
Sit Height	-	D'	0.53 **			
Sit Height	-	ASR	0.42			
Sit Height	-	MBT_L	.69 **			
Sit Height	-	MBT_M	.60 **			
Sit Height	-	MBT_H		.63 **		

Wingspan	-	MSS	0.70	***						
Wingspan	-	CS	0.54	*						
Wingspan	-	D'	0.37							
Wingspan	-	ASR	0.22							
Wingspan	-	MBT_L	.80	***						
Wingspan	-	MBT_M	.80	***						
Wingspan	-	MBT_H	.72	***						
HW	-	MSS	0.59	**						
HW	-	CS	0.47	*						
HW	-	D'	0.17							
HW	-	ASR	0.15							
HW	-	MBT_L			.63	**				
HW	-	MBT_M			.54	*				
HW	-	MBT_H			.51	*				
BM	-	MSS			0.42				0.44	*
BM	-	CS			0.10		0.14			
BM	-	D'	0.36						0.26	
BM	-	ASR	0.35						0.36	
BM	-	MBT_L			.73	***			.82	***
BM	-	MBT_M			.83	***			.78	***
BM	-	MBT_H			.82	***	.80	***		
BF%	-	MSS			-0.49	*	-0.73	***		
BF%	-	CS	-0.48	*			-0.50	*		
BF%	-	D'	-0.10				-0.49	*		
BF%	-	ASR	-0.04				-0.50	*		
FFM	-	MSS	0.59	**			0.71	***		
FFM	-	CS	0.30				0.38			
FFM	-	D'	0.41				0.41			
FFM	-	ASR	0.36						0.49	*
FFM	-	MBT_L	.91	***					.98	***
FFM	-	MBT_M			.94	***			.96	***
FFM	-	MBT_H			.89	***	.92	***		
MBT_L	-	MSS			0.66	**	0.68	***		
MBT_L	-	CS	0.24				0.42			
MBT_L	-	D'	0.42				0.28			
MBT_L	-	ASR	0.41						0.46	*
MBT_M	-	MSS			0.60	**			0.74	***
MBT_M	-	CS			0.26		0.37			
MBT_M	-	D'	0.35				0.31			
MBT_M	-	ASR			0.28		0.53	*		
MBT_H	-	MSS			0.66	**			0.74	***
MBT_H	-	CS			0.24				0.52	*
MBT_H	-	D'	0.45	*			0.30			
MBT_H	-	ASR	0.43	*					0.46	*
MSS	-	CS	0.63	**			0.73	***		
MSS	-	D'	0.62	**			0.50	*		

MSS	-	ASR	0.46	*	0.63	**		
CS	-	D'	-0.05		-0.13			
CS	-	ASR	-0.40		-0.07			
D'	-	ASR	0.79	***			0.91	***

* p < .05, ** p < .01, *** p < .001

Note: 3MT = three-minute all-out swimming test, HW = hand width, BM = body mass, BF% = body fat percentage, FFM = fat free mass, MBT_L = 2.7 kg medicine ball pulldown throw, MBT_M = 4.5 kg medicine ball pulldown throw, MBT_H = 6.8 kg medicine ball pulldown throw, MSS = maximum sprint speed, CS = critical speed, D' = distance capacity of available work above critical speed, ASR = anaerobic speed reserve.

Pre- and post-season comparisons

Pre- and post-season data for body composition and MBT performance variables are shown in Table 4.2. Shapiro-Wilkes normality tests showed that all pre- and post-season data interactions were normally distributed except for BM, $W = 0.86$, $p = 0.008$, for which Wilcoxon tests were used. A moderate increase was observed for FFM, $t(20) = -3.72$, $p = 0.008$, $d = -0.81$. This was accompanied by moderate decreases in BF%, $t(20) = 3.50$, $p = 0.011$, $d = 0.76$. Despite the body composition changes, no statistically significant changes for BM were observed ($p = 0.580$, $d = 0.14$). Moreover, the increase in FFM did not seem to amount to statistically significant changes in power produced during the MBT performances as they were trivial to small in effect size ($p = 0.078 – 0.642$, $d = -0.21 – -0.55$).

Table 4.4. Pre- and post-season changes for anthropometric measurements and medicine ball pulldown throws with 2.7 (MBT_L), 4.5 (MBT_M), and 6.8 kg (MBT_H) loads (n = 21).

Variable	**Pre-season**	**Post-season**	**Statistic**	**Holm-Šidàk correction**	**Effect Size (*d*)**
FFM*	56.02 ± 11.87	57.65 ± 11.87	-3.72	0.011	-0.81
BF%*	25.7 ± 9.08	22.73 ± 8.69	3.50	0.013	0.76
BM	75.73 ± 15.56	74.61 ± 13.43	132.00 ¥	0.58	0.14
MBT_L	6.07 ± 2.04	6.25 ± 1.81	-2.52	0.078	-0.55
MBT_M	4.16 ± 1.57	4.30 ± 1.35	-1.09	0.642	-0.24
MBT_H	2.69 ± 1.0	2.92 ± 1.01	-0.96	0.578	-0.21

*p <0.05; ¥ Wilcoxon test was used for analysis.

Note. For the Student t-test, effect size is given by Cohen's d. For the Wilcoxon test, effect size is given by the matched rank biserial correlation. Variables are ordered from smallest p-value according to the Holm-Šidàk correction protocol.

Seasonal changes for the 3MT performance variables

Mauchly's test of sphericity was violated for MSS ($p = 0.05$) and CS ($p < 0.001$), so Greenhouse-Geisser correction was used ($\varepsilon = 0.72$ & 0.63, respectively). Repeated measures ANOVA found no main effect interactions for MSS throughout the entire season, F = 41.29 [1.9, 31.9], $p = 0.08$, $\eta^2 = 0.14$ (Figure 4.1). However, there was a significant main effect for CS (F = 41.29 [1.9, 31.9], $p < 0.001$, $\eta^2 = 0.71$) and D' (F = 13.90 [3,51], $p < 0.001$, $\eta^2 = 0.45$)(Figure 4.2 and 4.3, respectively). Post-hoc analysis for CS revealed a large significant increase from 3MT1 to 3MT2, $t(1.9, 31.9) = -5.95$, $p < 0.001$, $d = -1.40$, with further large improvements from 3MT2 to 3MT3, $t(1.9, 31.9) = -3.57$, $p < 0.001$, $d = -0.84$, but no differences from 3MT3 to 3MT4, $t(1.9, 31.9) = -0.25$, $p = 1.00$, $d = -0.06$. However, D' only showed a significant decrease from 3MT1 to 3MT2, $t(3,51) = 3.93$, $p < 0.001$, $d = 0.93$, but no differences for subsequent consecutive trials, such as, 3MT2 to 3MT3, $t(3,51) = 1.70$, $p = 0.28$, $d = 0.40$, or 3MT3 to 3MT4, $t(3,51) = -0.08$, $p = 0.93$, $d = -0.02$. Post-hoc comparisons only showed a moderate decrease from 3MT1 to 3MT3, $t(3,51) = 5.63$, $p < 0.001$, $d = 1.33$ and which was also significantly different from 3MT1 to 3MT4, $t(3,51) = 5.55$, $p = 0.001$, $d = 1.31$. Table 4.3 contains the results of the seasonal changes of 3MT performance variables.

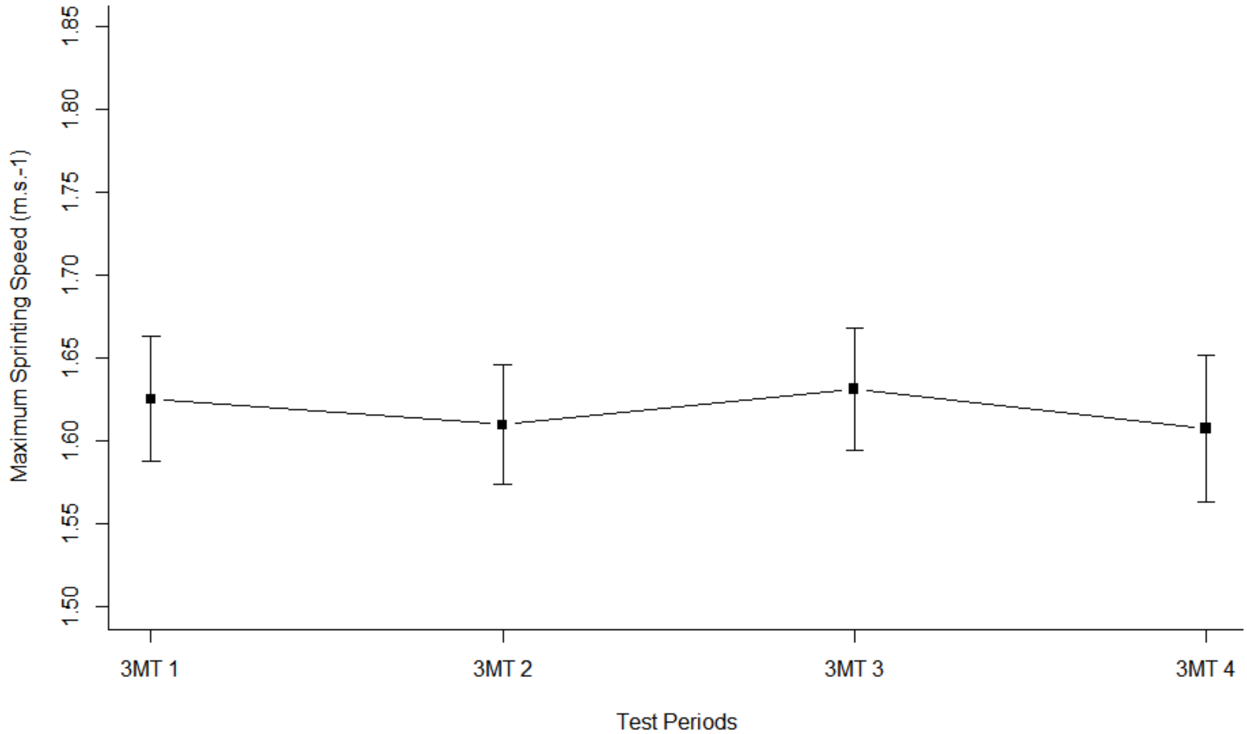

Figure 4.1. Seasonal changes for maximum sprinting speed during the 3MT.
Note: 3MT = three-minute all-out swimming test, 3MT1 = baseline performance testing period prior to strength-endurance block, 3MT2 = pre-basic strength block testing period, 3MT3 = pre-max strength block testing period, 3MT4 = post-season testing period.

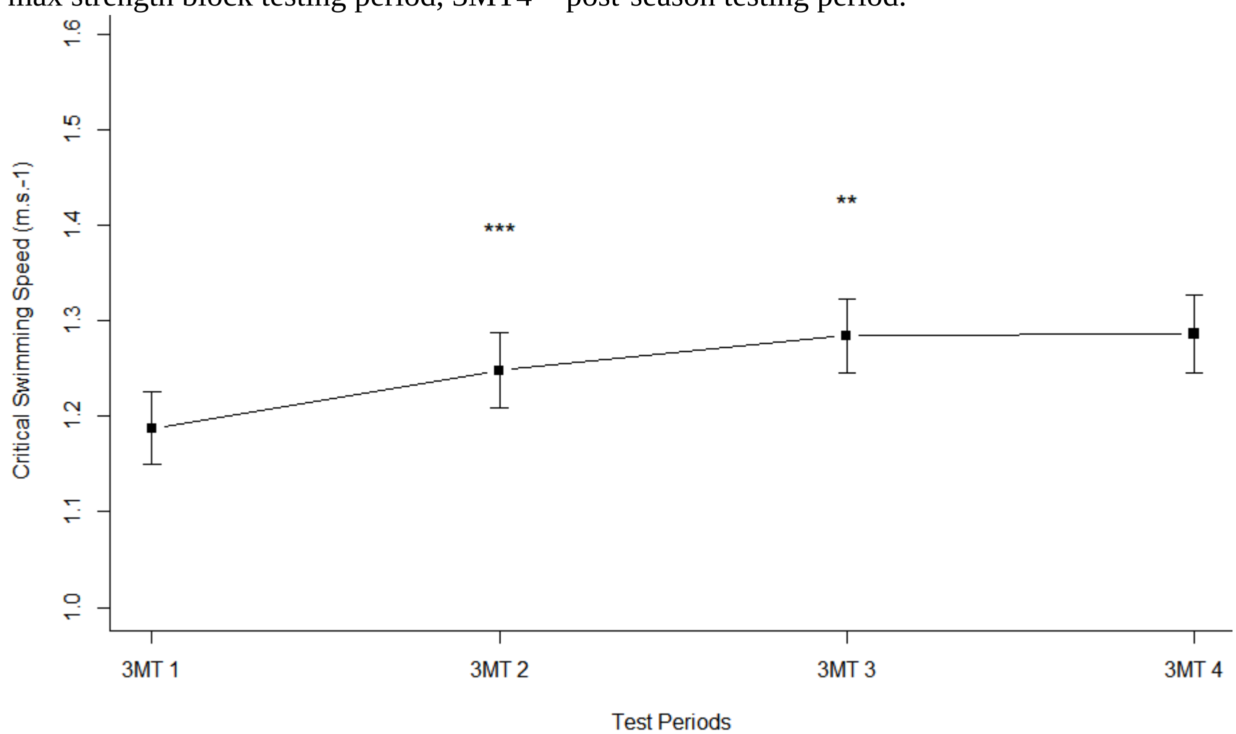

Figure 4.2. Seasonal changes for critical swimming speed during the 3MT.
$^{**}p < 0.01$, $^{***}p < 0.001$ when compared against previous testing period.

Note: 3MT = three-minute all-out swimming test, 3MT1 = baseline performance testing period prior to strength-endurance block, 3MT2 = pre-basic strength block testing period, 3MT3 = pre-max strength block testing period, 3MT4 = post-season testing period.

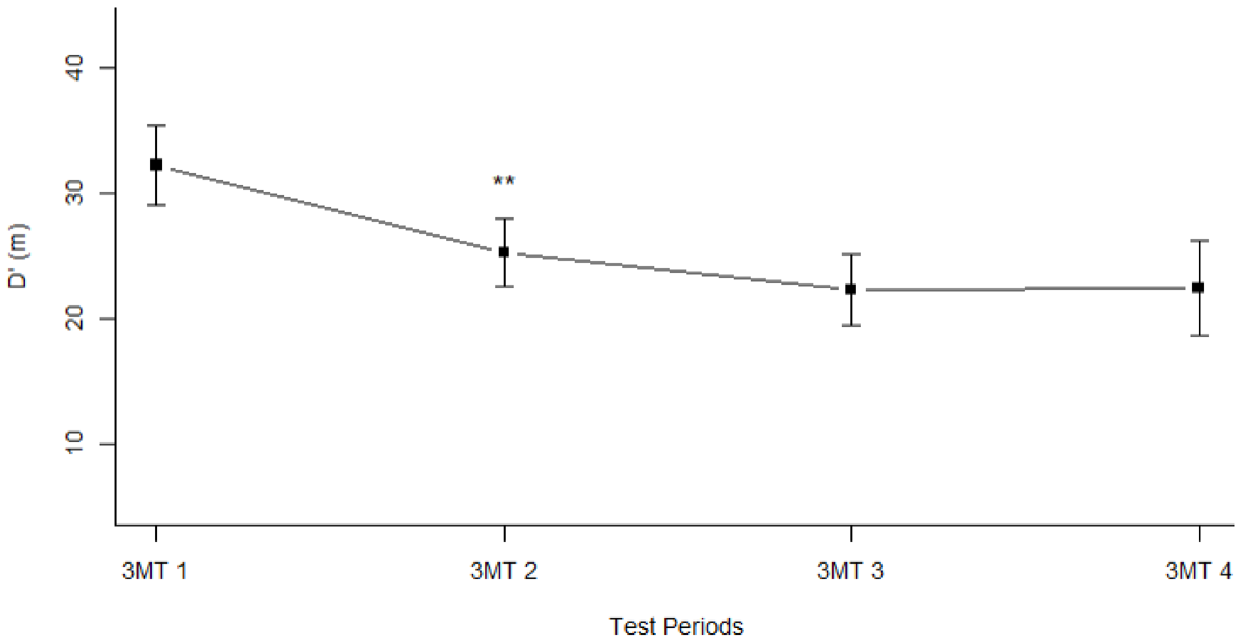

Figure 4.3. Seasonal changes for distance capacity above critical swimming speed during the 3MT.
*p < 0.05 when compared against previous testing period.
Note: 3MT = three-minute all-out swimming test, 3MT1 = baseline performance testing period prior to strength-endurance block, 3MT2 = pre-basic strength block testing period, 3MT3 = pre-max strength block testing period, 3MT4 = post-season testing period.

Table 4.5. Seasonal changes for 3MT variables assessed through one-way repeated measures ANOVA (n = 18).

Period	**MSS ($m.s^{-1}$)**	***F*(df)**	**CS ($m.s^{-1}$)**		***F*(df)**	**D' (m)**		***F*(df)**
3MT1	1.63 ± 0.09	2.68	1.19 ± 0.09		41.29	32.26 ± 7.87		13.90
3MT2	1.61 ± 0.09	(2.2,36.9)	1.25 ± 0.10	***	(1.9,31.9)	25.31 ± 6.62	**	(3,51)
3MT3	1.63 ± 0.09		1.28 ± 0.09	***¥		22.29 ± 6.83	***	
3MT4	1.61 ± 0.11		1.29 ± 0.10	*** ǂ		22.44 ± 9.38	***	

*p < 0.5, **p < 0.01, ***p < 0.001 when compared to baseline. ¥ = significant statistical difference when compared to 3MT2 p < 0.001, ǂ = significant statistical difference when compared to 3MT2 with p < 0.01.
Note: 3MT = three-minute all-out swimming test, 3MT1 = baseline performance testing period prior to strength-endurance block, 3MT2 = pre-basic strength block testing period, 3MT3 = pre-max strength block testing period, 3MT4 = post-season testing period, MSS = maximum sprint speed, CS = critical speed, D' = distance capacity performed above critical speed.

Table 4.6. Correlation table for pre- to post-season changes for body composition, medicine ball pulldown throws at low, medium, and high loads, and 3MT variables (n = 21).

			Pearson r		Spearman rho	
chBM	-	$chMBT_L$			0.55	*
chBF%	-	$chMBT_L$	0.46	*		
chFFM	-	$chMBT_M$	0.47	*		
chMSS	-	chD	0.48	*		
chMSS	-	chASR	0.72	***		
chCS	-	chASR	-0.50	*		
chD	-	chASR	0.73	***		

* $p < .05$, ** $p < .01$, *** $p < .001$
Note: chBM = change in body mass, $chMBT_L$ = change in low load medicine ball pulldown throw, $chMBT_M$ = change in medium load medicine ball pulldown throw, chBF% = change in body fat percentage, chFFM = change in fat free mass, chMSS = change in maximum sprinting speed, chCS = change in critical speed, chD' = change in D', chASR = change in anaerobic speed reserve, 3MT = three-minute all-out swimming test.

Discussion

To the author's knowledge, this was the first study to assess the relationships between body anthropometrics, MBT performance at low (MBT_L), medium (MBT_M), and high (MBT_H) loads, and the CS, D', and ASR variables derived from the 3MT in swimming. The primary findings of our study were that CS, D', and ASR significantly correlated with various anthropometric variables, and MBT at all loads during pre- and post-season. Many of these relationships were strengthened or weakened from pre- to post-season, but none of the changes were significantly different (Steiger, 1980). Significant increases in FFM ($d = -0.81$) with reductions of BF% ($d = 0.76$) were observed despite trivial changes in BM ($d = 0.14$). In a longitudinal study in elite swimmers, increases of 1.1% and 0.6% of lean mass index (males and females, respectively) were observed from pre-season to taper. Although we did not measure lean mass index in our data, we observed a moderate effect size total group increase of 2.9% in FFM with a moderate effect size change of -11.6% reduction of BF% from pre- to post-season. When splitting the group by sex this change amounted to a 2.5% and 3.3% increase in FFM coupled with a -6.8% and -18.0% decrease of BF% for females and males, respectively. These percent changes when compared to the study by Siders and associates (1993) in collegiate swimmers showed to have similar increases for FFM in females (+1.9%), but higher than their male subjects (+0.3%). Furthermore, our athletes exceeded their decreases in BF% as they only observed a -4.5% and -6.8% decrease for females and males, respectively. These improvements in body composition could be owed to the increased resistance training load performed during the season, however, it is important to note that many of our athletes could have experienced an increased activity load resulting from returning to normal activities after the COVID-19 lockdown mandates during the summer. Although the possibility of increased physical activity may have affected the athlete's body composition levels, these changes could have also been influenced by increases in strength and power evidenced by the small magnitude effect changes observed for the MBT at all loads ($d = -0.55 – -0.21$) albeit no statistical significance was attained. In particular, the pre- to post-season changes for low and medium loads in MBT correlated with pre- to post-season changes in BM and FFM, respectively (Table 4.4), which could indicate that strength and power gains were driven by increases in muscle mass induced by the resistance training protocol used throughout the season (Table 4.1 and 4.2). Nonetheless, a block periodization model, such as in Table 4.1 and 4.2, may help in improving body composition (Arroyo-Toledo et al., 2016).

Due to the novelty of our study using the 3MT, comparing our data to others seemed challenging. Nonetheless, height, HW, wingspan, sitting height, BM, BF%, FFM and other anthropometrical factors have all been shown to correlate across different swimming performance in different populations (Aksit et al., 2017; Latt et al., 2010; Pla et al., 2019; Strzala et al., 2019; Yarar et al., 2021). Yarar et al. (2021) found that height, length of arm, arm span, length of leg, and length of shank were associated to a 50 m swim trial, yet only length of arm was associated to the 100 m event. Aksit and others (2017) studied how anthropometric measurements were associated to CS and found that some skinfolds, limb lengths, linear morphology (i.e., ectomorph somatotype), as well as breadths and girths of different body parts correlated to CS. However, that study was performed in 12-year-old swimmers, and they used a two-trial method to calculate CS (i.e., 200 & 400 m all-out swims). Zacca and Castro (2010) explained how different multiple time-trial distance combinations may influence the calculated CS estimated in young swimmers (14 ± 0.5 years of age) and that the 200 m and 400 m all-out swim trial combinations may result in a higher trial error in this population. Furthermore, CS computed from the 200 m and 400 m swim trials were shown to not coincide with the MLSS in another study that assessed it through multiple 30-minute swim bouts at steady state (Espada & Alves, 2010). It seems that several factors such as the participant's maturity level, the tests protocols performed, and the inconsistencies with physiological threshold surrogate measures make comparisons of these data results to our study difficult.

Although no competitive performance trials were evaluated during the current study, swimmers with greater hand width, taller in height, and lankier bodies tended to have faster MSS, and CS while also significantly reaching farther in distance during the MBT at all loads (Table 4.3). It is expected that athletes that are taller and have larger frames will have greater BM and hence higher FFM. Larger body frames may be advantageous for higher MSS (Pla et al., 2019) and higher tethered swimming force (Strzala et al., 2019), possibly because of the biomechanical leverage and the capacity to pack more muscle, hence, producing more propulsive forces required to plow through the water at higher velocities (Toussaint & Beek, 1992). Observations within our data showed that those with higher FFM also had higher strength and power measured through distance of MBT at all loads (r = 0.89 – 0.98) during the pre- and post-season (Table 4.3). Taller athletes also have the physical advantage of reaching further distance from the wall after a flip turn compared to shorter athletes when aquadynamics and push-off forces are equal. Given that the 3MT involves many push-offs within the allotted 180 s time frame, these athletes can use their bodies throughout the test gaining advantage from the multiple ground reaction forces placed on the wall after each flip turn (Bishop et al., 2013; Toussaint & Beek, 1992).

Despite the advantages body anthropometrics may bring to swimming performance, it seems as this diminishes with age (Yarar et al., 2021). Yarar and others tested a group of males in the 50 m freestyle under race conditions (from the blocks) for which average times was 32.22 ± 2.51 s (± 63% of world record). Our sample included males and females who averaged 32.31 ± 2.19 s in the first 50 m of the 3MT1 (pre-season; males alone = 30.80 s) which was performed starting from inside the pool and pushing from the wall. It is possible that the subjects in the Yarar et al study did not produce the sufficient force to overcome such drag forces or were just not as efficient from a biomechanics standpoint. This could be evidenced by looking at their percentages of body fat (12.5 %) which were lower than our group of male subjects (18.7 %) and when considering that the BM for each group (75.3 and 81.9 kg, respectively), the FFM for both groups were relatively the same (65.9 and 65.4 kg, respectively). The only power and strength tests performed in the Yarar et al study were a countermovement jump (provided as power; 3778.7 ± 648.6) and back extension strength test (154.6 ± 22.23), respectively. It seemed that the athletes were sufficiently strong, yet still did not produce the sufficient power required to increase to higher speeds or possibly lacked efficient stroke mechanics. Given the very large to near perfect associations between FFM and MBT at all loads (MBT_L, MBT_M, MBT_H; r = .89

- .98) indicate that strength and power expressed through MBT was a significant contributor to performance since our athletes also had to carry extra body fat which in our data correlated negatively to MSS during pre- and post-season (r = -.49 and -.73, respectively) and CS (r = -.48 and .50, respectively).

To the authors knowledge, no study has evaluated the relationship of D' to body anthropometric variables in swimming. Interestingly in cycling, the cross-sectional area of the thigh has been shown to positively correlate with W' (r = .59), which is a derived parameter analogous to D' in swimming (Miura et al., 2002). Unfortunately, we did not conduct any cross-sectional area assessment in our study. However, D' negatively correlated to BF% at post-season (r = -.49). A negative correlation of D' to BF% could indicate that leaner athletes tend to have more distance capacity reserves throughout a 3MT, possibly due to not having to carry extra body fat which wastes energy and diminishes performance due to premature fatigue, hence, lowering the average speed at each lap (i.e., reducing the area under the power-time curve). Interestingly, FFM correlated to ASR during the post-season (r = .49), which was expected since MSS influences ASR (r = .46 & .63, for pre- and post-season, respectively). There were very large and near perfect correlations between D' and ASR (r = .79 - .91) which aligns with what Dalamitros et al. (2015) described as the speed reserve. However, in their study they used the average speed of a 50 m time trial as the upper boundary of the speed reserve and the average speed of a 400 m time trial as the bottom boundary. In our study, we decided to use the MSS derived as the average of the first 25 m at flip turn (equation 2) as the upper boundary and the CS as the lower boundary of the ASR. The reason for this goes in line with the detailed review by Burnley and Jones (2007) in which they describe the physiological characteristics of exercise at moderate (< LT; $\dot{V}O_2$ slow component and early steady state), heavy (> LT but < CS; $\dot{V}O_2$ slow component and delayed steady state), severe (> CS; continuous $\dot{V}O_2$ slow component and no steady state), and extreme intensities (no $\dot{V}O_2$ slow component; fatigue before reaching $\dot{V}O_{2max}$). Given the classification of these intensities, it is understood that any intensities above CS will be drawing from the D' reserve until these speeds cannot be sustained due to D' depletion driving the intensity of the activity down towards the CS which is the upper boundary for sustainable exercise (Bergstrom et al., 2021; Burnley & Jones, 2007; Jones et al., 2011; Jones & Vanhatalo, 2017; Poole et al., 2016; Poole & Jones, 2012). Hence, it seems more appropriate to use CS as the lower boundary for ASR and to possibly profile athletes.

We also set out to study the seasonal changes of MSS, CS, and D' through the repeated measurements of the 3MT at four different time periods (3MT1, 3MT2, 3MT3, and 3MT4). Despite small effect changes (d = -.50 – 0.56), MSS did not significantly change throughout the entire season (p = 0.08), CS reacted differently and had a large increase from 3MT1 to 3MT2, as well as for 3MT2 to 3MT3, which then stabilized from 3MT3 to 3MT4 (d = -1.40, -0.84, and -0.06, respectively). Expectedly, D' seemed to decrease from 3MT1 to 3MT2, but no changes were observed for subsequent time trial comparisons. Similar patterns seemed to be apparent between the changes in MSS and MBT (pre- and post-season) at all loads (d = -.21 – -.55, p = 0.08 – 0.64). Given that MBT and MSS were correlated in our data (r = .60 - .74), it is possible that power was minimally affected by the strength training program. These results are not exclusive to this current study, as others have observed mixed results within studies evaluating strength and conditioning training in swimmers (Amaro et al., 2018). Amaro and associates (2018), encountered seven different studies within their systematic review that did not report any negative nor positive effects on swimming performance with added strength and conditioning.

When programs are periodized in traditional or block periodization fashion, they are indeed superior to other methods (Stone et al., 2021) and can produce excellent swimming results (González-Ravé et al., 2021; Hellard et al., 2019; Hermosilla et al., 2021) then those programs that do not involve periodization or train to failure (Carroll et al., 2018; Painter et al., 2012). The prescribed program in our study focused on a set-repetition scheme as recommended by Amaro et al. (2018) (Tables 4.1 and 4.2). Nonetheless, the entire swimming periodization was prescribed by the head swimming coach using a best average swimming test (Bavg) and the resultant threshold parameter (average of 10 x 100 m in freestyle with 10-20 s rest interval) was used to delineate training zones through the traditional color zone method and unfortunately no training controls were guided using the 3MT data. Hence, swimming periodization followed a traditional approach of training all physical fitness components with a long-to-short model focus, in which more aerobic training is performed in the beginning of the season and volume is slowly and progressively increased. Speed training was added in one or two days a week and more focus to such intense anaerobic training intensities were given from the mid to the end of the season. Also, the Bavg pace may confound the expected physiological effects the coach desires to achieve in an athlete since this threshold parameter may reside at differing individual relative intensities (see Chapter 3).

A study that resembled our repeated measures protocol was performed by Piatrikova et al. (2020). In their study, they found trivial changes in MSS, and an increase in CS at the cost of D’. They mentioned that the explanation for their results were due to the HIIT design used. They prescribed HIIT by using a 60% percent depletion of the D’ for 3-minute intervals and

80% percent depletion of the D' for 3.5-minute intervals. The training load distribution for the season averaged about 75.2 ± 7.4 of total training volume in < CS intensity while 24.8 ± 7.4 of total training volume in > CS intensity (severe intensity domain). It seems as they also followed a traditional long-to-short periodization model since the distribution of training load at the beginning of the season (79.4% < CS and 20.6% > CS) differed from the final phase of the season (69.4% < CS and 30.6% > CS). In our study, no significant changes were observed for MSS, while CS increased at the expense of D'. Varied interval distances were used throughout the season for our study group with the typical separation of middle- and long-distance athletes as one group and sprint athletes as another. However, throughout the entire season the swimming volume load did not differ much between both groups (20.5 vs 21.7 km, for the lower and higher volume groups, respectively).

Another study that could be comparable to our current investigation are the results for Courtwright et al. (2016), who found that when prescribing eight sessions over a 4-week HIIT program for swimmers using the CS and a percentage expenditure of the D' derived from a 3MT in swimming, small improvements were observed for CS (d = 0.53) with small non-significant reductions in D' (d = 0.36) for the whole study group. Despite the non-significance, they reported that the short interval group dropped from 26.34 to 21.07 in D' (d = -0.46; small) while the long interval group went from 13.47 to 13.19 in D' (d = -0.04; trivial). Although it was not clear if they tested for changes within groups, the long interval group had a smaller sample size (n = 6) which could affect the results if statistical testing would have been performed. Moreover, the differences in metabolic response between using short and long intervals have previously been described (Buchheit & Luarsen, 2013). Due to the slow component in $\dot{V}O_2$ kinetics, the absolute time spent at or above the $v\dot{V}O_{2max}$ would be high for long intervals compared to short intervals, hence, it would be expected for long intervals to have a more glycolytic response than shorter intervals (Buchheit & Laursen, 2013). Taking this into consideration along with the fact that the percentage of D' expenditure was similar between groups (especially at 80% depletion of D'), it is possible that during long intervals more time was spent in a metabolic state that may be conducive to an accumulated lactate build up and muscle buffering adaptations which could have maintained certain qualities that are imbedded within the D' phenomena in the longer interval group (Buchheit & Laursen, 2013). This could explain the observed differences in pre and post D' responses between short and long interval groups while still improving CS in both groups. A similar explanation was offered by Clarke and others for similar results with their soccer athletes when using the CS and D' derived from a 3MT (Clark et al., 2013). They mentioned that the reduction of D' could have possibly been due to D' contributing less to the interval distance ran, especially during longer intervals, since the magnitude changes in their studies showed a moderate change for short (d = -1.06) and long intervals (r = 0.62). They also recommended that to improve D' shorter intervals with higher intensities would be required with longer rest intervals. Within our data, it is difficult to gauge how relative intensities affected physiological adaptations since training was guided by the color code system (from Bavg) rather than the CS method from the 3MT.

Some authors have demonstrated that phase order in periodization matters. In track sprinting a short to long model emphasizes a greater focus on improving the athlete's ability to develop acceleration skills early in the season while honing top speed sprinting skills through lower volume and sprinting skill rehearsal, which then deemphasizes accelerations to focus on top speed concentrated loads while retaining previous learnt skills in the hopes of increasing ASR (DeWeese et al., 2015). In the sport of swimming, researchers have shown that reversing the order of training phases can elicit increased 100 m swimming performance (Arroyo-Toledo et al., 2013). A periodization model that focuses on honing sprinting skills early in the season coupled with a focus on improving physical work capacities in the gym with proper resistance training protocols could elevate fitness in a swimmer to enable higher MSS and improved ASR, enhancing the potential for race modelling later in the season (DeWeese et al., 2015; DeWeese et al., 2019).

When considering the changes of the 3MT variables in our study, it seems that MSS does not require a consistent measurement throughout the season compared to CS and D'. Albeit this also could have been due to minimal strength and power improvements as explained above. Although further small reductions in D' were observed, it stabilized after 3MT2. However, CS continued to rise which is important since this is the upper boundary of sustainable exercise intensities. Many factors may influence the D' results, such as, poor nutrition (Miura et al., 2000), cadence (Vanhatalo et al., 2008), previous high-intensity exercise (Vanhatalo & Jones, 2009), interval duration (Triska et al., 2017), exercise modality (Cheng et al., 2012), protocol used to derived the D' parameter (Piatrikova et al., 2019), and mental fatigue (Salam et al., 2017).

Although safety measures were taken after government regulations due to the pandemic (Ramya et al., 2021), it was challenging to perform strength and power testing in the lab using force plates as typical for our athlete monitoring programs that would have provided more insight for analysis. Nonetheless, MBT have been shown to be reliable for assessing strength and power in the upper body for different populations (Beckham et al., 2019; Debanne & Laffaye, 2011; Palao & Valdés, 2013; Stockbrugger & Haennel, 2001). Performance in the MBT at all loads, showed large to very large positive correlations with MSS at pre- and post-season (r = .60 – .74). While MSS correlated to all loads at pre- and post-season, other 3MT variables were not as consistent. For example, while correlations for ASR with MBT_L and MBT_M were not significant during pre-season, these improved during the post-season and reached statistical significance. However, MBT_H was significantly correlated for both pre- and post-season which could point to the influence of strength factors influencing the ASR. Another factor to consider was that post-season testing was performed two days after the mid-season invitational. This could have also affected the results as athlete may have been fatigued from competition diminishing any possible gains obtained up to competition day.

One limitation to our current study is the lack of assessment of swimming stroke mechanical parameters. Stroke mechanics was shown to be the greatest contributor to 100 m swimming performance (Latt et al., 2010). Improved efficiency in the water has been observed when swim training is prescribed at stroke rates associated to CS (Piatrikova et al., 2020). This could help in understanding what other factors related to performance may be influencing improvements. Another limitation was that information concerning the amount of training within different zones were not provided. This could have eased the understanding of how much swimming training was being performed < CS or > CS which could have helped in comparing the training load distribution compared to other studies. It would have been also very beneficial to have performed additional strength and power assessments, such as, those performed with force plates (i.e., jumps and isometric strength testing). This could have given some additional information that could be comparable to a broader array of studies performing such tests. Future studies should focus on the longitudinal effects of concurrent resistance training using the CS method derived from the 3MT as this method can help in demarcating swimming training zones. It is also important to note that athletes began the season returning from the summer break of 2020, which in most cases were affected by the COVID-19 pandemic that could have affected their training regimes throughout this period due to lockdowns. Previous research has shown that the biggest improvements in a season are made by those athletes who were more detrained to start a season (Mujika et al., 1995).

Conclusion

Practitioners should assess swimmer's anthropometrical characteristics as these may influence performance during the 3MT and could be a helpful tool for talent identification. Improving body composition may influence 3MT performance variables by increasing FFM and reducing BF%. This increase in FFM can potentially enhance strength and power which could transfer into improved swimming performance. Consistent testing of the 3MT throughout a competitive season may ensure adequate intensities are always prescribed and adjustments are made, especially if using D' or a percentage of it to prescribe training. However, it seems that after a certain performance level has been reached, further improvements of CS may not be observed.

References

Abdi, H. (2010). Holm's Sequential Bonferroni Procedure. *Encyclopedia of Research Design.*, In Neil Salkind (Ed.), 1-8.

Abe, D., Tokumaru, H., Niihata, S., Muraki, S., Fukuoka, Y., Usui, S., & Yoshida, T. (2006). Assessment of Short-Distance Breastroke Swimming Performance With Critical Velocity. *Journal of Sports Science and Medicine*, 5: 340-348.

Aksit, T., Ozkol, M., Vural, F., Penkunlu, E., Aydinoglu, R., & Varol, R. (2017). Contribution of anthropometric characteristics to critical swimming velocity and estimated propulsive force. *Journal of Physical Education and Sport*, 17(1): 212-218.

Amaro, N., Morouco, P., Marques, M., Batalha, N., Neiva, H., & Marinho, D. (2018). A systematic review on dry-land strength and conditioning training on swimming performance. *Science & Sports*, 34(1): e1-e14.

Anderson, M., Hopkins, W., Roberts, A., & Pyne, D. (2006). Monitoring seasonal and long-term changes in test performance in elite swimmers. *European Journal of Sports Science*, 6(3): 145-154.

Arroyo-Toledo, J., Clemente, V., González-Ravé, J., Ramos Campo, D., & Sortwell, A. (2013). Comparison Between Traditional and Reverse Periodization: Swimming Performance and Specific Strength Values. *International Journal of Swimming Kinetics*, 2(1): 87-96.

Arroyo-Toledo, J., Clemente-Suárez, V., & Gonzales-Rave, J. (2016). Effects of Traditional and Reverse Periodization on Strength, Body-Composition and Swim Performance. *Imperial Journal of Interdisciplinary Research*, 2(12): 474-481.

Baldari, C., Fernandes, R., Meucci, M., Ribeiro, J., Vilas-Boas, J., & Guidetti, L. (2012). Is the New AquaTrainer Snorkel Valid for VO2 Assessment in Swimming? *International Journal of Sports Medicine*, 34(4): 336-344.

Balilionis, G., Nepocatych, S., Ellis, C., Richardson, M., Neggers, Y., & Bishop, P. (2012). Effects of Different Types of Warm-Up on Swimming Performance, Reaction Time, and Dive Distance. *Journal of Strength and Conditioning Research*, 26(12): 3297-3303.

Barbosa, T., Fernandes, R., Keskinen, K., & Vilas-Boas, J. (2008). The influence of stroke mechanics into energy cost of elite swimmers. *European Journal of Applies Physiology*, 130(2): 139-149.

Barbosa, T., Fernandes, R., Keskinen, K., Colaco, P., Cardoso, C., Silva, J., & Vilas-Boas, J. (2006). Evaluation of the Energy Expenditure in Competitive Swimming Strokes. *International Journal of Sports Medicine*, 27(11): 894-899.

Bassett, D. (2002). Scientific contributions of A.V. Hill: exercise physiology pioneer. *Journal of Applied Physiology*, 93: 1567-1582.

Batalha, N., Raimundo, A., Tomas-Carus, P., Paulo, J., Simao, R., & Silva, A. (2015). Does a land-based compensatory strength-training programme influences the rotator cuff balance of young competitive swimmers? *European Journal of Sports Science*, 15(8): 764-772.

Bazyler, C., Abbott, H., Bellon, C., Taber, C., & Stone, M. (2015). Strength for Endurance Athletes: Theory to Practice. *Journal of Strength and Conditioning*, 37(2): 1-12.

Beaver, W., Wasserman, K., & Whipp, B. (1986). A new method for detecting anaerobic threshold by gas exchange. *Journal of Applied Physiology*, 60(6): 2020-2027.

Beckham, G., Lish, S., Keebler, L., Longaker, C., Disney, C., DeBlasio, M., & Adams, K. (2019). The Reliability of the Seated Medicine Ball Throw for Distance. *Journal of Physical Activity Research*, 4(2): 131-136.

Bergstrom, H., Dinyer, T., Succi, P., Voskuil, C., & Housh, T. (2021). Applications of the Critical Power Model to Dynamic Constant External Resistance Exercise: A Brief Review of the Critical Load Test. *Sports*, 9(2): 1-15.

Billat, V. (2001). Interval Training for Performance: A Scientific and Empirical Practice. Special Recommendations for Middle- and Long-Distance Running. Part II: Anaerobic Interval Training. *Sports Medicine*, 31(2): 75-90.

Billat, V., Sirvent, P., Py, G., Koralsztein, J., & Mercier, J. (2003). The Concept of Maximal Lactate Steady State. *Sports Medicine*, 33(6): 407-426.

Bishop, C., Cree, J., Read, P., Chavda, S., Edwards, M., & Turner, A. (2013). Strength and Conditioning for Sprint Swimming. *Strength and Conditioning Journal*, 35(6): 1-6.

Bishop, D., & Jenkins, D. (1996). The Influence of Resistance Training on the Critical Power Function & Time to Fatigue at Critical Power. *The Australian Journal of Science and Medicine in Sport*, 28(4): 101-105.

Bonen, A., Wilson, B., Yarkony, M., & Belcastro, A. (1980). Maximal oxygen uptake during free, tethered, and swim flume swimming. *Journal of Applied Physiology*, 48(2): 232-235.

Brooks, G. (1985). Anaerobic threshold: review of the concept and directions for future research. *Medicine and Science in Sport and Exercise*, 17(1): 22-31.

Buchheit, M., & Laursen, P. (2013). High-Intensity Interval Training, Solutions to the Programming Puzzle: Part II: Anaerobic Energy, Neuromuscular Load and Practical Applications. *Sports Medicine*, 43(10): 927-954.

Buchheit, M., & Luarsen, P. (2013). High-Intensity Interval Training, Solutions to the Programming Puzzle - Part I: Cardiopulmonary Emphasis. *Sports Medicine*, 43(5): 313-338.

Bundle, M., & Weyand, P. (2012). Sprint Exercise Performance: Does Metabolic Power Matter? *Exercise and Sports Science Reviews*, 40(3): 174-182.

Burnley, M., & Jones, A. (2007). Oxygen uptake kinetics as a determinant of sports performance. *European Journal of Sports Science*, 7(2): 63-79.

Burnley, M., Doust, J., & Vanhatalo, A. (2006). A 3-min All-out Test to Determine Peak Oxygen Uptake and the Maximal Steady State. *Medicine and Science in Sport and Science*, 38(11): 1995-2003.

Carroll, K., Bernards, J., Bazyler, C., Taber, C., Stuart, C., DeWeese, B., . . . Stone, M. (2018). Divergent Performance Outcomes Following Resistance Training Using Repetition Maximums or Relative Intensity. *International Journal of Sports Physiology and Performance*, 14(1): 1-28.

Chaverri, D., Schuller, T., Iglesias, X., Hoffman, U., & Rodriguez, F. (2016). A New Model for Estimating Peak Oxygen Uptake Based on Postexercise Measurements in Swimming. *International Journal of Sports Physiology and Performance*, 11(4): 419-424.

Cheng, C., Yang, Y., Lin, H., Lee, C., & Wang, C. (2012). Determination of critical power in trained rowers using a three-minute all-out rowing test. *European Journal of Applied Physiology*, 112: 1251-1260.

Clark, I., West, B., Reynolds, S., Murray, S., & Pettitt, R. (2013). Applying the Critical Velocity Model for an Off-Season High Intensity Interval Training Program. *Journal of Strength and Conditioning Research*, 27(12): 3335-3341.

Corry, I., & Powers, N. (1982). Maximal Aerobic Power Measurement in Runners and Swimmers. *British Journal of Sports Medicine*, 16(3): 154-160.

Counsilman, J. (1968). *The Science of Swimming.* Hoboken, NJ: Prentice-Hall.

Courtwright, S., Williams, J., Clark, I., Pettitt, R., & Dicks, N. (2016). Monitoring Interval-traininf Responses for Swimming using the 3-min All-out Exercise Test. *International Journal of Exercise Science*, 9(5): 545-553.

Crowley, E., Harrison, A., & Lyons, M. (2018). Dry-Land Resistance Training Practices of Elite Swimming Strength and Conditioning Coaches. *Journal of Strength and Conditioning Research*, 32(9): 2592-2600.

Dalamitros, A., Fernandes, R., Toubekis, A., Manou, V., Loupos, D., & Kellis, S. (2015). Is speed reserve related to critical speed and anaerobic distance capacity in swimming? *Journal of Strength and Conditioning Research*, 29(7): 1830-1836.

Debanne, T., & Laffaye, G. (2011). Predicting the throwing velocity of the ball in handball with anthropometric variables and isotonic tests. *Journal of Sports Sciences*, 29(7): 705-713.

Dekerle, J., Sidney, M., Hespel, J., & Pelayo, P. (2002). Validity and Reliability of Critical Speed, Critical Stroke Rate, and Anaerobic Capacity in Relation to Front Crawl Swimming Performances. *International Journal of Sports Medicine*, 23: 93-98.

DeWeese, B., Sams, M., Williams, J., & Bellon, C. (2015). The Nature of Speed: Enhancing Sprint Abilities Through a Short to Long Training Approach. *Techniques for Track & Field and Cross Country*, 8(4): 8-22.

DeWeese, B., Wagle, J., & Bingham, G. (2019). Let the rhythm hit them: Adjusting the tempo to skilffully surf the intensity curve. . *Techniques Magazine*, 10(4): 52-59.

DiMenna, F., & Jones, A. (2019). Aerobic performance assessment. In P. Comfort, P. Jones, & J. McMahon, *Performance Assessment in Strength and Conditioning* (pp. 212-239). Abingdon, Oxon: Routledge.

Edge, J., Hill-Haas, S., Goodman, C., & Bishop, D. (2006). Effects of resistance training on H+ regulation, buffer capacity, and repeated sprints. *Medicine and Science in Sports and Exercise*, 38(11): 2004-2011.

Espada, M., & Alves, F. (2010). Critical Velocity and the Velocity at Maximal Lactate Steady State in Swimming. *Biomechanics and Medicine in Swimming XI* (pp. 194-196). Oslo: Norwegian School of Sports Science.

Espada, M., Costa, A., Louro, H., Conceiao, A., Filho, D., & Pereira, A. (2016). Anaerobic Critical Velocity and Sprint Swimming Performance in Masters Swimmers. *International Journal of Sports Science*, 6(1A): 31-35.

Farrell, P., Wilmore, J., Coyle, E., Billing, J., & Costill, D. (1979). Plasma lactate accumulation and distance running performance. *Medicine and Sciennce in Sports and Exercise*, 25(10): 1089-1090.

Ferguson, C., Rossiter, H., Whipp, B., Cathcart, A., Murgatroyd, S., & Ward, S. (2010). Effect of recovery duration from prior exhaustive exercise on the parameters of the power-duration relationship. *Journal of Applied Physiology*, 108(4): 866-874.

Fernandes, R., Sousa, M., Machado, L., & Vilas-Boas, J. (2011). Step Length and Individual Anaerobic Threshold Assessment in Swimming. *International Journal of Sports Medicine*, 32(12): 940-946.

Fig, G. (2010). Why Competitive Swimmers Need Explosive Power. *Strength and Conditioning Journal*, 32(4): 84-86.

Fone, L., & van den Tillar, R. (2022). Effects of Different Types of Strength Training on Swimming Performance in Competitive Swimmers: A Systematic Review. *Sports Medicine*, 8(1): 1-26.

Galbraith, A., Hopker, J., Lelliot, S., Diddams, L., & Passfield, L. (2014). A Single-Visit Field Test of Critical Speed. *International Journal of Sports Physiology and Performance*, 9(6): 931-935.

González-Ravé, J., Pyne, D., Castillo, J., González-Mohíno, F., & Stone, M. (2021). Training periodization for a world-class 400 meters individual medley swimmer. *Biology of Sport*, 39(4): 883-888.

Green, S. (1995). Measuring of Anaerobic Work Capacities in Humans. *Sports Medicine*, 19(1): 32-42.

Green, S., & Dawson, B. (1993). Measurment of Anaerobic Capacities in Humans: Definitions, Limitations, and Unsolved Problems. *Sports Medicine*, 15(5): 312-327.

Greenshields, J., Goss, C., & Stager, J. (2018). Variation in Critical Speed and Finite Distance Capacity of Elite Swimmers. *Annual Meeting of the American College of Sports Medicine* (p. 50(5S): 525). Minneapolis: Medicine and Science in Sports and Exercise.

Haff, G. (2019). The essentials of periodization. In I. Jeffreys, & J. Moody, *Strength and Conditioning for Sports Performance* (pp. 404-448). Abingdon, London: Routledge.

Hale, T. (2008). History of developments in sport and exercise physiology: A.V. Hill, maximal oxygen uptake, and oxygen debt. *Journal of Sports Sciences*, 26(4): 365-400.

Hall, G., & Murphy, D. (2020). *Fundamentals of Fast Swimming: How to Improve Your Swimming Technique.* Islamorada, FL: The Race Club.

Hamill, J., Knutzen, K., & Derrick, T. (2015). *Biomechanical Basis of Human Movement, 4th Ed.* Philadelphia, USA: Wolters Kluwer.

Hellard, P. P. (2018). Dynamics of the metabolic response during a competitive 100-m freestyle in elite male swimmers. *International Journal of Sports Physiology and Performance*, 13(10): 1011-1020.

Hellard, P., Avalos-Fernandes, M., Lefort, G., Pla, R., Mujika, I., Toussaint, J., & Pyne, D. (2019). Elite swimmers' training patterns in the 25 weeks prior to their season's best performances: insights into periodization from a 20-years cohort. *Frontiers in Physiology*, 10(363): 1-16.

Hellard, P., Pla, R., Rodríguez, F., Simbana, D., & Pyne, D. (2018). Dynamics of the metabolic response during a competitive 100-m freestyle in elite male swimmers. *International Journal of Sports Physiology and Performance*, 13(10): 1011-1020.

Hermosilla, F., González-Ravé, J., Del Castillo, J., & Pyne, D. (2021). Periodization and programming for individual 400 m medley swimmers. *International Journal of Environmental Research and Public Health*, 18(12): 6474.

Hill, A., & Lupton, H. (1923). Muscular Exercise, Lactic Acid, and the Supply and Utilization of Oxygen. *International Journal of Medicine*, 16(62): 135-171.

Hill, D. (1993). The critical power concept. A review. . *Sports Medicine*, 16(4): 237-254.

Hopkins, W. (2015). *Spreadsheets for analysis of validity and reliability. Sportscience 19, 36-42*. Retrieved from Sportscience: sportsci.org/2015/ValidRely.htm

Hopkins, W., Marshall, S., Batterham, A., & Hanin, J. (2009). Progressive Statistics for Studies in Sports Medicine and Exercise Science. *Medicine & Science in Sports & Exercise*, 41(1): 3-12.

Hurd, K., Surges, M., & Farell, J. (2022). Use of Exercise Training to Enhance the Power-Duration Curve: A Systematic Review. *Journal of Strength and Conditioning Research*, XX(X): 000-000.

Issurin, V. (2008). Block periodization versus traditional training theory: a review. *Journal of Sports Medicine and Physical Fitness*, 48(1): 65-75.

Jones, A., & Vanhatalo, A. (2017). The 'Critical Power' Concept: Applications to Sports Performance with a Focus on Intermittent High-Intensity Exercise. *Sports Medicine,* 47(1): S65-S78.

Jones, A., Grassi, B., Christensen, P., Krustrup, P., Bangsbo, J., & Poole, D. (2011). Slow Component of V̇O2 Kinetics: Mechanistic Bases and Practical. *Medicine and Science in Sport and Exercise*, 43(11): 2046-2062.

Jorgić, B., Puletić, M., Okičić, T., & Meškovska, N. (2011). Importance of Maximal Oxygen Consumption During Swimming. *Physical Education and Sport*, 9(2): 183-191.

Kao, S., Ishida, A., & Ainsworth, B. (2018). The Correlation Between Strength and Power Measures with Sprint Freestyle Performance in Division 1 Collegiate Swimmers. *Journal of Swimming Research*, 26(1): 22-31.

Karsten, B., Stevens, L., Colpus, M., Larumbe-Zabala, E., & Naclerio, F. (2014). The Effects of Sport-Specific Maximal Strength and Conditioning Training on Critical Velocity, Anaerobic Running Distance, and 5-km Race Performance. *International Journal of Sports Physiology and Performance*, 11(1): 80-85.

Keiner, M., Wirth, K., Fuhrmann, S., Kunz, M., Hartmann, H., & Haff, G. (2019). The Influence of Upper- and Lower-Body Maximum Strength on Swim Block Start, Turn, and Overall Swim Performance in Sprint Swimming. *Journal of Strength and Conditioning Research*, 35(10): 2839-2845.

Koo, T., & Li, M. (2016). A Guideline of Selecting and Reporting Intraclass Correlation Coefficients for Reliability Research. *Journal of Chiropractic Medicine*, 15: 155-163.

Kramer, M., Du Randt, R., Watson, M., & Pettitt, R. (2019). Bi-exponential modeling derives novel parameters for the critical speed concept. *Physiological Reports*, 7(4): 1-9 e13993.

Latt, E., Jurimae, J., Maestu, J., Purge, P., Ramson, R., Haljaste, K., . . . Jurimae, T. (2010). Physiological, biomechanical, and anthropometrical predictors of sprint swimming performance in adolescent swimmers. *Journal of Sport Sciences and Medicine*, 9(1): 398-404.

Lavoie, J., Lèger, L., Leone, M., & Provencher, P. (1985). A Maximal Multistage Swim Test to Determine the Functional and Maximal Aerobic Power of Competitive Swimmers. *Journal of Swimming Research*, 1(2): 17-22.

Leblanc, H., Seifert, L., Tourny-Chollet, C., & Chollet, D. (2007). Intra-cyclic Distance per Stroke Phase, Velocity Fluctuations and Acceleration Time Ratio of a Breastroker's Hip: A Comparison between Elite and Nonelite Swimmers at Different Race Paces. *International Journal of Sports Medicine*, 28(2): 140-147.

Libicz, S., Roels, B., & Millet, G. (2005). VO2 Responses to Intermittent Swimming Sets at Velocity Associated to VO2max. *Canadian Journal of Applied Physiology*, 30(5): 543-553.

Lopes, T., Goncalves, C., Graca, C., Neiva, H., & Marinho, D. (2019). The Relationship between Front Crawl Swimming Performance and Strength Variables in College Swimmers. *Ergonomics International Journal*, 3(2): 1-9.

Machado, M., Borges, J., Galdino, I., Cunha, L., Souza-Sá Filho, A., Soares, D., & Junior, I. (2018). Does critical velocity represent the maximal lactate steady state in youth swimmers? *Science & Sport*, 34(3): 1-7.

Machado, M., Junior, O., Marques, A., Colantonio, E., Cyrino, E., & De Mello, M. (2011). Effect of 12 weeks of training on critical velocity and maximal lactate steady state in swimmers. *European Journal of Sport Science*, 11(3): 165-170.

Magel, J., & Faulkner, J. (1967). Maximum oxygen uptakes of college swimmers. *Journal of Applied Physiology*, 22(5): 929-938.

Mann, B., Ivey, P., Brechue, W., & Mayhew, J. (2015). Validity and Reliability of Hand and Electronic Timing for 40-yd Sprint in College Football Players. *Journal of Strength and Conditioning Research*, 29(6): 1509-1514.

Marinho, D., Amorim, R., Costa, A., Marques, M., Pérez-Turpin, J., & Neiva, H. (2011). "Anaerobic" critical velocity and swimming performance in young swimmers. *Journal of Human Sport and Exercise*, 6(1): 80-86.

Marinho, D., Barbosa, T., Silva, A., & Neiva, H. (2012). Applying Anaerobic Critical Velocity in Non-Elite Swimmers. *International Journal of Swimming Kinetics*, 1(1): 33-50.

Mattioni-Maturana, F., Fontana, F., Pogliaghi, S., Passfield, L., & Murias, J. (2018). Critical power: How different protocols and models affect its determination. *Journal of Science and Medicine in Sport*, 21(7): 742-747.

Mauger, A., Neuloh, J., & Castle, P. (2012). Analysis of Pacing Strategy Selection in Elite 400-m Freestyle Swimming. *Medicine and Science in Sport and Exercise*, 44(11): 2205-2212.

McArdle, W., Katch, F., & Katch, V. (2015). *Exercise Physiology: Nutrition, Energy, and Human Performance.* Baltimore, MD: Wolters-Kluwers.

Mitchell, L., Pyne, D., Saunders, P., & Rattray, B. (2017). Reliability and validity of a modified 3-minute all-out swimming test in elite swimmers. *European Journal of Sports Science*, 18(3): 307-314.

Miura, A., Endo, M., Sato, H., Sato, H., Barstow, T., & Fukuba, Y. (2002). Relationship between the curvature constant parameter of the power-duration curve and muscle cross-sectional area of the thigh for cycle ergometry in humans. *European Journal of Applied Physiology*, 87(3): 238-244.

Miura, A., Sato, H., Sato, H., Whipp, B., & Fukuba, Y. (2000). The effect of glycogen depletion on the curvature constant parameter of the power-duration curve for cycle-ergometry. *Ergonomics*, 43(1): 133-141.

Monod, H., & Scherrer, J. (1965). The work capacity of a synergic muscular group. *Ergonomics*, 8: 329-338.

Montpetit, R., Léger, L., Lavoie, J., & Cazorla, G. (1981). V̇02 Peak During Free Swimming Using the Backward Extrapolation of the O2 Recovery Curve. *European Journal of Applied Physiology*, 47(4): 385-391.

Morán-Navarro, R., Pérez, C., Mora-Rodríguez, R., de la Cruz-Sánchez, E., González-Badillo, J., Sánchez-Medina, L., & Pallarés, J. (2017). Time course of recovery following resistance training leading or not to failure. . *European Journal of Applied Physiology*, 117(12): 2387-2399.

Moritani, T., Nagata, A., DeVries, H., & Muro, M. (1981). Critical power as measure of physical work capacity and anaerobic threshold. *Ergonomics*, 24(5): 339-350.

Morouco, P., Marinho, D., Keskinen, K., Badillo, J., & Marques, M. (2014). Thethered Swimming Can Be Used to Evaluate Force Contribution for Short-Distance Swimming Performance. *Journal of Strength and Conditioning Research*, 28(11): 3093-3099.

Mougios, V. (2006). *Exercise Biochemistry.* Champaign, Ill. : Human Kinetics.

Mujika, I., & Crowley, E. (2019). Strength Training for Swimmers. In M. Schumann, & B. Ronnestad, *Concurrent Aerobic and Strength Training: Scientific Basics and Practical Applications* (pp. 369-386). Switzerland: Springer International Publishing AG.

Mujika, I., Chatard, J., Busso, T., Geyssant, A., Barale, F., & Lacoste, L. (1995). Effects of training on performance in competitive swimming. *Canadian journal of applied physiology*, 20(4): 395-406.

Neiva, H., Fernandes, R., & Vilas-Boas, J. (2010). Anaerobic Critical Velocity in Four Swimming Techniques. *International Journal of Sports Medicine*, 32(1): 195-198.

Neiva, H., Fernandes, R., & Vilas-Boas, J. (2011). Anaerobic Critical Velocity in Four Swimming Techniques. *International Journal of Sports Medicine*, 32: 195-198.

Nevill, A., Negra, Y., Myers, T., Sammond, S., & Chaabene, H. (2020). Key somatic variables associated with, and differences between the 4 swimming strokes. *Journal of Sports Sciences*, 38(7): 787-794.

Noakes, T. (2008a). How did AV Hill understand the V̇O2max and the "plateau phenomenon"? Still no clarity? *British Journal of Sports Medicine*, 42: 574-580.

Noakes, T. (2008b). Testing for maximum oxygen consumption has produced a brainless mode of human exercise performance. *British Journal of Sports Medicine*, 42(7): 551-555.

Noordhof, D., Koning, J., & Foster, C. (2010). The Maximal Accumulated Oxygen Deficit Method. *Sports Medicine*, 40(4): 285-302.

Norouzi, M., Cabuk, R., Balki, G., As, H., & Ozkaya, O. (2021). The Effect of Using Different Exhaustion Intervals and Mathematical Models on Critical Power Estimations. *Hacettepe Journal of Sports Sciences*, 32(3): 151-166.

Nugent, F., Comyns, T., Kearney, P., & Warrington, G. (2019). Ultra-Short Race-Pace Training (USRPT) In Swimming: Current Perspectives. *Open Access Journal of Sports Medicine*, 10(1): 133-144.

Ogita, F. (2006). Energetics in competitive swimming and its applications for training. . *International Symposium on Biomechanics and Medicine in Swimming* (pp. 6(2): 117-121). Porto Faculdade de Desporto da Universidade do Porto.

Olbrecht, J. (2013). *The Science of Winning: Planning, Periodizing and Optimizing Swim Training.* Antwerp, Belgium: F&G Partners.

Painter, K., Haff, G., Ramsey, M., McBride, J., Triplett, T., Sands, W., . . . Stone, M. (2012). Strength gains: block versus daily undulating periodization weight training among track and field athletes. *International Journal of Sports Physiology and Performance*, 7(2): 161-169.

Painter, K., Rodriguez-Castellano, L., & Stone, M. (2020). High Volume Resistance Training and its Effects on Anaerobic Work Capacity Over Time: A Review. *The Sport Journal*, 3(1): 1-17.

Palao, J., & Valdés, D. (2013). Testing protocol for monitoring upper-body strength using medicine balls. *Journal of Human Sport & Exercise*, 8(2): 334-341.

Papoti, M., da Silva, A., Araujo, G., Santiago, V., Martins, L., Cunha, C., & Gobatto, C. (2013). Aerobic and Anaerobic Performances in Tethered Swimming. *International Journal of Sports Medicine*, 34: 712-719.

Pareja-Blanco, F., Rodríguez-Rosell, D., Aagaard, P., Sánchesz-Medina, L., Ribas-Serna, J., Mora-Custodio, R., . . . González-Badillo, J. (2020). Time Course of Recovery From Resistance Exercise With Different Set Configurations. *Journal of Strength and Conditioning Research*, 34(10): 2867-2876.

Pelayo, P., & Alberty, M. (2011). The History of Swimming Research. In L. Seifert, D. Chollet, & I. Mujika, *World Book of Swimming: From Science to Performance* (pp. ix - xxvi). Hauppauge, New York: Nova Science Publishers, Inc.

Peters, M., Berry, S., & Koley, S. (2014). Relationship of physical characteristics, power and swimming time in sprint swimmers. *Annals of Biological Research*, 5(8): 24-29.

Pettitt, R. (2016). Applying the Critical Speed Concept to Racing Strategy and Interval Training Prescription. *International Journal for Sports Physiology and Performance*, 11(7): 842-847.

Pettitt, R., Jamnick, N., & Clark, E. (2012). 3-min All-out Exercise Test for Running. *International Journal of Sports Medicine*, 33: 426-431.

Piatrikova, E., Sousa, A., Gonzalez, J., & Williams, S. (2019). Validity and reliability of the 3-minute all-out test in national and international competitive swimmers. *International Journal of Sports Physiology and Performance*, 13(9): 1190-1198.

Piatrikova, E., Sousa, A., Willsmer, N., Gonzalez, J., & Williams, S. (2018). Demarcating exercise intensity domains in freestyle swimming: is there and alternative to incremental step test and beats below HRmax method? . *Journal of Strength and Conditioning Research*, 34(9): 2575-2584.

Piatrikova, E., Willsmer, N., Altini, M., Mladen, J., Lachlan, M., Gonzalez, J., . . . Williams, S. (2021). Monitoring the heart rate variability responses to training loads in competitive swimmers using a smartphone application and the Banister Impulse-Response model. *International Journal of Sports Physiology and Performance*, 16(6):787-795.

Piatrikova, E., Willsmer, N., Sousa, A., Gonzalez, J., & Williams, S. (2020). Individualising training in swimming; is there a place for the application of the critical speed and critical stroke rate concepts? *International Journal of Sports Physiology and Performance*, 15(5): 1-17 .

Pla, R., Leroy, A., Massal, R., Bellami, M., Kaillani, F., Hellard, P., . . . Sedeaud, A. (2019). Bayesian approach to quantify morphological impact on performance in international elite freestyle swimming. *BMJ Open Sport & Exercise Medicine*, 5: 1-7.

Poole, D., & Jones, A. (2012). Oxygen Uptake Kinetics. *Comprehensive Physiology*, 2(2): 933-996.

Poole, D., Burnley, M., Vanhatalo, H., Rossiter, B., & Jones, A. (2016). Critical Power: An Important Fatigue Threshold in Exercise Physiology. *Medicine and Science in Sports and Exercise*, 48(11): 2320-2334.

Poole, D., Rossiter, H., Brooks, G., & Gladden, L. (2021). The Anaerobic Threshold: 50+ Years of Controversy. *The Journal of Physiology*, 599(3): 737-767.

Pyne, D., Lee, H., & Swanick, K. (2001). Monitoring the lactate threshold in world-ranked swimmers. *Medicine and Science in Sports and Exercise*, 33(2): 291-297.

Pyne, D., Maw, G., & Goldsmith, W. (2000). Protocols for the Physiological Assessment of Swimmers. In A. S. Commission, *Physiological Tests for Elite Athletes* (pp. 372-382). Champaign, Ill: Human Kinetics.

Ramos, R., Requena, B., Suarez-Arrones, L., Newton, R., & Sáez de Villareal, E. (2014). Effects of 18-Week In-Season Heavy-Resistance and Power Training on Throwing Velocity, Strength, Jumping, and Maximal Sprint Swim Performance of Elite Male Water Polo Players. *Journal of Strength and Conditioning Research*, 28(4): 1007-1014.

Ramos-Veliz, R., Requena, B., Suarez-Arrones, L., Newton, R., & Sáez de Villareal, E. (2014). Effects of 18-week in-season heavy resistance and power training on throwing velocity, strength, jumping, and maximal sprint swim performance of elite male water polo players. *Journal of Strength and Conditioning Research*, 28(4): 1007-1014.

Ramya, G., Guru, C., Banodhe, G., Dominic, D., & Sharma, H. (2021). Resumption to Swimming Post COVID 19 Lockdown. *Journal of Clinical and Diagnostic Research*, 15(1): 1-5.

Raymond, D. (2012). The effect of aerobic fitness on the cardiovascular and sympathetic nervous system response to physiological stress at rest and during dynamic exercise. *Thesis*.

Reis, V., Marinho, D., Barbosa, F., Reis, A., Guidetti, L., & Silva, A. (2010). Examining the Accumulated Oxygen Deficit Method in Breaststroke Swimming. *European Journal of Applied Physiology*, 109(6): 1129-1135.

Reis, V., Marinho, D., Policarpo, F., Carneiro, A., Baldari, C., & Silva, A. (2010). Examining the Accumulated Oxygen Deficit Method in Front Crawl Swimming. *International Journal of Sports Medicine*, 31(6): 421-427.

Rodríguez, F., & Mader, A. (2011). Energy Systems in Swimming. In L. Seifert, D. Chollet, & I. Mujika, *World Book of Swimming: From Science to Performance* (pp. 225-240). New York: Nova Science.

Rodríguez, F., Keskinen, K., Keskinen, O., & Malvela, M. (2003). Oxygen uptake kinetics during free swimming: a pilot study. *In: Chartard, JC, Biomechanics and Medicine in Swimming IX*, 379-384.

Rushall, B. (2016, March 14). *USRPT Defined: After Two Years USRPT Comes of Age.* Retrieved from Swimming Science Bulletin #49: https://coachsci.sdsu.edu/swim/bullets/49DEFINED.pdf

Salam, H., Marcora, S., & Hopker, J. (2017). The effect of mental fatigue on critical power during cycling exercise. *European Journal of Applied Physiology*, Available from: https://link.springer.com/article/10.1007/s00421-017-3747-1 [Accessed 22 March 2022].

Saltin, B., & Astrand, P. (1967). Maximal oxygen uptake in athletes. *Journal of Applied Physiology*, 23(3): 353-358.

Sandford, G., & Stellingwerff, T. (2019). "Questioning Your Categories": the Misunderstood Complexity of Middle-Distance Running Profiles With Implications for Research Methods and Application. *Frontiers in Sports and Active Living*, 1(28): 1-8.

Sandford, G., Kilding, A., Ross, A., & Luarsen, P. (2018). Maximal Sprint Speed and the Anaerobic Speed Reserve Domain: The Untapped Tools that Differentiate the World's Best 800 m Runners. *Sports Medicine*, 49(6): 843-852.

Sanford, G., Laursen, P., & Buchheit, M. (2021). Anaerobic Speed/Power Reserve and Sport Performance: Scientific Basis, Current Applications and Future Directions. *Sports Medicine*, 51(10): 2017-2028.

Sawyer, B., Stokes, D., Womack, C., Hugh, M., Weltman, A., & Gaesser, G. (2014). Strength Training Increases Endurance Time to Exhaustion During High-Intensity Exercise Despite No Change in Critical Power. *Journal of Strength and Conditioning Research*, 28(3): 601-609.

Scott, B., Burden, R., & Dekerle, J. (2020). Critical speed, D' and pacing in swimming: reliability of a popular critical speed protocol applied to all four strokes. *Research Square*, 10.21203/rs.3.rs-77508/v1.

Shiyoyama, Y., Okita, K., Baba, Y., & Sato, D. (2010). Does the Y-Intercept of a Regression Line in the Critical Velocity Concept Represent the Index for Evaluating Anaerobic Capacity? *Biomechanics and Medicine in Swimming XI* (pp. 288-290). Oslo: Nordbergtrykk as.

Siders, W., Lukaski, H., & Bolonchuk, W. (1993). Relationship among swimming performance, body composition and somatotype in competitive collegiate swimmers. *Journal of Sports Medicine and Physical Fitness*, 33(2): 166-171.

Smith, D., Norris, S., & Hogg, J. (2002). Performance Evaluation of Swimmers: Scientific Tools. *Sports Medicine*, 32(9): 539-554.

Sousa, A., Figueiredo, P., Pendergast, D., Kjendlie, P., Vilas-Boas, J., & Fernandes, R. (2014). Critical Evaluation of Oxygen-Uptake Assessment in Swimming. *International Journal of Sports Physiology and Performance*, 9(2): 190-202.

Steiger, J. (1980). Tests for comparing elements of a correlation matrix. *Psychological Bulletin*, 87: 245-251.

Stockbrugger, B., & Haennel, R. (2001). Validity and Reliability of a Medicine Ball Explosive Power Test. *Journal of Strength and Conditioning Research*, 15(4): 431-438.

Stone, M., Hornsby, W., Haff, G., Fry, A., Suárez, D., Liu, J., . . . Pierce, K. (2021). Periodization and Block Periodization in Sports: Emphasis on Strength-Power Training-

A Provocative and Challenging Narrative. *Journal of Strength and Conditioning Research*, 35(8): 2351-2371.

Stone, M., Stone, M., & Sands, W. (2007). *Principles and Practices of Resistance Training.* Champaign, Ill.: Human Kinetics.

Strzala, M., Stanula, A., Krezalek, P., Ostrowski, A., Kaca, M., & Glab, G. (2019). Influence of Morphology and Strength on Front Crawl Swimming Speed in Junior and Youth Age-Group Swimmers. *Journal of Strength and Conditioning Research*, 33(10): 2836-2845.

Toubekis, A., Gourgoulis, V., & Tokmakidis, S. (2010). Tethered Swimming as an Evaluation Tool of Single Arm-Stroke Force. *XIth International Symposium for Biomechanics and Medicine in Swimming.* Oslo, Norway: Norwegian School of Sports Sciences .

Toussaint, H. (2002). Biomechanics of Propulsion and Drag in Front Crawl Swimming. *Applied proceedings - XXth International Symposium on Biomechanics in Sports. University of Extremadura*, (pp. 11-22). Caceres, Spain.

Toussaint, H., & Beek, P. (1992). Biomechanics of Competitive Front Crawl Swimming. *Sports Medicine*, 13(1): 8-24.

Toussaint, H., Beelen, A., Rodenburg, A., Sargeant, A., de Groot, G., Hollander, A., & van Ingen Schenau, G. (1988). Propelling efficiency of front-crawl swimming. *Journal of Applied Physiology*, 65(6): 2506-2512.

Triska, C., Karsten, B., Nimmeritcher, A., & Tschan, H. (2017). Different exhaustive protocols affect estimates of critical speed and D´. *22nd Annual Congress of the European College of Sport Science.* Essen, Germany.

Tsai, M., & Thomas, S. (2017). 3-Min All-Out in Swimming. . *International Journal of Sports Physiology and Performance*, 12(1): 1-17.

Tsunokawa, T., Kadi, T., Mankyu, H., & Ogita, F. (2019). Estimation of hand propulsion forces at four swimming techniques using pressure measurement and underwater motion capture. *24th Annual Congress of the European College of Sport Science* (p. Abstract). Prague, Czech Republic: European College of Sports Science.

Vanhatalo, A., & Jones, A. (2009). Influence of prior sprint exercise on the parameters of the 'all-out critical power test' in men. *Experimental Physiology*, 94(2): 255-263.

Vanhatalo, A., Black, M., DiMenna, F., Blackwell, J., Schmidt, J., Thompson, C., . . . Jones, A. (2016). The mechanistic bases of the power-time relationship: muscle metabolic responses and relationship to muscle fiber type. *Journal of Physiology*, 594(15): 4407-4423.

Vanhatalo, A., Doust, J., & Burnley, M. (2007). Determination of Critical Power Using a 3-min All-out Cycling Test. *Medicine and Science in Sports and Exercise*, 39(3): 548-555.

Vanhatalo, A., Doust, J., & Burnley, M. (2008). Robustness of a 3 min all-out cycling test to manipulations of power profile and cadence in humans. *Experimental Physiology*, 93(3): 383-390.

Vanhatalo, A., Fulford, J., DiMenna, F., & Jones, A. (2010). Influence of hyperoxia on muscle metabolic responses and the power-duration relationship during severe-intensity exercise in humans: a 31P magnetic resonance spectroscopy study. *Experimental Physiology*, 95(4): 528-540.

Vucetic, V., Mozek, M., & Rakovac, M. (2015). Peak Blood Lactate Parameters in Athletes of Different Running Events During Low-Intensity Recovery After Ramp-Type Protocol. *Journal of Strength and Conditioning Research*, 29(4): 1057-1063.

Wakayoshi, K., Ikuta, K., Yoshida, T., Udo, M., Moritani, T., Mutoh, Y., & Miyashita, M. (1992). Determination and validity of critical velocity as an index of swimming performance in the competitive swimmer. . *European Journal of Physiology and Occupational Physiology*, 64(2): 153-157.

Wakayoshi, K., Yoshida, T., Udo, M., Harada, T., Moritani, T., Mutoh, Y., & Miyashita, M. (1993). Does critical swimming velocity represent exercise intensity at maximal lactate steady state? *European Journal of Applied Physiology and Ocuppational Physiology*, 66(1): 90-95.

Walsh, M., & Bannister, E. (1988). Possible Mechanisms of the Anaerobic Threshold. *Sports Medicine*, 5(5): 269-302.

Wasserman, K., Whipp, B., Koyal, S., & Beaver, W. (1973). Anaerobic threshold and respiratory gas exchange during exercise. *Journal of Applied Physiology*, 35(2): 236-243.

Yarar, H., Barug, D., Bostan, A., Kaya, A., & Aydin, E. (2021). Influence of Physical and Anthropometric Properties on Sprint Swimming Performance. *Pakistan Journal of Medical & Health Sciences*, 15(2): 814-818.

Zacca, R., & Castro, F. (2010). Critical Swimming Speed Obtained by the 200-400 Meters Model in Young Swimmers. *Biomechanics and Medicine in Swimming XI* (pp. 307-309). Oslo, Norway: Norwegian School of Sport Sciences.

Zacca, R., Azevedo, R., Chainok, P., Vilas-Boas, J., Castro, F., Pyne, D., & Fernandes, R. (2020). Monitoring Ag-Group Swimmers Over a Training Macrocycle: Energetics, Technique, and Anthropometrics. *Journal of Strength and Conditioning Research*, 34(3): 818-827.

Zacca, R., Azevedo, R., Peterson-Silveira, R., Vilas-Boas, J., Pyne, D., Castro, F., & Fernandes, R. (2019). Comparison of Incremental Intermittent and Time Trial Testing in Age-Group Swimmers. *Journal of Strength and Conditioning Research*, 33(3): 801-810.

Zacca, R., Fernandes, R., Pyne, D., & de S Castro, F. (2016). Swimming Training Assessment: The Critical Velocity and the 400-m Test for Age-Group Swimmers. *Journal of Strength and Conditioning Research*, 30(5): 1365-1372.

Zarzeczny, R., Kuberski, M., Deska, A., Zarzeczna, D., & Rydz, K. (2013). The Evaluation of Critical Swimming Speed in 12-Year-Old Boys. *Human Movement*, 14(1): 35-40.

Chapter 5. Comparing the Speed Rate Drop-Off During the 3-Minute All-Out Swimming Test Using Freestyle and a Secondary Stroke

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Introduction

In the sport of competitive swimming, athletes may compete in a vast number of events with durations ranging from about 18 s (i.e., 45.7 m freestyle) in elite level males to about 16 minutes (i.e., 1509 m freestyle) in elite level females (± 95% of WR). Nonetheless, just over 81% of these events are swum in < 5 minutes and about 69% of those involve swimming strokes other than freestyle. While it is possible that swimmers specialize in a single stroke, especially at higher competitive levels, many athletes may swim various strokes (i.e., individual medley) and a few might even be good at all of them (i.e., Michael Phelps). It is well known that shorter distances heavily depend on high anaerobic energy contribution, while aerobic capacity becomes increasingly more important with longer durations (Rodríguez & Mader, 2011). However, backstroke, butterfly, and breaststroke are less efficient than freestyle, respectively (Barbosa et al., 2006), making these strokes slower in average velocity per distance, hence increasing duration and aerobic energy requirements for a given distance, including short events such as the 100 m (Hellard et al., 2018).

Testing for sports-specific performance in swimming has been carried out with many distinct protocols for measuring aerobic capacity and power (Espada & Alves, 2010; Lavoie et al., 1985), maximum lactate steady state or critical swimming speed (CS) (Machado et al., 2011; Wakayoshi et al., 1992), maximum sprinting speed (Ramos et al., 2014) and swimming specific power (Papoti et al., 2013). One validated and reliable method has been the three-minute all-out test (3MT), which has been used to derive the CS and the finite distance capacity available above CS (D') (Piatrikova et al., 2019; Tsai & Thomas, 2017). It is a time-efficient and accurate tool for demarcating training zones (Piatrikova et al., 2018), high intensity interval training (HIIT) set prescriptions (Courtwright et al., 2016), and useful for monitoring performance throughout the season (Piatrikova et al., 2020). However, a great majority of these tests have been performed in the freestyle stroke only. Although some researchers did have their swimmers perform the 3MT in their best strokes other than freestyle (Mitchell et al., 2017; Piatrikova et al., 2020), to the author's knowledge no study has attempted the within-athlete comparisons of the 3MT in distinct strokes. An attempt was previously made to derive the CS for breaststroke (Abe et al., 2006), but this study used multiple shorter distances of 75, 100 and 150 m, rendering it more of an anaerobic CS, no other strokes were studied, and would still need multiple trials to derive a variable that can be attainable from just one test.

Moreover, anthropometrics (Yarar et al., 2021) and morphological indicators (Pla et al., 2019) have been shown to be related to swimming performance, including the CS (Aksit et al., 2017). More importantly, certain anthropometric characteristics might be beneficial for some strokes, but less for others (Nevill et al., 2020). Particularly, the breaststroke uses a great deal of the propulsion from the legs compared to freestyle and backstroke that are driven mainly by the upper body limbs. Researchers mentioned that because of the discontinuous nature of the butterfly and breaststroke, these would show higher performance decrements in the latter portions of a 100 m (Neiva et al., 2011), which could possibly lead to even larger velocity drop-offs at longer durations, such as when reaching the asymptote of the hyperbolic speed-time relationship during a 3MT. Although the 3MT has been performed across various modalities and sports successfully (Burnley et al., 2006; Cheng et al., 2012; Clark et al., 2013; Mitchell et al., 2017; Pettitt et al., 2012; Piatrikova et al., 2019), variability within the physical and stroke characteristics of the swimmers must be considered. This becomes especially true when prescribing training for an athlete in a stroke other than that was performed in the 3MT. For example, a swimmer who needs to train in a secondary stroke or all strokes (as in individual medley) when the test was performed in freestyle.

The purpose of this study was to compare the key performance variables and the speed drop-offs of a 3MT performed with breaststroke, backstroke, and butterfly against the 3MT in freestyle. Furthermore, the influence of the interactions of the athlete's anthropometrical characteristics to the relationships of the key performance variables for each stroke will be explored.

Methods

Athletes

Athletes that completed all testing and performance measures with proper standards were included in the study (n = 20; males = 11 & females = 9, performance level = 79.8 ± 3.6% [ranging from 71.3% - 85.3%] of world record) were apparently healthy (as assessed by preseason sports medicine screening), ≥18 years of age, and currently participating with a local National Athletics Intercollegiate Association (NAIA) swimming team. Initially the selection pool consisted of 28 athletes, but 7 athletes were excluded due to apparent acceleration towards the end of the 3MT which violated the established criteria for each respective test (n = 4 females & 3 male). Another athlete's data was discarded due to health issues towards the end of the season (n = 1 male).

The study was performed after the Fall semester of the swimming season – post mid-season competition after summer break. Athletes were tested for body composition one day prior to the first 3MT in freestyle. Forty-eight hours later, the athletes performed the 3MT in their main stroke other than freestyle. No randomized ordering for the tests was done because the freestyle was part of on-going performance monitoring throughout the prior season and the idea for the study arose after issues of individualizing training considering stroke differences. Age, school year, and training history was collected for descriptive purposes prior to the beginning of the season.

Prior to data collection, athletes signed a written informed consent approved by the University Institutional Review Board (IRB) in the spirit of the Helsinki Declaration, to store their data for further analysis. Data was collected as part of an on-going athlete monitoring program and was later stored in the East Tennessee State University Sports Science Research Repository (ETSU-SSRR). Due to the COVID-19 pandemic, which limited face to face contact, additional approval by the IRB was sought to use an online video conference call with all athletes. Athletes were explained about the details of how their data from the ETSU-SSRR was going to be used. After the conference call, each athlete was individually contacted to via cellphone to seek their verbal consent.

Body Anthropometrics

Anthropometric measurements were collected at the end of the season competition one day before the 3MT in freestyle. Skinfold measurements were taken (ICC [3,1] = 0.991 – 0.999, CV = 0.00 – 5.46%) using a Lange Skinfold Caliper (Seko, USA) by an ISAK Level 1 anthropometrist with at least 10 years' experience performing skinfold measurements. Body mass was measured using a digital scale (Health-o-meter Professional 498KL, Ill., USA) and was measured to the nearest 0.1 kilogram. Standing and sitting height, wingspan and hand width were measured to the nearest 0.1 centimeters using a measuring tape and a Health-o-meter Universal Wall Mounted Height Rod (MFI Medical, San Diego, CA).

The 3-minute All-out Swimming Test

Tests were held at regularly scheduled practices to comply with NAIA regulations. Athletes performed a mixed standardized 1,100 m warm-up as they performed prior to competition (Balilionis et al., 2012). Swimmers rested 10 minutes between warm-up and the swimming tests to recover from warm-up (Ferguson et al., 2010) and to reduce the negative effect on D' (Vanhatalo & Jones, 2009). Swimmers were instructed to swim as fast as possible from the first whistle until they heard the second whistle signifying the end (180 s) and were strictly warned about not pacing themselves throughout the entire duration of the test. Strong verbal encouragement was given to ensure a maximum effort.

Video footage was captured using a digital video camera (CANON EOS 700D, Australia) at a sample rate of 30 FPS similar to other studies (Clark et al., 2013; Courtwright et al., 2016). The camera was set up at one end of the pool towards one corner at 2.0 m above the ground and all lane line markers were visible. Windows Media Player 12 (Windows 10 Microsoft 2021, Washington, USA) was used to analyze video footage for split times using a stopwatch (3X300 Memory Stopwatch, FINIS Australia) upon the athlete's feet touching the wall after a flip turn during backstroke and freestyle and the first hand-touch on the wall during butterfly and breaststroke (Tsai & Thomas, 2017).

Data Analysis & Statistics

A criterion was used to ensure all athletes performed the test with all-out maximal effort and if they did not meet the criteria, then that athlete's 3MT data was discarded from analysis. The criterion was that if the average speed of the last two laps performed (CS; Equation 1) were faster than the combined average speed at 100 and 125 m for freestyle (or 50 and 75 m for the secondary strokes test) then that athlete's data would be flagged as it would be evidence of submaximal effort and acceleration towards the end of the 3MT. The distances of 100 and 125 m (or 50 and 75 m for secondary strokes) were selected because the athletes in our study averaged around 68 to 78 s (60 – 81 s for strokes) for those distances during the 3MT, respectively. This is approximately where the aerobic energy pathway becomes the predominant energy source (Mougios, 2006), and if the athlete gave a maximal all-out effort, the evident time-dependent speed drop-off would have been caused by an accumulation of metabolic by-products resulting from anaerobic metabolism which would inhibit maximal muscle fiber recruitment for accelerations (Bundle & Weyand, 2012).

Maximum sprint speed was measured as the average speed of the first 25 m (Equation 2). each time the swimmer touched the wall with their feet after each flip turn for freestyle and backstroke, while splits were taken on the first hand-touch before the turn for butterfly and breaststroke. To calculate the finite capacity of work available above CS (D') Equation 3 was used. The anaerobic speed reserve (ASR) was calculated using Equation 4. Fatigue index (FI) was calculated using Equation 5.

Equation 1. CS ($m.s^{-1}$) = Distance of Last 2 Laps (50 m) /Time in Seconds to Complete Last 2 Laps

Equation 2. MSS ($m.s^{-1}$) = Lap Distance (25 m) /Time in seconds to complete 1st Lap

Equation 3. D' (m) = $\sum_i (SSi - \mathrm{CS})$

Equation 4. *ASR* = MSS - CS

Equation 5. FI (%) = (MSS – CS)/MSS

Statistical analysis was performed using JASP (Version 0.14.1). Independent *t*-tests were performed to assess the differences of MSS, CS, D', ASR, and FI within the freestyle and stroke 3MT's. Holm-Šidàk sequential correction was performed to increase the power of the statistical tests while keeping under control the familywise Type I error (Abdi, 2010). Pearson's correlation coefficient (on bivariate normally distributed data) and Spearman's ranked correlations (on bivariate non-normally distributed data) were used to assess the relationships between freestyle and stroke performance variables from their respective 3MT. The relationship between variables will be rated as trivial, small, moderate, large, very large, nearly perfect, or perfect based on the respective r values: 0.00-0.1, 0.1-0.3, 0.3-0.5, 0.5-0.7, 0.7-0.9, 0.9-1.0. Cohen's *d* effect size differences were also calculated and interpreted with magnitude thresholds of 0-0.20, 0.21-0.60, 0.61-1.20, 1.21-2.0 and 2.0 and above as trivial, small, moderate, large, and very large (Hopkins et al., 2009). The level of significance was set at $p \leq 0.05$. Data are reported as mean ± SD.

Results

Data was normally distributed except for FI% in the freestyle 3MT of the breaststroke group, $W = 0.82$, $p = 0.05$, and Levene's test for D' showed heteroscedasticity, $F(1) = 5.20$, $p = 0.03$. Due to the violation of assumptions in these parameters, independent T-Tests were performed using Welch's test for such variable comparison.

The comparisons for both the freestyle and secondary stroke 3MT groups are shown in Table 5.1. In the backstroke group, large significant differences were observed for MSS, $t(20) = 4.12$, $p < 0.01$, $d = 1.79$ and ASR, $t(20) = 2.97$, $p < 0.05$, $d = 1.27$, with a moderate effect size difference for CS, $t(20) = 2.70$, $p < 0.01$, $d = 1.15$ and FI%, $t(20) = 2.05$, $p < 0.001$, $d = 0.88$. No significant differences were observed for D', $p = -0.205$. In the breaststroke group, very large differences were observed for the MSS, $t(14) = 4.77$, $p = 0.001$, $d = 2.38$, and CS, $t(14) = 5.29$, $p < 0.001$, $d = 2.65$. No statistical differences were observed in D' for which no further comparisons were made.

Table 5.1. Comparisons of 3MT performance variables for freestyle and secondary stroke per group (mean ± SD).

Variable	Freestyle 3MT	2nd stroke 3MT	Statistic	Effect Size
Backstroke (n = 11)				
MSS	1.60 ± 0.11	1.40 ± 0.12	4.12***	1.79
CS	1.28 ± 0.10	1.17 ± 0.09	2.70**	1.15
D'	21.79 ± 10.21	16.82 ± 5.29	1.43 ¥	0.61
ASR	0.32 ± 0.09	0.22 ± 0.06	2.97**	1.27
FI%	0.20 ± 0.05	0.16 ± 0.03	2.05*	0.88
Breaststroke (n = 8)				
MSS	1.57 ± 0.13	1.29 ± 0.11	4.77***	2.38
CS	1.26 ± 0.09	1.03 ± 0.09	5.29***	2.65
D'	21.70 ± 9.30	14.36 ± 5.03	1.96	0.98
ASR	0.31 ± 0.09	0.26 ± 0.08	1.26	0.63
FI%	0.20 ± 0.05	0.20 ± 0.05	-0.07 ¥	-0.03
Butterfly (n = 1)				
MSS	1.60	1.52		

CS	1.42	1.26
D'	13.31	14.34
ASR	0.18	0.26
FI%	0.11	0.17

$*p < 0.05$, $**p < 0.01$, $***p < 0.001$; ¥ Wilcoxon test was used for analysis.
Note. For the Student t-test, effect size is given by Cohen's d. For the Wilcoxon test, effect size is given by the matched rank biserial correlation.

Interestingly, when comparing the relationship between each freestyle 3MT variable to their stroke technique counterpart, they showed large to nearly perfect correlations, $r = 0.62$ – 0.93, $p < 0.001$ – 0.05 (Table 5.2). The exception was in D' for the backstroke group which had a large non-significant correlation, $r = 0.53$, $p = 0.09$.

Table 5.2. Correlation between 3MT performance variables of different stroke modalities.

	Free vs Backstroke 3MT	**Free vs Breaststroke 3MT**
MSS	0.81**	0.93***
CS ¥	0.85**	0.76*
D'	0.53	0.83*
FI%	0.62*	0.71*
ASR	0.63*	0.76*

* p < .05, ** p < .01, *** p < .001. ¥ = indicates that Spearman's rho was used for analysis.

Due to the demanding nature of performing a 3MT, planning to perform multiple 3MT tests for athletes who swim events using many or all strokes (i.e., individual medley swimmers) could be a highly fatiguing and cumbersome task. If a coach desires to accurately predict the CS for other strokes for training purposes, since FI% between both 3MT were not different and correlated to each other, we could attempt to predict them by multiplying FI% from the freestyle 3MT with the MSS from other strokes measured by a simple 25m sprint swim using Equation 6.

Equation 6. CS_{STR} ($m.s^{-1}$) = MSS_{STR} x (1 – $FI\%_{FR}$ of 3MT in freestyle) where CS_{STR} is the predicted CS of the secondary stroke, MSS_{STR} is the actual MSS of the secondary stroke measured by a 25 m sprint swim pushing from the wall, $FI\%_{FR}$ is the actual FI% of the 3MT in freestyle.

When comparing the actual and predicted CS for the backstroke and breaststroke groups using their respective freestyle 3MT FI%, no statistically significant differences were found, p = 0.27 and p = 0.97, respectively (Table 5.3). A graphical representation of the speed profiles of one athlete performing the 3MT in freestyle and their respective secondary stroke is shown in figure 5.1.

Table 5.3. Comparing actual vs predicted critical speed of secondary strokes using freestyle 3MT fatigue index and secondary stroke maximum sprinting speed.

Group	N	Mean	Statistic	*p*	Effect Size
Backstroke					
Actual	11	1.17 ± 0.09	1.14	0.27	0.49
Predicted	11	1.12 ± 0.11			
Breaststroke					
Actual	8	1.03 ± 0.09	-0.03	0.97	-0.02
Predicted	8	1.04 ± 0.06			
Butterfly					
Actual	1	1.26			
Predicted	1	1.35			

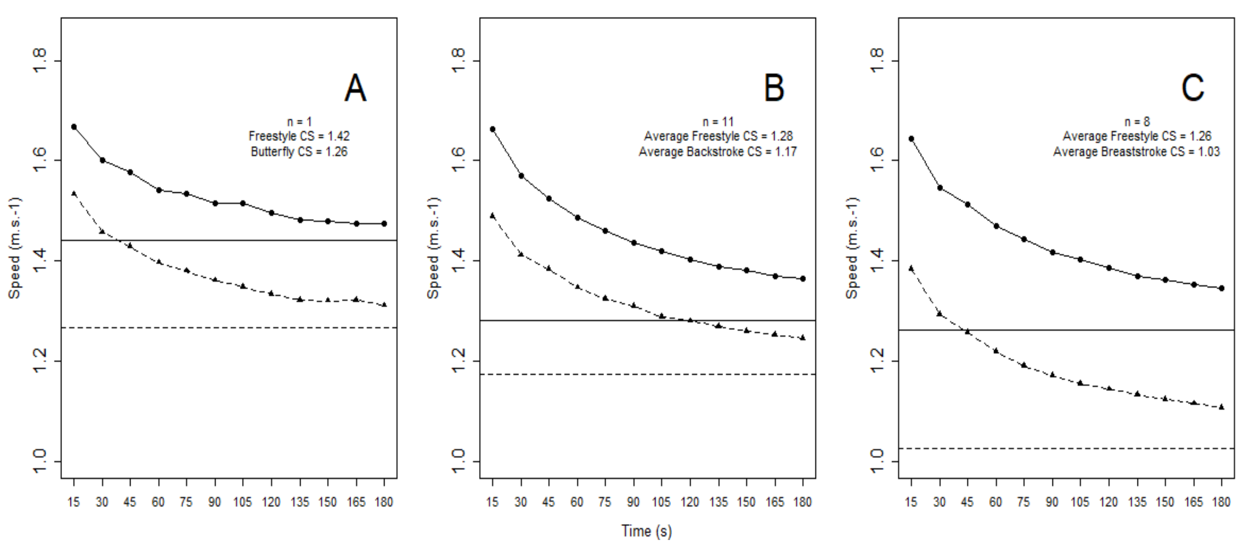

Figure 5.1. Average speed drop-off for swimmers who performed the three-minute all-out swimming test (3MT) in freestyle (solid black line with solid black circles) and secondary stroke (dashed line with solid triangles), such as, butterfly (A), backstroke (B), and breaststroke (C). The solid horizontal line represents the CS for the freestyle 3MT, while the dashed horizontal line represents the CS for the secondary stroke 3MT.
Note: 3MT = three-minute all-out swimming test.

Discussion

The current study was the first seeking to compare the speed profiles and the variables derived from two 3MT in swimming using the freestyle and a secondary stroke (butterfly, backstroke, or breaststroke) within the same athlete. As expected, the speed decay followed a similar rate drop-off pattern across different strokes (Figure 5.1). However, the differences in the MSS and CS in the backstroke group had differing magnitude effect size classifications ($d = 1.79$ and 1.15, for MSS and CS, respectively) compared to the breaststroke group ($d = 2.38$ and 2.65, for MSS and CS, respectively) when analyzing them against their respective freestyle 3MT variables. Moreover, ASR and FI% statistical comparisons also differed between stroke groups. The backstroke group reached statistical significance with moderate and large magnitude effect differences in FI% and ASR, respectively ($p < 0.01$), but moderate and small non-significant changes were observed for the breaststroke group ($p = 0.23$ - .93). On the other hand, D' did not reach statistical significance despite moderate changes in both groups. It is possible that the differences in the resulting comparisons for each group may be due to biomechanical and energetic efficiency differences given that backstroke has a continuous stroke pattern while breaststroke is discontinuous (Barbosa et al., 2006; Neiva et al., 2010). This shows the importance of the specificity principle when performing testing to prescribe training. One possible reason for the backstroke group presenting differences in ASR and FI% could be due to the MSS in the secondary stroke (backstroke) which was not as fast relative to their freestyle counterpart. The large magnitude effect difference in MSS for the backstroke group was greater than that for the CS, and research has shown that steeper drops from peak velocities tend to show greater FI% (Kramer et al., 2019). Interestingly, despite the very large to near perfect correlations between ASR and D’ during pre- and post-season data (see Chapter 4) the latter had moderate non-statistically significant differences in both groups when compared to their freestyle counterparts. This may indicate that swimming at intensities above CS for different strokes may have differing energy rate usage of available D’, but more research needs to be done to reach a solid conclusion on this aspect.

If we follow the “SAID” principle, swimmers that perform multiple events involving a variety of strokes, especially individual medley swimmers, may need to identify threshold parameters that are specific to each swimming stroke to drive training prescription (Hermosilla et al., 2021). However, performing multiple 3MT may not be feasible and may add to unnecessary fatigue. Hence, while maintaining time efficiency with testing protocols is important, performing one 3MT in freestyle and additional MSS tests in other strokes may help in predicting the CS for a secondary stroke by using the FI% obtained in the freestyle 3MT (Equation 6). Our analysis showed that secondary stroke CS predictions did not statistically differ from the actual CS in either group, although the backstroke group had a moderate magnitude effect difference ($d = 0.49$). These result differences between groups could be due to the backstroke group not reaching a higher MSS relative to their freestyle 3MT homologous variable. For example, the percentage of MSS in which the CS was expressed at for both the secondary (breaststroke) and freestyle 3MT was about 80%, while in the backstroke group it was about 84% and 80%, respectively. This likely affected the FI% for the backstroke group as MSS would not have had such a steep drop-off compared to freestyle (Kramer et al., 2019).

Although the same did not happen in breaststroke, given that it has a discontinuous mechanical stroking pattern coupled with being the least energy efficient of the four strokes (Barbosa et al., 2006), it would have been expected for the speed to decay further and not have the same result as in the secondary stroke in the backstroke group. This could also explain how both ASR parameters obtained from the breaststroke group (freestyle and breaststroke 3MT) did not statistically differ despite small magnitude effect differences ($d = 0.23$). Discrepancies were also observed when correlating the 3MT variables within groups (freestyle 3MT vs secondary stroke 3MT variables). The breaststroke group showed stronger correlations for all variables except CS, while D' in the backstroke group did not reach statistical significance ($p = 0.09$).

Interestingly, the only athlete to perform the 3MT in butterfly observed a similar hyperbolic relationship when compared to in freestyle (Figure 5.1). A greater FI% was observed for the butterfly than in freestyle 3MT (17% and 11%, respectively), which could be expected given its discontinuous nature that has been shown to induce higher fatigue in the latter portion of a 100 m swimming race (Neiva et al., 2010). Hence, given the nature of a 3MT being an all-out exercise and of longer duration, this effect should be accentuated. Looking at Table 5.3, it seems that the prediction of CS in butterfly from the use of the freestyle 3MT data seems dubious in this athlete. This also puts in question the individual results from the backstroke and breaststroke groups, as although they did not statistically differ, individual variations may place confounding elements that could hinder such predictions. It might be possible that a preliminary prediction could be made, and this predicted CS be tested prior to training prescription with possible adjustments through practice.

Despite the differences in ASR and FI%, the D' in this case was similar in both 3MT (freestyle = 13.3 m vs butterfly = 14.3 m). This gives us a single case evidence showing similarities in D’ between a 3MT performed in different strokes despite other variables resulting differently. Other studies have shown variability in the results of D’ (Piatrikova et al., 2019; Tsai & Thomas, 2017) similar to that observed in the current study (CV = 31.5 - 46.9%). It is important to note that CS manifested at different percentages of the respective MSS for freestyle compared to butterfly (89% vs 83%, respectively). It must be understood that some aspects may affect D’, such as, glycogen status (Miura et al., 2000), anaerobic substrate breakdown capacity (Vanhatalo et al., 2016), exercise intensity prior to 3MT (Vanhatalo & Jones, 2009), calculation method used (see Chapter 3), and exercise modality (Cheng et al., 2012). This is an important detail to consider since other researchers studying the 3MT in swimming have had athletes perform the test in their best strokes combined in one group (Mitchell et al., 2017; Piatrikova et al., 2020) which could limit the comparability of D’ since it may not correlate to their homologous values across different strokes as shown in this study.

This study is not without its limitations, as no randomized order for testing was used since we chose to have the freestyle 3MT first to allow its continuity within the second study of Chapter 4 that could have affected the results of that study. Moreover, although test-retest reliability has been performed using freestyle for 3MT in swimming in freestyle (Piatrikova et al., 2019; Tsai & Thomas, 2017), none was performed specifically for the secondary strokes. Given the issues confronted with differences in variables between both secondary stroke groups and the single athlete in butterfly, this would need to be investigated in further research. Further research would need to be performed to understand how the speed decay from a 3MT in all four swimming strokes would result.

Conclusion

Speed decay during a 3MT using different strokes in swimming seems to follow similar drop-off patterns. Prediction of CS of secondary swimming strokes seems enticing, but special considerations must be placed on individual variations depending on swimming strokes. Caution must be taken concerning the derived variables, such as ASR, D', and FI% as differences may exist between different strokes used possibly due to the distinct stroke patterns involved in each swimming technique.

References

Abdi, H. (2010). Holm's Sequential Bonferroni Procedure. *Encyclopedia of Research Design.*, In Neil Salkind (Ed.), 1-8.

Abe, D., Tokumaru, H., Niihata, S., Muraki, S., Fukuoka, Y., Usui, S., & Yoshida, T. (2006). Assessment of Short-Distance Breastroke Swimming Performance With Critical Velocity. *Journal of Sports Science and Medicine*, 5: 340-348.

Aksit, T., Ozkol, M., Vural, F., Penkunlu, E., Aydinoglu, R., & Varol, R. (2017). Contribution of anthropometric characteristics to critical swimming velocity and estimated propulsive force. *Journal of Physical Education and Sport*, 17(1): 212-218.

Amaro, N., Morouco, P., Marques, M., Batalha, N., Neiva, H., & Marinho, D. (2018). A systematic review on dry-land strength and conditioning training on swimming performance. *Science & Sports*, 34(1): e1-e14.

Anderson, M., Hopkins, W., Roberts, A., & Pyne, D. (2006). Monitoring seasonal and long-term changes in test performance in elite swimmers. *European Journal of Sports Science*, 6(3): 145-154.

Arroyo-Toledo, J., Clemente, V., González-Ravé, J., Ramos Campo, D., & Sortwell, A. (2013). Comparison Between Traditional and Reverse Periodization: Swimming Performance and Specific Strength Values. *International Journal of Swimming Kinetics*, 2(1): 87-96.

Arroyo-Toledo, J., Clemente-Suárez, V., & Gonzales-Rave, J. (2016). Effects of Traditional and Reverse Periodization on Strength, Body-Composition and Swim Performance. *Imperial Journal of Interdisciplinary Research*, 2(12): 474-481.

Baldari, C., Fernandes, R., Meucci, M., Ribeiro, J., Vilas-Boas, J., & Guidetti, L. (2012). Is the New AquaTrainer Snorkel Valid for VO2 Assessment in Swimming? *International Journal of Sports Medicine*, 34(4): 336-344.

Balilionis, G., Nepocatych, S., Ellis, C., Richardson, M., Neggers, Y., & Bishop, P. (2012). Effects of Different Types of Warm-Up on Swimming Performance, Reaction Time, and Dive Distance. *Journal of Strength and Conditioning Research*, 26(12): 3297-3303.

Barbosa, T., Fernandes, R., Keskinen, K., & Vilas-Boas, J. (2008). The influence of stroke mechanics into energy cost of elite swimmers. *European Journal of Applies Physiology*, 130(2): 139-149.

Barbosa, T., Fernandes, R., Keskinen, K., Colaco, P., Cardoso, C., Silva, J., & Vilas-Boas, J. (2006). Evaluation of the Energy Expenditure in Competitive Swimming Strokes. *International Journal of Sports Medicine*, 27(11): 894-899.

Bassett, D. (2002). Scientific contributions of A.V. Hill: exercise physiology pioneer. *Journal of Applied Physiology*, 93: 1567-1582.

Batalha, N., Raimundo, A., Tomas-Carus, P., Paulo, J., Simao, R., & Silva, A. (2015). Does a land-based compensatory strength-training programme influences the rotator cuff balance of young competitive swimmers? *European Journal of Sports Science*, 15(8): 764-772.

Bazyler, C., Abbott, H., Bellon, C., Taber, C., & Stone, M. (2015). Strength for Endurance Athletes: Theory to Practice. *Journal of Strength and Conditioning*, 37(2): 1-12.

Beaver, W., Wasserman, K., & Whipp, B. (1986). A new method for detecting anaerobic threshold by gas exchange. *Journal of Applied Physiology*, 60(6): 2020-2027.

Beckham, G., Lish, S., Keebler, L., Longaker, C., Disney, C., DeBlasio, M., & Adams, K. (2019). The Reliability of the Seated Medicine Ball Throw for Distance. *Journal of Physical Activity Research*, 4(2): 131-136.

Bergstrom, H., Dinyer, T., Succi, P., Voskuil, C., & Housh, T. (2021). Applications of the Critical Power Model to Dynamic Constant External Resistance Exercise: A Brief Review of the Critical Load Test. *Sports*, 9(2): 1-15.

Billat, V. (2001). Interval Training for Performance: A Scientific and Empirical Practice. Special Recommendations for Middle- and Long-Distance Running. Part II: Anaerobic Interval Training. *Sports Medicine*, 31(2): 75-90.

Billat, V., Sirvent, P., Py, G., Koralsztein, J., & Mercier, J. (2003). The Concept of Maximal Lactate Steady State. *Sports Medicine*, 33(6): 407-426.

Bishop, C., Cree, J., Read, P., Chavda, S., Edwards, M., & Turner, A. (2013). Strength and Conditioning for Sprint Swimming. *Strength and Conditioning Journal*, 35(6): 1-6.

Bishop, D., & Jenkins, D. (1996). The Influence of Resistance Training on the Critical Power Function & Time to Fatigue at Critical Power. *The Australian Journal of Science and Medicine in Sport*, 28(4): 101-105.

Bonen, A., Wilson, B., Yarkony, M., & Belcastro, A. (1980). Maximal oxygen uptake during free, tethered, and swim flume swimming. *Journal of Applied Physiology*, 48(2): 232-235.

Brooks, G. (1985). Anaerobic threshold: review of the concept and directions for future research. *Medicine and Science in Sport and Exercise*, 17(1): 22-31.

Buchheit, M., & Laursen, P. (2013). High-Intensity Interval Training, Solutions to the Programming Puzzle: Part II: Anaerobic Energy, Neuromuscular Load and Practical Applications. *Sports Medicine*, 43(10): 927-954.

Buchheit, M., & Luarsen, P. (2013). High-Intensity Interval Training, Solutions to the Programming Puzzle - Part I: Cardiopulmonary Emphasis. *Sports Medicine*, 43(5): 313-338.

Bundle, M., & Weyand, P. (2012). Sprint Exercise Performance: Does Metabolic Power Matter? *Exercise and Sports Science Reviews*, 40(3): 174-182.

Burnley, M., & Jones, A. (2007). Oxygen uptake kinetics as a determinant of sports performance. *European Journal of Sports Science*, 7(2): 63-79.

Burnley, M., Doust, J., & Vanhatalo, A. (2006). A 3-min All-out Test to Determine Peak Oxygen Uptake and the Maximal Steady State. *Medicine and Science in Sport and Science*, 38(11): 1995-2003.

Carroll, K., Bernards, J., Bazyler, C., Taber, C., Stuart, C., DeWeese, B., . . . Stone, M. (2018). Divergent Performance Outcomes Following Resistance Training Using Repetition Maximums or Relative Intensity. *International Journal of Sports Physiology and Performance*, 14(1): 1-28.

Chaverri, D., Schuller, T., Iglesias, X., Hoffman, U., & Rodriguez, F. (2016). A New Model for Estimating Peak Oxygen Uptake Based on Postexercise Measurements in Swimming. *International Journal of Sports Physiology and Performance*, 11(4): 419-424.

Cheng, C., Yang, Y., Lin, H., Lee, C., & Wang, C. (2012). Determination of critical power in trained rowers using a three-minute all-out rowing test. *European Journal of Applied Physiology*, 112: 1251-1260.

Clark, I., West, B., Reynolds, S., Murray, S., & Pettitt, R. (2013). Applying the Critical Velocity Model for an Off-Season High Intensity Interval Training Program. *Journal of Strength and Conditioning Research*, 27(12): 3335-3341.

Corry, I., & Powers, N. (1982). Maximal Aerobic Power Measurement in Runners and Swimmers. *British Journal of Sports Medicine*, 16(3): 154-160.

Courtwright, S., Williams, J., Clark, I., Pettitt, R., & Dicks, N. (2016). Monitoring Interval-traininf Responses for Swimming using the 3-min All-out Exercise Test. *International Journal of Exercise Science*, 9(5): 545-553.

Crowley, E., Harrison, A., & Lyons, M. (2018). Dry-Land Resistance Training Practices of Elite Swimming Strength and Conditioning Coaches. *Journal of Strength and Conditioning Research*, 32(9): 2592-2600.

Dalamitros, A., Fernandes, R., Toubekis, A., Manou, V., Loupos, D., & Kellis, S. (2015). Is speed reserve related to critical speed and anaerobic distance capacity in swimming? *Journal of Strength and Conditioning Research*, 29(7): 1830-1836.

Debanne, T., & Laffaye, G. (2011). Predicting the throwing velocity of the ball in handball with anthropometric variables and isotonic tests. *Journal of Sports Sciences*, 29(7): 705-713.

Dekerle, J., Sidney, M., Hespel, J., & Pelayo, P. (2002). Validity and Reliability of Critical Speed, Critical Stroke Rate, and Anaerobic Capacity in Relation to Front Crawl Swimming Performances. *International Journal of Sports Medicine,* 23: 93-98.

DeWeese, B., Sams, M., Williams, J., & Bellon, C. (2015). The Nature of Speed: Enhancing Sprint Abilities Through a Short to Long Training Approach. *Techniques for Track & Field and Cross Country,* 8(4): 8-22.

DeWeese, B., Wagle, J., & Bingham, G. (2019). Let the rhythm hit them: Adjusting the tempo to skilffully surf the intensity curve. . *Techniques Magazine*, 10(4): 52-59.

DiMenna, F., & Jones, A. (2019). Aerobic performance assessment. In P. Comfort, P. Jones, & J. McMahon, *Performance Assessment in Strength and Conditioning* (pp. 212-239). Abingdon, Oxon: Routledge.

Edge, J., Hill-Haas, S., Goodman, C., & Bishop, D. (2006). Effects of resistance training on H+ regulation, buffer capacity, and repeated sprints. *Medicine and Science in Sports and Exercise,* 38(11): 2004-2011.

Espada, M., & Alves, F. (2010). Critical Velocity and the Velocity at Maximal Lactate Steady State in Swimming. *Biomechanics and Medicine in Swimming XI* (pp. 194-196). Oslo: Norwegian School of Sports Science.

Espada, M., Costa, A., Louro, H., Conceiao, A., Filho, D., & Pereira, A. (2016). Anaerobic Critical Velocity and Sprint Swimming Performance in Masters Swimmers. *International Journal of Sports Science*, 6(1A): 31-35.

Farrell, P., Wilmore, J., Coyle, E., Billing, J., & Costill, D. (1979). Plasma lactate accumulation and distance running performance. *Medicine and Sciennce in Sports and Exercise*, 25(10): 1089-1090.

Ferguson, C., Rossiter, H., Whipp, B., Cathcart, A., Murgatroyd, S., & Ward, S. (2010). Effect of recovery duration from prior exhaustive exercise on the parameters of the power-duration relationship. *Journal of Applied Physiology*, 108(4): 866-874.

Fernandes, R., Sousa, M., Machado, L., & Vilas-Boas, J. (2011). Step Length and Individual Anaerobic Threshold Assessment in Swimming. *International Journal of Sports Medicine*, 32(12): 940-946.

Fig, G. (2010). Why Competitive Swimmers Need Explosive Power. *Strength and Conditioning Journal*, 32(4): 84-86.

Fone, L., & van den Tillar, R. (2022). Effects of Different Types of Strength Training on Swimming Performance in Competitive Swimmers: A Systematic Review. *Sports Medicine*, 8(1): 1-26.

Galbraith, A., Hopker, J., Lelliot, S., Diddams, L., & Passfield, L. (2014). A Single-Visit Field Test of Critical Speed. *International Journal of Sports Physiology and Performance*, 9(6): 931-935.

González-Ravé, J., Pyne, D., Castillo, J., González-Mohíno, F., & Stone, M. (2021). Training periodization for a world-class 400 meters individual medley swimmer. *Biology of Sport*, 39(4): 883-888.

Green, S. (1995). Measuring of Anaerobic Work Capacities in Humans. *Sports Medicine*, 19(1): 32-42.

Green, S., & Dawson, B. (1993). Measurment of Anaerobic Capacities in Humans: Definitions, Limitations, and Unsolved Problems. *Sports Medicine*, 15(5): 312-327.

Greenshields, J., Goss, C., & Stager, J. (2018). Variation in Critical Speed and Finite Distance Capacity of Elite Swimmers. *Annual Meeting of the American College of Sports Medicine* (p. 50(5S): 525). Minneapolis: Medicine and Science in Sports and Exercise.

Haff, G. (2019). The essentials of periodization. In I. Jeffreys, & J. Moody, *Strength and Conditioning for Sports Performance* (pp. 404-448). Abingdon, London: Routledge.

Hale, T. (2008). History of developments in sport and exercise physiology: A.V. Hill, maximal oxygen uptake, and oxygen debt. *Journal of Sports Sciences*, 26(4): 365-400.

Hall, G., & Murphy, D. (2020). *Fundamentals of Fast Swimming: How to Improve Your Swimming Technique.* Islamorada, FL: The Race Club.

Hellard, P. P. (2018). Dynamics of the metabolic response during a competitive 100-m freestyle in elite male swimmers. *International Journal of Sports Physiology and Performance*, 13(10): 1011-1020.

Hellard, P., Avalos-Fernandes, M., Lefort, G., Pla, R., Mujika, I., Toussaint, J., & Pyne, D. (2019). Elite swimmers' training patterns in the 25 weeks prior to their season's best performances: insights into periodization from a 20-years cohort. *Frontiers in Physiology*, 10(363): 1-16.

Hellard, P., Pla, R., Rodríguez, F., Simbana, D., & Pyne, D. (2018). Dynamics of the metabolic response during a competitive 100-m freestyle in elite male swimmers. *International Journal of Sports Physiology and Performance*, 13(10): 1011-1020.

Hermosilla, F., González-Ravé, J., Del Castillo, J., & Pyne, D. (2021). Periodization and programming for individual 400 m medley swimmers. *International Journal of Environmental Research and Public Health*, 18(12): 6474.

Hill, A., & Lupton, H. (1923). Muscular Exercise, Lactic Acid, and the Supply and Utilization of Oxygen. *International Journal of Medicine*, 16(62): 135-171.

Hill, D. (1993). The critical power concept. A review. . *Sports Medicine*, 16(4): 237-254.

Hopkins, W. (2015). *Spreadsheets for analysis of validity and reliability. Sportscience 19, 36-42*. Retrieved from Sportscience: sportsci.org/2015/ValidRely.htm

Hopkins, W., Marshall, S., Batterham, A., & Hanin, J. (2009). Progressive Statistics for Studies in Sports Medicine and Exercise Science. *Medicine & Science in Sports & Exercise*, 41(1): 3-12.

Hurd, K., Surges, M., & Farell, J. (2022). Use of Exercise Training to Enhance the Power-Duration Curve: A Systematic Review. *Journal of Strength and Conditioning Research*, XX(X): 000-000.

Issurin, V. (2008). Block periodization versus traditional training theory: a review. *Journal of Sports Medicine and Physical Fitness*, 48(1): 65-75.

Jones, A., & Vanhatalo, A. (2017). The 'Critical Power' Concept: Applications to Sports Performance with a Focus on Intermittent High-Intensity Exercise. *Sports Medicine*, 47(1): S65-S78.

Jones, A., Grassi, B., Christensen, P., Krustrup, P., Bangsbo, J., & Poole, D. (2011). Slow Component of V̇O2 Kinetics: Mechanistic Bases and Practical. *Medicine and Science in Sport and Exercise*, 43(11): 2046-2062.

Jorgić, B., Puletić, M., Okičić, T., & Meškovska, N. (2011). Importance of Maximal Oxygen Consumption During Swimming. *Physical Education and Sport*, 9(2): 183-191.

Kao, S., Ishida, A., & Ainsworth, B. (2018). The Correlation Between Strength and Power Measures with Sprint Freestyle Performance in Division 1 Collegiate Swimmers. *Journal of Swimming Research*, 26(1): 22-31.

Karsten, B., Stevens, L., Colpus, M., Larumbe-Zabala, E., & Naclerio, F. (2014). The Effects of Sport-Specific Maximal Strength and Conditioning Training on Critical Velocity, Anaerobic Running Distance, and 5-km Race Performance. *International Journal of Sports Physiology and Performance*, 11(1): 80-85.

Keiner, M., Wirth, K., Fuhrmann, S., Kunz, M., Hartmann, H., & Haff, G. (2019). The Influence of Upper- and Lower-Body Maximum Strength on Swim Block Start, Turn, and Overall Swim Performance in Sprint Swimming. *Journal of Strength and Conditioning Research*, 35(10): 2839-2845.

Koo, T., & Li, M. (2016). A Guideline of Selecting and Reporting Intraclass Correlation Coefficients for Reliability Research. *Journal of Chiropractic Medicine*, 15: 155-163.

Kramer, M., Du Randt, R., Watson, M., & Pettitt, R. (2019). Bi-exponential modeling derives novel parameters for the critical speed concept. *Physiological Reports*, 7(4): 1-9 e13993.

Latt, E., Jurimae, J., Maestu, J., Purge, P., Ramson, R., Haljaste, K., . . . Jurimae, T. (2010). Physiological, biomechanical, and anthropometrical predictors of sprint swimming performance in adolescent swimmers. *Journal of Sport Sciences and Medicine*, 9(1): 398-404.

Lavoie, J., Lèger, L., Leone, M., & Provencher, P. (1985). A Maximal Multistage Swim Test to Determine the Functional and Maximal Aerobic Power of Competitive Swimmers. *Journal of Swimming Research*, 1(2): 17-22.

Leblanc, H., Seifert, L., Tourny-Chollet, C., & Chollet, D. (2007). Intra-cyclic Distance per Stroke Phase, Velocity Fluctuations and Acceleration Time Ratio of a Breastroker's Hip: A Comparison between Elite and Nonelite Swimmers at Different Race Paces. *International Journal of Sports Medicine*, 28(2): 140-147.

Libicz, S., Roels, B., & Millet, G. (2005). VO2 Responses to Intermittent Swimming Sets at Velocity Associated to VO2max. *Canadian Journal of Applied Physiology*, 30(5): 543-553.

Lopes, T., Goncalves, C., Graca, C., Neiva, H., & Marinho, D. (2019). The Relationship between Front Crawl Swimming Performance and Strength Variables in College Swimmers. *Ergonomics International Journal*, 3(2): 1-9.

Machado, M., Borges, J., Galdino, I., Cunha, L., Souza-Sá Filho, A., Soares, D., & Junior, I. (2018). Does critical velocity represent the maximal lactate steady state in youth swimmers? *Science & Sport*, 34(3): 1-7.

Machado, M., Junior, O., Marques, A., Colantonio, E., Cyrino, E., & De Mello, M. (2011). Effect of 12 weeks of training on critical velocity and maximal lactate steady state in swimmers. *European Journal of Sport Science*, 11(3): 165-170.

Magel, J., & Faulkner, J. (1967). Maximum oxygen uptakes of college swimmers. *Journal of Applied Physiology*, 22(5): 929-938.

Mann, B., Ivey, P., Brechue, W., & Mayhew, J. (2015). Validity and Reliability of Hand and Electronic Timing for 40-yd Sprint in College Football Players. *Journal of Strength and Conditioning Research*, 29(6): 1509-1514.

Marinho, D., Amorim, R., Costa, A., Marques, M., Pérez-Turpin, J., & Neiva, H. (2011). "Anaerobic" critical velocity and swimming performance in young swimmers. *Journal of Human Sport and Exercise*, 6(1): 80-86.

Marinho, D., Barbosa, T., Silva, A., & Neiva, H. (2012). Applying Anaerobic Critical Velocity in Non-Elite Swimmers. *International Journal of Swimming Kinetics*, 1(1): 33-50.

Mattioni-Maturana, F., Fontana, F., Pogliaghi, S., Passfield, L., & Murias, J. (2018). Critical power: How different protocols and models affect its determination. *Journal of Science and Medicine in Sport*, 21(7): 742-747.

Mauger, A., Neuloh, J., & Castle, P. (2012). Analysis of Pacing Strategy Selection in Elite 400-m Freestyle Swimming. *Medicine and Science in Sport and Exercise*, 44(11): 2205-2212.

McArdle, W., Katch, F., & Katch, V. (2015). *Exercise Physiology: Nutrition, Energy, and Human Performance.* Baltimore, MD: Wolters-Kluwers.

Mitchell, L., Pyne, D., Saunders, P., & Rattray, B. (2017). Reliability and validity of a modified 3-minute all-out swimming test in elite swimmers. *European Journal of Sports Science*, 18(3): 307-314.

Miura, A., Endo, M., Sato, H., Sato, H., Barstow, T., & Fukuba, Y. (2002). Relationship between the curvature constant parameter of the power-duration curve and muscle cross-sectional area of the thigh for cycle ergometry in humans. *European Journal of Applied Physiology*, 87(3): 238-244.

Miura, A., Sato, H., Sato, H., Whipp, B., & Fukuba, Y. (2000). The effect of glycogen depletion on the curvature constant parameter of the power-duration curve for cycle-ergometry. *Ergonomics*, 43(1): 133-141.

Monod, H., & Scherrer, J. (1965). The work capacity of a synergic muscular group. *Ergonomics*, 8: 329-338.

Montpetit, R., Léger, L., Lavoie, J., & Cazorla, G. (1981). V̇02 Peak During Free Swimming Using the Backward Extrapolation of the O2 Recovery Curve. *European Journal of Applied Physiology*, 47(4): 385-391.

Morán-Navarro, R., Pérez, C., Mora-Rodríguez, R., de la Cruz-Sánchez, E., González-Badillo, J., Sánchez-Medina, L., & Pallarés, J. (2017). Time course of recovery following resistance training leading or not to failure. . *European Journal of Applied Physiology*, 117(12): 2387-2399.

Moritani, T., Nagata, A., DeVries, H., & Muro, M. (1981). Critical power as measure of physical work capacity and anaerobic threshold. *Ergonomics*, 24(5): 339-350.

Morouco, P., Marinho, D., Keskinen, K., Badillo, J., & Marques, M. (2014). Thethered Swimming Can Be Used to Evaluate Force Contribution for Short-Distance Swimming Performance. *Journal of Strength and Conditioning Research*, 28(11): 3093-3099.

Mougios, V. (2006). *Exercise Biochemistry*. Champaign, Ill. : Human Kinetics.

Mujika, I., & Crowley, E. (2019). Strength Training for Swimmers. In M. Schumann, & B. Ronnestad, *Concurrent Aerobic and Strength Training: Scientific Basics and Practical Applications* (pp. 369-386). Switzerland: Springer International Publishing AG.

Mujika, I., Chatard, J., Busso, T., Geyssant, A., Barale, F., & Lacoste, L. (1995). Effects of training on performance in competitive swimming. *Canadian journal of applied physiology*, 20(4): 395-406.

Neiva, H., Fernandes, R., & Vilas-Boas, J. (2010). Anaerobic Critical Velocity in Four Swimming Techniques. *International Journal of Sports Medicine*, 32(1): 195-198.

Nevill, A., Negra, Y., Myers, T., Sammond, S., & Chaabene, H. (2020). Key somatic variables associated with, and differences between the 4 swimming strokes. *Journal of Sports Sciences*, 38(7): 787-794.

Noakes, T. (2008a). How did AV Hill understand the V̇O2max and the "plateau phenomenon"? Still no clarity? *British Journal of Sports Medicine*, 42: 574-580.

Noakes, T. (2008b). Testing for maximum oxygen consumption has produced a brainless mode of human exercise performance. *British Journal of Sports Medicine*, 42(7): 551-555.

Noordhof, D., Koning, J., & Foster, C. (2010). The Maximal Accumulated Oxygen Deficit Method. *Sports Medicine*, 40(4): 285-302.

Norouzi, M., Cabuk, R., Balki, G., As, H., & Ozkaya, O. (2021). The Effect of Using Different Exhaustion Intervals and Mathematical Models on Critical Power Estimations. *Hacettepe Journal of Sports Sciences*, 32(3): 151-166.

Nugent, F., Comyns, T., Kearney, P., & Warrington, G. (2019). Ultra-Short Race-Pace Training (USRPT) In Swimming: Current Perspectives. *Open Access Journal of Sports Medicine*, 10(1): 133-144.

Ogita, F. (2006). Energetics in competitive swimming and its applications for training. . *International Symposium on Biomechanics and Medicine in Swimming* (pp. 6(2): 117-121). Porto Faculdade de Desporto da Universidade do Porto.

Olbrecht, J. (2013). *The Science of Winning: Planning, Periodizing and Optimizing Swim Training.* Antwerp, Belgium: F&G Partners.

Painter, K., Haff, G., Ramsey, M., McBride, J., Triplett, T., Sands, W., . . . Stone, M. (2012). Strength gains: block versus daily undulating periodization weight training among track and field athletes. *International Journal of Sports Physiology and Performance*, 7(2): 161-169.

Painter, K., Rodriguez-Castellano, L., & Stone, M. (2020). High Volume Resistance Training and its Effects on Anaerobic Work Capacity Over Time: A Review. *The Sport Journal*, 3(1): 1-17.

Palao, J., & Valdés, D. (2013). Testing protocol for monitoring upper-body strength using medicine balls. *Journal of Human Sport & Exercise*, 8(2): 334-341.

Papoti, M., da Silva, A., Araujo, G., Santiago, V., Martins, L., Cunha, S., & Gobatto, C. (2011). Aerobic and Anaerobic Performances in Tethered Swimming. *International Journal of Sports Medicine*, 34(8): 712-719.

Pareja-Blanco, F., Rodríguez-Rosell, D., Aagaard, P., Sánchesz-Medina, L., Ribas-Serna, J., Mora-Custodio, R., . . . González-Badillo, J. (2020). Time Course of Recovery From Resistance Exercise With Different Set Configurations. *Journal of Strength and Conditioning Research*, 34(10): 2867-2876.

Pelayo, P., & Alberty, M. (2011). The History of Swimming Research. In L. Seifert, D. Chollet, & I. Mujika, *World Book of Swimming: From Science to Performance* (pp. ix - xxvi). Hauppauge, New York: Nova Science Publishers, Inc.

Peters, M., Berry, S., & Koley, S. (2014). Relationship of physical characteristics, power and swimming time in sprint swimmers. *Annals of Biological Research*, 5(8): 24-29.

Pettitt, R. (2016). Applying the Critical Speed Concept to Racing Strategy and Interval Training Prescription. *International Journal for Sports Physiology and Performance*, 11(7): 842-847.

Pettitt, R., Jamnick, N., & Clark, E. (2012). 3-min All-out Exercise Test for Running. *International Journal of Sports Medicine*, 33: 426-431.

Piatrikova, E., Sousa, A., Gonzalez, J., & Williams, S. (2019). Validity and reliability of the 3-minute all-out test in national and international competitive swimmers. *International Journal of Sports Physiology and Performance*, 13(9): 1190-1198.

Piatrikova, E., Sousa, A., Willsmer, N., Gonzalez, J., & Williams, S. (2018). Demarcating exercise intensity domains in freestyle swimming: is there and alternative to incremental step test and beats below HRmax method? . *Journal of Strength and Conditioning Research*, 34(9): 2575-2584.

Piatrikova, E., Willsmer, N., Altini, M., Mladen, J., Lachlan, M., Gonzalez, J., . . . Williams, S. (2021). Monitoring the heart rate variability responses to training loads in competitive swimmers using a smartphone application and the Banister Impulse-Response model. *International Journal of Sports Physiology and Performance*, 16(6):787-795.

Piatrikova, E., Willsmer, N., Sousa, A., Gonzalez, J., & S, W. (2020). Individualizing training in swimming; is there a place for the application of the critical speed and critical stroke rate concepts? *International Journal of Sports Physiology and Performance*, 15(5): 1-8.

Pla, R., Leroy, A., Massal, R., Bellami, M., Kaillani, F., Hellard, P., . . . Sedeaud, A. (2019). Bayesian approach to quantify morphological impact on performance in international elite freestyle swimming. *BMJ Open Sport & Exercise Medicine*, 5: 1-7.

Poole, D., & Jones, A. (2012). Oxygen Uptake Kinetics. *Comprehensive Physiology*, 2(2): 933-996.

Poole, D., Burnley, M., Vanhatalo, H., Rossiter, B., & Jones, A. (2016). Critical Power: An Important Fatigue Threshold in Exercise Physiology. *Medicine and Science in Sports and Exercise*, 48(11): 2320-2334.

Poole, D., Rossiter, H., Brooks, G., & Gladden, L. (2021). The Anaerobic Threshold: 50+ Years of Controversy. *The Journal of Physiology*, 599(3): 737-767.

Pyne, D., Maw, G., & Goldsmith, W. (2000). Protocols for the Physiological Assessment of Swimmers. In A. S. Commission, *Physiological Tests for Elite Athletes* (pp. 372-382). Champaign, Ill: Human Kinetics.

Ramos, R., Requena, B., Suarez-Arrones, L., Newton, R., & Sáez de Villareal, E. (2014). Effects of 18-Week In-Season Heavy-Resistance and Power Training on Throwing Velocity, Strength, Jumping, and Maximal Sprint Swim Performance of Elite Male Water Polo Players. *Journal of Strength and Conditioning Research*, 28(4): 1007-1014.

Ramos-Veliz, R., Requena, B., Suarez-Arrones, L., Newton, R., & Sáez de Villareal, E. (2014). Effects of 18-week in-season heavy resistance and power training on throwing velocity, strength, jumping, and maximal sprint swim performance of elite male water polo players. *Journal of Strength and Conditioning Research*, 28(4): 1007-1014.

Ramya, G., Guru, C., Banodhe, G., Dominic, D., & Sharma, H. (2021). Resumption to Swimming Post COVID 19 Lockdown. *Journal of Clinical and Diagnostic Research*, 15(1): 1-5.

Raymond, D. (2012). The effect of aerobic fitness on the cardiovascular and sympathetic nervous system response to physiological stress at rest and during dynamic exercise. *Thesis*.

Reis, V., Marinho, D., Barbosa, F., Reis, A., Guidetti, L., & Silva, A. (2010b). Examining the Accumulated Oxygen Deficit Method in Breaststroke Swimming. *European Journal of Applied Physiology*, 109(6): 1129-1135.

Reis, V., Marinho, D., Policarpo, F., Carneiro, A., Baldari, C., & Silva, A. (2010a). Examining the Accumulated Oxygen Deficit Method in Front Crawl Swimming. *International Journal of Sports Medicine*, 31(6): 421-427.

Rodríguez, F., & Mader, A. (2011). Energy Systems in Swimming. In L. Seifert, D. Chollet, & I. Mujika, *World Book of Swimming: From Science to Performance* (pp. 225-240). New York: Nova Science.

Rodríguez, F., Keskinen, K., Keskinen, O., & Malvela, M. (2003). Oxygen uptake kinetics during free swimming: a pilot study. *In: Chartard, JC, Biomechanics and Medicine in Swimming IX*, 379-384.

Rushall, B. (2016, March 14). *USRPT Defined: After Two Years USRPT Comes of Age.* Retrieved from Swimming Science Bulletin #49: https://coachsci.sdsu.edu/swim/bullets/49DEFINED.pdf

Salam, H., Marcora, S., & Hopker, J. (2017). The effect of mental fatigue on critical power during cycling exercise. *European Journal of Applied Physiology*, Available from: https://link.springer.com/article/10.1007/s00421-017-3747-1 [Accessed 22 March 2022].

Saltin, B., & Astrand, P. (1967). Maximal oxygen uptake in athletes. *Journal of Applied Physiology*, 23(3): 353-358.

Sandford, G., & Stellingwerff, T. (2019). "Questioning Your Categories": the Misunderstood Complexity of Middle-Distance Running Profiles With Implications for Research Methods and Application. *Frontiers in Sports and Active Living*, 1(28): 1-8.

Sandford, G., Kilding, A., Ross, A., & Luarsen, P. (2018). Maximal Sprint Speed and the Anaerobic Speed Reserve Domain: The Untapped Tools that Differentiate the World's Best 800 m Runners. *Sports Medicine*, 49(6): 843-852.

Sanford, G., Laursen, P., & Buchheit, M. (2021). Anaerobic Speed/Power Reserve and Sport Performance: Scientific Basis, Current Applications and Future Directions. *Sports Medicine*, 51(10): 2017-2028.

Sawyer, B., Stokes, D., Womack, C., Hugh, M., Weltman, A., & Gaesser, G. (2014). Strength Training Increases Endurance Time to Exhaustion During High-Intensity Exercise Despite No Change in Critical Power. *Journal of Strength and Conditioning Research*, 28(3): 601-609.

Scott, B., Burden, R., & Dekerle, J. (2020). Critical speed, D’ and pacing in swimming: reliability of a popular critical speed protocol applied to all four strokes. *Research Square*, 10.21203/rs.3.rs-77508/v1.

Shiyoyama, Y., Okita, K., Baba, Y., & Sato, D. (2010). Does the Y-Intercept of a Regression Line in the Critical Velocity Concept Represent the Index for Evaluating Anaerobic Capacity? *Biomechanics and Medicine in Swimming XI* (pp. 288-290). Oslo: Nordbergtrykk as.

Siders, W., Lukaski, H., & Bolonchuk, W. (1993). Relationship among swimming performance, body composition and somatotype in competitive collegiate swimmers. *Journal of Sports Medicine and Physical Fitness*, 33(2): 166-171.

Smith, D., Norris, S., & Hogg, J. (2002). Performance Evaluation of Swimmers: Scientific Tools. *Sports Medicine*, 32(9): 539-554.

Sousa, A., Figueiredo, P., Pendergast, D., Kjendlie, P., Vilas-Boas, J., & Fernandes, R. (2014). Critical Evaluation of Oxygen-Uptake Assessment in Swimming. *International Journal of Sports Physiology and Performance*, 9(2): 190-202.

Steiger, J. (1980). Tests for comparing elements of a correlation matrix. *Psychological Bulletin*, 87: 245-251.

Stockbrugger, B., & Haennel, R. (2001). Validity and Reliability of a Medicine Ball Explosive Power Test. *Journal of Strength and Conditioning Research*, 15(4): 431-438.

Stone, M., Hornsby, W., Haff, G., Fry, A., Suárez, D., Liu, J., . . . Pierce, K. (2021). Periodization and Block Periodization in Sports: Emphasis on Strength-Power Training-A Provocative and Challenging Narrative. *Journal of Strength and Conditioning Research*, 35(8): 2351-2371.

Stone, M., Stone, M., & Sands, W. (2007). *Principles and Practices of Resistance Training.* Champaign, Ill.: Human Kinetics.

Strzala, M., Stanula, A., Krezalek, P., Ostrowski, A., Kaca, M., & Glab, G. (2019). Influence of Morphology and Strength on Front Crawl Swimming Speed in Junior and Youth Age-Group Swimmers. *Journal of Strength and Conditioning Research*, 33(10): 2836-2845.

Toubekis, A., Gourgoulis, V., & Tokmakidis, S. (2010). Tethered Swimming as an Evaluation Tool of Single Arm-Stroke Force. *XIth International Symposium for Biomechanics and Medicine in Swimming.* Oslo, Norway: Norwegian School of Sports Sciences .

Toussaint, H. (2002). Biomechanics of Propulsion and Drag in Front Crawl Swimming. *Applied proceedings - XXth International Symposium on Biomechanics in Sports. University of Extremadura*, (pp. 11-22). Caceres, Spain.

Toussaint, H., & Beek, P. (1992). Biomechanics of Competitive Front Crawl Swimming. *Sports Medicine*, 13(1): 8-24.

Toussaint, H., Beelen, A., Rodenburg, A., Sargeant, A., de Groot, G., Hollander, A., & van Ingen Schenau, G. (1988). Propelling efficiency of front-crawl swimming. *Journal of Applied Physiology*, 65(6): 2506-2512.

Triska, C., Karsten, B., Nimmeritcher, A., & Tschan, H. (2017). Different exhaustive protocols affect estimates of critical speed and D´. *22nd Annual Congress of the European College of Sport Science.* Essen, Germany.

Tsai, M., & Thomas, S. (2017). 3-Min All-Out in Swimming. . *International Journal of Sports Physiology and Performance*, 12(1): 1-17.

Tsunokawa, T., Kadi, T., Mankyu, H., & Ogita, F. (2019). Estimation of hand propulsion forces at four swimming techniques using pressure measurement and underwater motion capture. *24th Annual Congress of the European College of Sport Science* (p. Abstract). Prague, Czech Republic: European College of Sports Science.

Vanhatalo, A., & Jones, A. (2009). Influence of prior sprint exercise on the parameters of the 'all-out critical power test' in men. *Experimental Physiology*, 94(2): 255-263.

Vanhatalo, A., Black, M., DiMenna, F., Blackwell, J., Schmidt, J., Thompson, C., . . . Jones, A. (2016). The mechanistic bases of the power-time relationship: muscle metabolic responses and relationship to muscle fiber type. *Journal of Physiology*, 594(15): 4407-4423.

Vanhatalo, A., Doust, J., & Burnley, M. (2007). Determination of Critical Power Using a 3-min All-out Cycling Test. *Medicine and Science in Sports and Exercise*, 39(3): 548-555.

Vanhatalo, A., Doust, J., & Burnley, M. (2008). Robustness of a 3 min all-out cycling test to manipulations of power profile and cadence in humans. *Experimental Physiology*, 93(3): 383-390.

Vanhatalo, A., Fulford, J., DiMenna, F., & Jones, A. (2010). Influence of hyperoxia on muscle metabolic responses and the power-duration relationship during severe-intensity exercise in humans: a 31P magnetic resonance spectroscopy study. *Experimental Physiology*, 95(4): 528-540.

Vucetic, V., Mozek, M., & Rakovac, M. (2015). Peak Blood Lactate Parameters in Athletes of Different Running Events During Low-Intensity Recovery After Ramp-Type Protocol. *Journal of Strength and Conditioning Research*, 29(4): 1057-1063.

Wakayoshi, K., Ikuta, K., Yoshida, T., Udo, M., Moritani, T., Mutoh, Y., & Miyashita, M. (1992). Determination and validity of critical velocity as an index of swimming performance in the competitive swimmer. . *European Journal of Physiology and Occupational Physiology*, 64(2): 153-157.

Wakayoshi, K., Yoshida, T., Udo, M., Harada, T., Moritani, T., Mutoh, Y., & Miyashita, M. (1993). Does critical swimming velocity represent exercise intensity at maximal lactate steady state? *European Journal of Applied Physiology and Ocuppational Physiology*, 66(1): 90-95.

Walsh, M., & Bannister, E. (1988). Possible Mechanisms of the Anaerobic Threshold. *Sports Medicine*, 5(5): 269-302.

Wasserman, K., Whipp, B., Koyal, S., & Beaver, W. (1973). Anaerobic threshold and respiratory gas exchange during exercise. *Journal of Applied Physiology*, 35(2): 236-243.

Yarar, H., Barug, D., Bostan, A., Kaya, A., & Aydin, E. (2021). Influence of Physical and Anthropometric Properties on Sprint Swimming Performance. *Pakistan Journal of Medical & Health Sciences*, 15(2): 814-818.

Zacca, R., & Castro, F. (2010). Critical Swimming Speed Obtained by the 200-400 Meters Model in Young Swimmers. *Biomechanics and Medicine in Swimming XI* (pp. 307-309). Oslo: Norwegian School of Sports Science.

Zacca, R., Azevedo, R., Chainok, P., Vilas-Boas, J., Castro, F., Pyne, D., & Fernandes, R. (2020). Monitoring Ag-Group Swimmers Over a Training Macrocycle: Energetics, Technique, and Anthropometrics. *Journal of Strength and Conditioning Research*, 34(3): 818-827.

Zacca, R., Azevedo, R., Peterson-Silveira, R., Vilas-Boas, J., Pyne, D., Castro, F., & Fernandes, R. (2019). Comparison of Incremental Intermittent and Time Trial Testing in Age-Group Swimmers. *Journal of Strength and Conditioning Research*, 33(3): 801-810.

Zacca, R., Fernandes, R., Pyne, D., & de S Castro, F. (2016). Swimming Training Assessment: The Critical Velocity and the 400-m Test for Age-Group Swimmers. *Journal of Strength and Conditioning Research*, 30(5): 1365-1372.

Zarzeczny, R., Kuberski, M., Deska, A., Zarzeczna, D., & Rydz, K. (2013). The Evaluation of Critical Swimming Speed in 12-Year-Old Boys. *Human Movement*, 14(1): 35-40.

Chapter 6. Summary and Conclusions

Due to the lack of time, resources, and expertise that collegiate coaches encounter, the 3MT is a reliable, valid, and time-efficient sport-specific test that can aid in understanding the physiological performance status of a swimmer (Piatrikova et al., 2019). By using a simple stopwatch and recorded video many athletes can be tested at once and calculations can be easily performed using simple spreadsheets afterwards. From the results of the 3MT, athletic performance profiles can be built to understand how to better program HIIT sets with each individual swimmer.

This test has been shown to identify the CS which is the intensity demarcating the heavy and severe domains and training zones could be identified from such test (Burnley & Jones, 2007; Piatrikova E. , Sousa, Willsmer, Gonzalez, & Williams, 2018). Performance variables from the 3MT may be influenced by anthropometric variables and resistance training that can create adaptations to some of the former. Due to the adaptations garnered from training, it seems reasonable to evaluate swimming performance through the 3MT at least every 3 weeks to adjust training as CS seems to increase at the expense of D’, which will influence exercise tolerance above CS. Coaching efforts should be made to periodize and prescribe concurrent swimming and strength training in a manner that improves all physical performance characteristics involved in competitive swimming and to not neglect certain training components (González-Ravé, Pyne, Castillo, González-Mohíno, & Stone, 2021; Hermosilla, González-Ravé, Del Castillo, & Pyne, 2021).

If an athlete competes in multiple events involving distinct swimming strokes, it is important to understand that stroke modalities may influence the results of the 3MT performance variables due to stroke efficiency. Although most training in some individual medley swimmers may be denser in freestyle volume, further research is needed to understand if it possible to predict the CS of a secondary stroke technique using the MSS of that stroke and the speed decay of the 3MT in freestyle.

References

Abdi, H. (2010). Holm's Sequential Bonferroni Procedure. *Encyclopedia of Research Design.*, In Neil Salkind (Ed.), 1-8.

Abe, D., Tokumaru, H., Niihata, S., Muraki, S., Fukuoka, Y., Usui, S., & Yoshida, T. (2006). Assessment of Short-Distance Breastroke Swimming Performance With Critical Velocity. *Journal of Sports Science and Medicine*, 5: 340-348.

Aksit, T., Ozkol, M., Vural, F., Penkunlu, E., Aydinoglu, R., & Varol, R. (2017). Contribution of anthropometric characteristics to critical swimming velocity and estimated propulsive force. *Journal of Physical Education and Sport*, 17(1): 212-218.

Amaro, N., Morouco, P., Marques, M., Batalha, N., Neiva, H., & Marinho, D. (2018). A systematic review on dry-land strength and conditioning training on swimming performance. *Science & Sports*, 34(1): e1-e14.

Anderson, M., Hopkins, W., Roberts, A., & Pyne, D. (2006). Monitoring seasonal and long-term changes in test performance in elite swimmers. *European Journal of Sports Science*, 6(3): 145-154.

Arroyo-Toledo, J., Clemente, V., González-Ravé, J., Ramos Campo, D., & Sortwell, A. (2013). Comparison Between Traditional and Reverse Periodization: Swimming Performance and Specific Strength Values. *International Journal of Swimming Kinetics*, 2(1): 87-96.

Arroyo-Toledo, J., Clemente-Suárez, V., & Gonzales-Rave, J. (2016). Effects of Traditional and Reverse Periodization on Strength, Body-Composition and Swim Performance. *Imperial Journal of Interdisciplinary Research*, 2(12): 474-481.

Baldari, C., Fernandes, R., Meucci, M., Ribeiro, J., Vilas-Boas, J., & Guidetti, L. (2012). Is the New AquaTrainer Snorkel Valid for VO2 Assessment in Swimming? *International Journal of Sports Medicine*, 34(4): 336-344.

Balilionis, G., Nepocatych, S., Ellis, C., Richardson, M., Neggers, Y., & Bishop, P. (2012). Effects of Different Types of Warm-Up on Swimming Performance, Reaction Time, and Dive Distance. *Journal of Strength and Conditioning Research*, 26(12): 3297-3303.

Barbosa, T., Fernandes, R., Keskinen, K., & Vilas-Boas, J. (2008). The influence of stroke mechanics into energy cost of elite swimmers. *European Journal of Applies Physiology*, 130(2): 139-149.

Barbosa, T., Fernandes, R., Keskinen, K., Colaco, P., Cardoso, C., Silva, J., & Vilas-Boas, J. (2006). Evaluation of the Energy Expenditure in Competitive Swimming Strokes. *International Journal of Sports Medicine*, 27: 894-899.

Barbosa, T., Fernandes, R., Keskinen, K., Colaco, P., Cardoso, C., Silva, J., & Vilas-Boas, J. (2006). Evaluation of the Energy Expenditure in Competitive Swimming Strokes. *International Journal of Sports Medicine*, 27(11): 894-899.

Bassett, D. (2002). Scientific contributions of A.V. Hill: exercise physiology pioneer. *Journal of Applied Physiology*, 93: 1567-1582.

Batalha, N., Raimundo, A., Tomas-Carus, P., Paulo, J., Simao, R., & Silva, A. (2015). Does a land-based compensatory strength-training programme influences the rotator cuff balance of young competitive swimmers? *European Journal of Sports Science*, 15(8): 764-772.

Bazyler, C., Abbott, H., Bellon, C., Taber, C., & Stone, M. (2015). Strength for Endurance Athletes: Theory to Practice. *Journal of Strength and Conditioning*, 37(2): 1-12.

Beaver, W., Wasserman, K., & Whipp, B. (1986). A new method for detecting anaerobic threshold by gas exchange. *Journal of Applied Physiology*, 60(6): 2020-2027.

Beckham, G., Lish, S., Keebler, L., Longaker, C., Disney, C., DeBlasio, M., & Adams, K. (2019). The Reliability of the Seated Medicine Ball Throw for Distance. *Journal of Physical Activity Research*, 4(2): 131-136.

Bergstrom, H., Dinyer, T., Succi, P., Voskuil, C., & Housh, T. (2021). Applications of the Critical Power Model to Dynamic Constant External Resistance Exercise: A Brief Review of the Critical Load Test. *Sports*, 9(2): 1-15.

Billat, V. (2001). Interval Training for Performance: A Scientific and Empirical Practice. Special Recommendations for Middle- and Long-Distance Running. Part II: Anaerobic Interval Training. *Sports Medicine*, 31(2): 75-90.

Billat, V., Sirvent, P., Py, G., Koralsztein, J., & Mercier, J. (2003). The Concept of Maximal Lactate Steady State. *Sports Medicine*, 33(6): 407-426.

Bishop, C., Cree, J., Read, P., Chavda, S., Edwards, M., & Turner, A. (2013). Strength and Conditioning for Sprint Swimming. *Strength and Conditioning Journal*, 35(6): 1-6.

Bishop, D., & Jenkins, D. (1996). The Influence of Resistance Training on the Critical Power Function & Time to Fatigue at Critical Power. *The Australian Journal of Science and Medicine in Sport*, 28(4): 101-105.

Bonen, A., Wilson, B., Yarkony, M., & Belcastro, A. (1980). Maximal oxygen uptake during free, tethered, and swim flume swimming. *Journal of Applied Physiology*, 48(2): 232-235.

Brooks, G. (1985). Anaerobic threshold: review of the concept and directions for future research. *Medicine and Science in Sport and Exercise*, 17(1): 22-31.

Buchheit, M., & Laursen, P. (2013). High-Intensity Interval Training, Solutions to the Programming Puzzle: Part II: Anaerobic Energy, Neuromuscular Load and Practical Applications. *Sports Medicine*, 43(10): 927-954.

Buchheit, M., & Luarsen, P. (2013). High-Intensity Interval Training, Solutions to the Programming Puzzle - Part I: Cardiopulmonary Emphasis. *Sports Medicine*, 43(5): 313-338.

Bundle, M., & Weyand, P. (2012). Sprint Exercise Performance: Does Metabolic Power Matter? *Exercise and Sports Science Reviews*, 40(3): 174-182.

Burnley, M., & Jones, A. (2007). Oxygen uptake kinetics as a determinant of sports performance. *European Journal of Sports Science*, 7(2): 63-79.

Burnley, M., Doust, J., & Vanhatalo, A. (2006). A 3-min All-out Test to Determine Peak Oxygen Uptake and the Maximal Steady State. *Medicine and Science in Sport and Science*, 38(11): 1995-2003.

Carroll, K., Bernards, J., Bazyler, C., Taber, C., Stuart, C., DeWeese, B., . . . Stone, M. (2018). Divergent Performance Outcomes Following Resistance Training Using Repetition

Maximums or Relative Intensity. *International Journal of Sports Physiology and Performance*, 14(1): 1-28.

Chaverri, D., Schuller, T., Iglesias, X., Hoffman, U., & Rodriguez, F. (2016). A New Model for Estimating Peak Oxygen Uptake Based on Postexercise Measurements in Swimming. *International Journal of Sports Physiology and Performance*, 11(4): 419-424.

Cheng, C., Yang, Y., Lin, H., Lee, C., & Wang, C. (2012). Determination of critical power in trained rowers using a three-minute all-out rowing test. *European Journal of Applied Physiology*, 112: 1251-1260.

Clark, I., West, B., Reynolds, S., Murray, S., & Pettitt, R. (2013). Applying the Critical Velocity Model for an Off-Season High Intensity Interval Training Program. *Journal of Strength and Conditioning Research*, 27(12): 3335-3341.

Corry, I., & Powers, N. (1982). Maximal Aerobic Power Measurement in Runners and Swimmers. *British Journal of Sports Medicine*, 16(3): 154-160.

Counsilman, J. (1968). *The Science of Swimming.* Hoboken, NJ: Prentice-Hall.

Courtwright, S., Williams, J., Clark, I., Pettitt, R., & Dicks, N. (2016). Monitoring Interval-Training Responses for Swimming using the 3-min All-out Exercise Test. *International Journal of Exercise Science*, 9(5): 545-553.

Crowley, E., Harrison, A., & Lyons, M. (2018). Dry-Land Resistance Training Practices of Elite Swimming Strength and Conditioning Coaches. *Journal of Strength and Conditioning Research*, 32(9): 2592-2600.

Dalamitros, A., Fernandes, R., Toubekis, A., Manou, V., Loupos, D., & Kellis, S. (2015). Is Speed Reserve Related to Critical Speed and Anaerobic Distance Capacity in Swimming? *Journal of Strength and Conditioning Research*, 29(7): 1830-1836.

Debanne, T., & Laffaye, G. (2011). Predicting the throwing velocity of the ball in handball with anthropometric variables and isotonic tests. *Journal of Sports Sciences*, 29(7): 705-713.

Dekerle, J., Sidney, M., Hespel, J., & Pelayo, P. (2002). Validity and Reliability of Critical Speed, Critical Stroke Rate, and Anaerobic Capacity in Relation to Front Crawl Swimming Performances. *International Journal of Sports Medicine*, 23: 93-98.

DeWeese, B., Sams, M., Williams, J., & Bellon, C. (2015). The Nature of Speed: Enhancing Sprint Abilities Through a Short to Long Training Approach. *Techniques for Track & Field and Cross Country*, 8(4): 8-22.

DeWeese, B., Wagle, J., & Bingham, G. (2019). Let the rhythm hit them: Adjusting the tempo to skilffully surf the intensity curve. . *Techniques Magazine*, 10(4): 52-59.

DiMenna, F., & Jones, A. (2019). Aerobic performance assessment. In P. Comfort, P. Jones, & J. McMahon, *Performance Assessment in Strength and Conditioning* (pp. 212-239). Abingdon, Oxon: Routledge.

Edge, J., Hill-Haas, S., Goodman, C., & Bishop, D. (2006). Effects of resistance training on H+ regulation, buffer capacity, and repeated sprints. *Medicine and Science in Sports and Exercise*, 38(11): 2004-2011.

Espada, M., & Alves, F. (2010). Critical Velocity and the Velocity at Maximal Lactate Steady State in Swimming. *Biomechanics and Medicine in Swimming XI* (pp. 194-196). Oslo: Norwegian School of Sports Science.

Espada, M., Costa, A., Louro, H., Conceiao, A., Filho, D., & Pereira, A. (2016). Anaerobic Critical Velocity and Sprint Swimming Performance in Masters Swimmers. *International Journal of Sports Science*, 6(1A): 31-35.

Farrell, P., Wilmore, J., Coyle, E., Billing, J., & Costill, D. (1979). Plasma lactate accumulation and distance running performance. *Medicine and Sciennce in Sports and Exercise*, 25(10): 1089-1090.

Ferguson, C., Rossiter, H., Whipp, B., Cathcart, A., Murgatroyd, S., & Ward, S. (2010). Effect of recovery duration from prior exhaustive exercise on the parameters of the power-duration relationship. *Journal of Applied Physiology*, 108(4): 866-874.

Fernandes, R., Sousa, M., Machado, L., & Vilas-Boas, J. (2011). Step Length and Individual Anaerobic Threshold Assessment in Swimming. *International Journal of Sports Medicine*, 32(12): 940-946.

Fig, G. (2010). Why Competitive Swimmers Need Explosive Power. *Strength and Conditioning Journal*, 32(4): 84-86.

Fone, L., & van den Tillar, R. (2022). Effects of Different Types of Strength Training on Swimming Performance in Competitive Swimmers: A Systematic Review. *Sports Medicine*, 8(1): 1-26.

Galbraith, A., Hopker, J., Lelliot, S., Diddams, L., & Passfield, L. (2014). A Single-Visit Field Test of Critical Speed. *International Journal of Sports Physiology and Performance*, 9(6): 931-935.

González-Ravé, J., Pyne, D., Castillo, J., González-Mohíno, F., & Stone, M. (2021). Training periodization for a world-class 400 meters individual medley swimmer. *Biology of Sport*, 39(4): 883-888.

Green, S. (1995). Measuring of Anaerobic Work Capacities in Humans. *Sports Medicine*, 19(1): 32-42.

Green, S., & Dawson, B. (1993). Measurment of Anaerobic Capacities in Humans: Definitions, Limitations, and Unsolved Problems. *Sports Medicine*, 15(5): 312-327.

Greenshields, J., Goss, C., & Stager, J. (2018). Variation in Critical Speed and Finite Distance Capacity of Elite Swimmers. *Annual Meeting of the American College of Sports Medicine* (p. 50(5S): 525). Minneapolis: Medicine and Science in Sports and Exercise.

Haff, G. (2019). The essentials of periodization. In I. Jeffreys, & J. Moody, *Strength and Conditioning for Sports Performance* (pp. 404-448). Abingdon, London: Routledge.

Hale, T. (2008). History of developments in sport and exercise physiology: A.V. Hill, maximal oxygen uptake, and oxygen debt. *Journal of Sports Sciences*, 26(4): 365-400.

Hall, G., & Murphy, D. (2020). *Fundamentals of Fast Swimming: How to Improve Your Swimming Technique.* Islamorada, FL: The Race Club.

Hamill, J., Knutzen, K., & Derrick, T. (2015). *Biomechanical Basis of Human Movement, 4th Ed.* Philadelphia, USA: Wolters Kluwer.

Hellard, P. P. (2018). Dynamics of the metabolic response during a competitive 100-m freestyle in elite male swimmers. *International Journal of Sports Physiology and Performance*, 13(10): 1011-1020.

Hellard, P., Avalos-Fernandes, M., Lefort, G., Pla, R., Mujika, I., Toussaint, J., & Pyne, D. (2019). Elite swimmers' training patterns in the 25 weeks prior to their season's best performances: insights into periodization from a 20-years cohort. *Frontiers in Physiology*, 10(363): 1-16.

Hellard, P., Pla, R., Rodríguez, F., Simbana, D., & Pyne, D. (2018). Dynamics of the metabolic response during a competitive 100-m freestyle in elite male swimmers. *International Journal of Sports Physiology and Performance*, 13(10): 1011-1020.

Hermosilla, F., González-Ravé, J., Del Castillo, J., & Pyne, D. (2021). Periodization and programming for individual 400 m medley swimmers. *International Journal of Environmental Research and Public Health*, 18(12): 6474.

Hill, A., & Lupton, H. (1923). Muscular Exercise, Lactic Acid, and the Supply and Utilization of Oxygen. *International Journal of Medicine*, 16(62): 135-171.

Hill, D. (1993). The critical power concept. A review. . *Sports Medicine*, 16(4): 237-254.

Hopkins, W. (2015). *Spreadsheets for analysis of validity and reliability. Sportscience 19, 36-42*. Retrieved from Sportscience: sportsci.org/2015/ValidRely.htm

Hopkins, W., Marshall, S., Batterham, A., & Hanin, J. (2009). Progressive Statistics for Studies in Sports Medicine and Exercise Science. *Medicine & Science in Sports & Exercise,* 41(1): 3-12.

Hurd, K., Surges, M., & Farell, J. (2022). Use of Exercise Training to Enhance the Power-Duration Curve: A Systematic Review. *Journal of Strength and Conditioning Research*, XX(X): 000-000.

Issurin, V. (2008). Block periodization versus traditional training theory: a review. *Journal of Sports Medicine and Physical Fitness*, 48(1): 65-75.

Jones, A., & Vanhatalo, A. (2017). The 'Critical Power' Concept: Applications to Sports Performance with a Focus on Intermittent High-Intensity Exercise. *Sports Medicine*, 47(1): S65-S78.

Jones, A., Grassi, B., Christensen, P., Krustrup, P., Bangsbo, J., & Poole, D. (2011). Slow Component of V̇O2 Kinetics: Mechanistic Bases and Practical. *Medicine and Science in Sport and Exercise*, 43(11): 2046-2062.

Jorgić, B., Puletić, M., Okičić, T., & Meškovska, N. (2011). Importance of Maximal Oxygen Consumption During Swimming. *Physical Education and Sport*, 9(2): 183-191.

Kao, S., Ishida, A., & Ainsworth, B. (2018). The Correlation Between Strength and Power Measures with Sprint Freestyle Performance in Division 1 Collegiate Swimmers. *Journal of Swimming Research*, 26(1): 22-31.

Karsten, B., Stevens, L., Colpus, M., Larumbe-Zabala, E., & Naclerio, F. (2014). The Effects of Sport-Specific Maximal Strength and Conditioning Training on Critical Velocity, Anaerobic Running Distance, and 5-km Race Performance. *International Journal of Sports Physiology and Performance*, 11(1): 80-85.

Keiner, M., Wirth, K., Fuhrmann, S., Kunz, M., Hartmann, H., & Haff, G. (2019). The Influence of Upper- and Lower-Body Maximum Strength on Swim Block Start, Turn, and Overall Swim Performance in Sprint Swimming. *Journal of Strength and Conditioning Research*, 35(10): 2839-2845.

Koo, T., & Li, M. (2016). A Guideline of Selecting and Reporting Intraclass Correlation Coefficients for Reliability Research. *Journal of Chiropractic Medicine*, 15: 155-163.

Kramer, M., Du Randt, R., Watson, M., & Pettitt, R. (2019). Bi-exponential modeling derives novel parameters for the critical speed concept. *Physiological Reports*, 7(4): 1-9 e13993.

Latt, E., Jurimae, J., Maestu, J., Purge, P., Ramson, R., Haljaste, K., . . . Jurimae, T. (2010). Physiological, biomechanical, and anthropometrical predictors of sprint swimming performance in adolescent swimmers. *Journal of Sport Sciences and Medicine*, 9(1): 398-404.

Lavoie, J., Lèger, L., Leone, M., & Provencher, P. (1985). A Maximal Multistage Swim Test to Determine the Functional and Maximal Aerobic Power of Competitive Swimmers. *Journal of Swimming Research*, 1(2): 17-22.

Leblanc, H., Seifert, L., Tourny-Chollet, C., & Chollet, D. (2007). Intra-cyclic Distance per Stroke Phase, Velocity Fluctuations and Acceleration Time Ratio of a Breastroker's Hip: A Comparison between Elite and Nonelite Swimmers at Different Race Paces. *International Journal of Sports Medicine*, 28(2): 140-147.

Libicz, S., Roels, B., & Millet, G. (2005). VO2 Responses to Intermittent Swimming Sets at Velocity Associated to VO2max. *Canadian Journal of Applied Physiology*, 30(5): 543-553.

Lopes, T., Goncalves, C., Graca, C., Neiva, H., & Marinho, D. (2019). The Relationship between Front Crawl Swimming Performance and Strength Variables in College Swimmers. *Ergonomics International Journal*, 3(2): 1-9.

Machado, M., Borges, J., Galdino, I., Cunha, L., Souza-Sá Filho, A., Soares, D., & Junior, I. (2018). Does critical velocity represent the maximal lactate steady state in youth swimmers? *Science & Sport*, 34(3): 1-7.

Machado, M., Junior, O., Marques, A., Colantonio, E., Cyrino, E., & De Mello, M. (2011). Effect of 12 weeks of training on critical velocity and maximal lactate steady state in swimmers. *European Journal of Sport Science*, 11(3): 165-170.

Magel, J., & Faulkner, J. (1967). Maximum oxygen uptakes of college swimmers. *Journal of Applied Physiology*, 22(5): 929-938.

Mann, B., Ivey, P., Brechue, W., & Mayhew, J. (2015). Validity and Reliability of Hand and Electronic Timing for 40-yd Sprint in College Football Players. *Journal of Strength and Conditioning Research*, 29(6): 1509-1514.

Marinho, D., Amorim, R., Costa, A., Marques, M., Pérez-Turpin, J., & Neiva, H. (2011). "Anaerobic" critical velocity and swimming performance in young swimmers. *Journal of Human Sport and Exercise*, 6(1): 80-86.

Marinho, D., Barbosa, T., Silva, A., & Neiva, H. (2012). Applying Anaerobic Critical Velocity in Non-Elite Swimmers. *International Journal of Swimming Kinetics*, 1(1): 33-50.

Mattioni-Maturana, F., Fontana, F., Pogliaghi, S., Passfield, L., & Murias, J. (2018). Critical power: How different protocols and models affect its determination. *Journal of Science and Medicine in Sport*, 21(7): 742-747.

Mauger, A., Neuloh, J., & Castle, P. (2012). Analysis of Pacing Strategy Selection in Elite 400-m Freestyle Swimming. *Medicine and Science in Sport and Exercise*, 44(11): 2205-2212.

McArdle, W., Katch, F., & Katch, V. (2015). *Exercise Physiology: Nutrition, Energy, and Human Performance.* Baltimore, MD: Wolters-Kluwers.

Mitchell, L., Pyne, D., Saunders, P., & Rattray, B. (2017). Reliability and validity of a modified 3-minute all-out swimming test in elite swimmers. *European Journal of Sports Science*, 18(3): 307-314.

Miura, A., Endo, M., Sato, H., Sato, H., Barstow, T., & Fukuba, Y. (2002). Relationship between the curvature constant parameter of the power-duration curve and muscle cross-sectional area of the thigh for cycle ergometry in humans. *European Journal of Applied Physiology*, 87(3): 238-244.

Miura, A., Sato, H., Sato, H., Whipp, B., & Fukuba, Y. (2000). The effect of glycogen depletion on the curvature constant parameter of the power-duration curve for cycle-ergometry. *Ergonomics*, 43(1): 133-141.

Monod, H., & Scherrer, J. (1965). The work capacity of a synergic muscular group. *Ergonomics*, 8: 329-338.

Montpetit, R., Léger, L., Lavoie, J., & Cazorla, G. (1981). V̇02 Peak During Free Swimming Using the Backward Extrapolation of the O2 Recovery Curve. *European Journal of Applied Physiology*, 47(4): 385-391.

Morán-Navarro, R., Pérez, C., Mora-Rodríguez, R., de la Cruz-Sánchez, E., González-Badillo, J., Sánchez-Medina, L., & Pallarés, J. (2017). Time course of recovery following resistance training leading or not to failure. . *European Journal of Applied Physiology*, 117(12): 2387-2399.

Moritani, T., Nagata, A., DeVries, H., & Muro, M. (1981). Critical power as measure of physical work capacity and anaerobic threshold. *Ergonomics*, 24(5): 339-350.

Morouco, P., Marinho, D., Keskinen, K., Badillo, J., & Marques, M. (2014). Thethered Swimming Can Be Used to Evaluate Force Contribution for Short-Distance Swimming Performance. *Journal of Strength and Conditioning Research*, 28(11): 3093-3099.

Mougios, V. (2006). *Exercise Biochemistry*. Champaign, Ill. : Human Kinetics.

Mujika, I., & Crowley, E. (2019). Strength Training for Swimmers. In M. Schumann, & B. Ronnestad, *Concurrent Aerobic and Strength Training: Scientific Basics and Practical Applications* (pp. 369-386). Switzerland: Springer International Publishing AG.

Mujika, I., Chatard, J., Busso, T., Geyssant, A., Barale, F., & Lacoste, L. (1995). Effects of training on performance in competitive swimming. *Canadian journal of applied physiology*, 20(4): 395-406.

Neiva, H., Fernandes, R., & Vilas-Boas, J. (2010). Anaerobic Critical Velocity in Four Swimming Techniques. *International Journal of Sports Medicine*, 32(1): 195-198.

Neiva, H., Fernandes, R., & Vilas-Boas, J. (2011). Anaerobic Critical Velocity in Four Swimming Techniques. *International Journal of Sports Medicine*, 32: 195-198.

Nevill, A., Negra, Y., Myers, T., Sammond, S., & Chaabene, H. (2020). Key somatic variables associated with, and differences between the 4 swimming strokes. *Journal of Sports Sciences*, 38(7): 787-794.

Noakes, T. (2008a). How did AV Hill understand the V̇O2max and the "plateau phenomenon"? Still no clarity? *British Journal of Sports Medicine*, 42: 574-580.

Noakes, T. (2008b). Testing for maximum oxygen consumption has produced a brainless mode of human exercise performance. *British Journal of Sports Medicine*, 42(7): 551-555.

Noordhof, D., Koning, J., & Foster, C. (2010). The Maximal Accumulated Oxygen Deficit Method. *Sports Medicine*, 40(4): 285-302.

Norouzi, M., Cabuk, R., Balki, G., As, H., & Ozkaya, O. (2021). The Effect of Using Different Exhaustion Intervals and Mathematical Models on Critical Power Estimations. *Hacettepe Journal of Sports Sciences*, 32(3): 151-166.

Nugent, F., Comyns, T., Kearney, P., & Warrington, G. (2019). Ultra-Short Race-Pace Training (USRPT) In Swimming: Current Perspectives. *Open Access Journal of Sports Medicine*, 10(1): 133-144.

Ogita, F. (2006). Energetics in competitive swimming and its applications for training. . *International Symposium on Biomechanics and Medicine in Swimming* (pp. 6(2): 117-121). Porto Faculdade de Desporto da Universidade do Porto.

Olbrecht, J. (2013). *The Science of Winning: Planning, Periodizing and Optimizing Swim Training.* Antwerp, Belgium: F&G Partners.

Painter, K., Haff, G., Ramsey, M., McBride, J., Triplett, T., Sands, W., . . . Stone, M. (2012). Strength gains: block versus daily undulating periodization weight training among track and field athletes. *International Journal of Sports Physiology and Performance*, 7(2): 161-169.

Painter, K., Rodriguez-Castellano, L., & Stone, M. (2020). High Volume Resistance Training and its Effects on Anaerobic Work Capacity Over Time: A Review. *The Sport Journal*, 3(1): 1-17.

Palao, J., & Valdés, D. (2013). Testing protocol for monitoring upper-body strength using medicine balls. *Journal of Human Sport & Exercise*, 8(2): 334-341.

Papoti, M., da Silva, A., Araujo, G., Santiago, V., Martins, L., Cunha, C., & Gobatto, C. (2013). Aerobic and Anaerobic Performances in Tethered Swimming. *International Journal of Sports Medicine*, 34(8): 712-719.

Pareja-Blanco, F., Rodríguez-Rosell, D., Aagaard, P., Sánchesz-Medina, L., Ribas-Serna, J., Mora-Custodio, R., . . . González-Badillo, J. (2020). Time Course of Recovery From Resistance Exercise With Different Set Configurations. *Journal of Strength and Conditioning Research*, 34(10): 2867-2876.

Pelayo, P., & Alberty, M. (2011). The History of Swimming Research. In L. Seifert, D. Chollet, & I. Mujika, *World Book of Swimming: From Science to Performance* (pp. ix - xxvi). Hauppauge, New York: Nova Science Publishers, Inc.

Peters, M., Berry, S., & Koley, S. (2014). Relationship of physical characteristics, power and swimming time in sprint swimmers. *Annals of Biological Research*, 5(8): 24-29.

Pettitt, R. (2016). Applying the Critical Speed Concept to Racing Strategy and Interval Training Prescription. *International Journal for Sports Physiology and Performance*, 11(7): 842-847.

Pettitt, R., Jamnick, N., & Clark, E. (2012). 3-min All-out Exercise Test for Running. *International Journal of Sports Medicine*, 33: 426-431.

Piatrikova, E., Sousa, A., Gonzalez, J., & Williams, S. (2019). Validity and reliability of the 3-minute all-out test in national and international competitive swimmers. *International Journal of Sports Physiology and Performance*, 13(9): 1190-1198.

Piatrikova, E., Sousa, A., Willsmer, N., Gonzalez, J., & Williams, S. (2018). Demarcating exercise intensity domains in freestyle swimming: is there and alternative to incremental step test and beats below HRmax method? . *Journal of Strength and Conditioning Research*, 34(9): 2575-2584.

Piatrikova, E., Willsmer, N., Altini, M., Mladen, J., Lachlan, M., Gonzalez, J., . . . Williams, S. (2021). Monitoring the heart rate variability responses to training loads in competitive swimmers using a smartphone application and the Banister Impulse-Response model. *International Journal of Sports Physiology and Performance*, 16(6):787-795.

Piatrikova, E., Willsmer, N., Sousa, A., Gonzalez, J., & Williams, S. (2020). Individualising training in swimming; is there a place for the application of the critical speed and critical stroke rate concepts? *International Journal of Sports Physiology and Performance*, 15(5): 1-17 .

Pla, R., Leroy, A., Massal, R., Bellami, M., Kaillani, F., Hellard, P., . . . Sedeaud, A. (2019). Bayesian approach to quantify morphological impact on performance in international elite freestyle swimming. *BMJ Open Sport & Exercise Medicine*, 5: 1-7.

Poole, D., & Jones, A. (2012). Oxygen Uptake Kinetics. *Comprehensive Physiology*, 2(2): 933-996.

Poole, D., Burnley, M., Vanhatalo, H., Rossiter, B., & Jones, A. (2016). Critical Power: An Important Fatigue Threshold in Exercise Physiology. *Medicine and Science in Sports and Exercise*, 48(11): 2320-2334.

Poole, D., Rossiter, H., Brooks, G., & Gladden, L. (2021). The Anaerobic Threshold: 50+ Years of Controversy. *The Journal of Physiology*, 599(3): 737-767.

Pyne, D., Lee, H., & Swanick, K. (2001). Monitoring the lactate threshold in world-ranked swimmers. *Medicine and Science in Sports and Exercise*, 33(2): 291-297.

Pyne, D., Maw, G., & Goldsmith, W. (2000). Protocols for the Physiological Assessment of Swimmers. In A. S. Commission, *Physiological Tests for Elite Athletes* (pp. 372-382). Champaign, Ill: Human Kinetics.

Ramos, R., Requena, B., Suarez-Arrones, L., Newton, R., & Sáez de Villareal, E. (2014). Effects of 18-Week In-Season Heavy-Resistance and Power Training on Throwing Velocity, Strength, Jumping, and Maximal Sprint Swim Performance of Elite Male Water Polo Players. *Journal of Strength and Conditioning Research*, 28(4): 1007-1014.

Ramos-Veliz, R., Requena, B., Suarez-Arrones, L., Newton, R., & Sáez de Villareal, E. (2014). Effects of 18-week in-season heavy resistance and power training on throwing velocity, strength, jumping, and maximal sprint swim performance of elite male water polo players. *Journal of Strength and Conditioning Research*, 28(4): 1007-1014.

Ramya, G., Guru, C., Banodhe, G., Dominic, D., & Sharma, H. (2021). Resumption to Swimming Post COVID 19 Lockdown. *Journal of Clinical and Diagnostic Research*, 15(1): 1-5.

Raymond, D. (2012). The effect of aerobic fitness on the cardiovascular and sympathetic nervous system response to physiological stress at rest and during dynamic exercise. *Thesis*.

Reis, V., Marinho, D., Barbosa, F., Reis, A., Guidetti, L., & Silva, A. (2010). Examining the Accumulated Oxygen Deficit Method in Breaststroke Swimming. *European Journal of Applied Physiology*, 109(6): 1129-1135.

Reis, V., Marinho, D., Policarpo, F., Carneiro, A., Baldari, C., & Silva, A. (2010). Examining the Accumulated Oxygen Deficit Method in Front Crawl Swimming. *International Journal of Sports Medicine*, 31(6): 421-427.

Rodríguez, F., & Mader, A. (2011). Energy Systems in Swimming. In L. Seifert, D. Chollet, & I. Mujika, *World Book of Swimming: From Science to Performance* (pp. 225-240). New York: Nova Science.

Rodríguez, F., Keskinen, K., Keskinen, O., & Malvela, M. (2003). Oxygen uptake kinetics during free swimming: a pilot study. *In: Chartard, JC, Biomechanics and Medicine in Swimming IX*, 379-384.

Rushall, B. (2016, March 14). *USRPT Defined: After Two Years USRPT Comes of Age.* Retrieved from Swimming Science Bulletin #49: https://coachsci.sdsu.edu/swim/bullets/49DEFINED.pdf

Salam, H., Marcora, S., & Hopker, J. (2017). The effect of mental fatigue on critical power during cycling exercise. *European Journal of Applied Physiology*, Available from: https://link.springer.com/article/10.1007/s00421-017-3747-1 [Accessed 22 March 2022].

Saltin, B., & Astrand, P. (1967). Maximal oxygen uptake in athletes. *Journal of Applied Physiology*, 23(3): 353-358.

Sandford, G., & Stellingwerff, T. (2019). "Questioning Your Categories": the Misunderstood Complexity of Middle-Distance Running Profiles With Implications for Research Methods and Application. *Frontiers in Sports and Active Living*, 1(28): 1-8.

Sandford, G., Kilding, A., Ross, A., & Luarsen, P. (2018). Maximal Sprint Speed and the Anaerobic Speed Reserve Domain: The Untapped Tools that Differentiate the World's Best 800 m Runners. *Sports Medicine*, 49(6): 843-852.

Sanford, G., Laursen, P., & Buchheit, M. (2021). Anaerobic Speed/Power Reserve and Sport Performance: Scientific Basis, Current Applications and Future Directions. *Sports Medicine*, 51(10): 2017-2028.

Sawyer, B., Stokes, D., Womack, C., Hugh, M., Weltman, A., & Gaesser, G. (2014). Strength Training Increases Endurance Time to Exhaustion During High-Intensity Exercise Despite No Change in Critical Power. *Journal of Strength and Conditioning Research*, 28(3): 601-609.

Scott, B., Burden, R., & Dekerle, J. (2020). Critical speed, D' and pacing in swimming: reliability of a popular critical speed protocol applied to all four strokes. *Research Square*, 10.21203/rs.3.rs-77508/v1.

Shiyoyama, Y., Okita, K., Baba, Y., & Sato, D. (2010). Does the Y-Intercept of a Regression Line in the Critical Velocity Concept Represent the Index for Evaluating Anaerobic Capacity? *Biomechanics and Medicine in Swimming XI* (pp. 288-290). Oslo: Nordbergtrykk as.

Siders, W., Lukaski, H., & Bolonchuk, W. (1993). Relationship among swimming performance, body composition and somatotype in competitive collegiate swimmers. *Journal of Sports Medicine and Physical Fitness*, 33(2): 166-171.

Smith, D., Norris, S., & Hogg, J. (2002). Performance Evaluation of Swimmers: Scientific Tools. *Sports Medicine*, 32(9): 539-554.

Sousa, A., Figueiredo, P., Pendergast, D., Kjendlie, P., Vilas-Boas, J., & Fernandes, R. (2014). Critical Evaluation of Oxygen-Uptake Assessment in Swimming. *International Journal of Sports Physiology and Performance*, 9(2): 190-202.

Steiger, J. (1980). Tests for comparing elements of a correlation matrix. *Psychological Bulletin*, 87: 245-251.

Stockbrugger, B., & Haennel, R. (2001). Validity and Reliability of a Medicine Ball Explosive Power Test. *Journal of Strength and Conditioning Research*, 15(4): 431-438.

Stone, M., Hornsby, W., Haff, G., Fry, A., Suárez, D., Liu, J., . . . Pierce, K. (2021). Periodization and Block Periodization in Sports: Emphasis on Strength-Power Training-

A Provocative and Challenging Narrative. *Journal of Strength and Conditioning Research*, 35(8): 2351-2371.

Stone, M., Stone, M., & Sands, W. (2007). *Principles and Practices of Resistance Training.* Champaign, Ill.: Human Kinetics.

Strzala, M., Stanula, A., Krezalek, P., Ostrowski, A., Kaca, M., & Glab, G. (2019). Influence of Morphology and Strength on Front Crawl Swimming Speed in Junior and Youth Age-Group Swimmers. *Journal of Strength and Conditioning Research*, 33(10): 2836-2845.

Toubekis, A., Gourgoulis, V., & Tokmakidis, S. (2010). Tethered Swimming as an Evaluation Tool of Single Arm-Stroke Force. *XIth International Symposium for Biomechanics and Medicine in Swimming.* Oslo, Norway: Norwegian School of Sports Sciences .

Toussaint, H. (2002). Biomechanics of Propulsion and Drag in Front Crawl Swimming. *Applied proceedings - XXth International Symposium on Biomechanics in Sports. University of Extremadura*, (pp. 11-22). Caceres, Spain.

Toussaint, H., & Beek, P. (1992). Biomechanics of Competitive Front Crawl Swimming. *Sports Medicine*, 13(1): 8-24.

Toussaint, H., Beelen, A., Rodenburg, A., Sargeant, A., de Groot, G., Hollander, A., & van Ingen Schenau, G. (1988). Propelling efficiency of front-crawl swimming. *Journal of Applied Physiology*, 65(6): 2506-2512.

Triska, C., Karsten, B., Nimmeritcher, A., & Tschan, H. (2017). Different exhaustive protocols affect estimates of critical speed and D´. *22nd Annual Congress of the European College of Sport Science.* Essen, Germany.

Tsai, M., & Thomas, S. (2017). 3-Min All-Out in Swimming. . *International Journal of Sports Physiology and Performance*, 12(1): 1-17.

Tsunokawa, T., Kadi, T., Mankyu, H., & Ogita, F. (2019). Estimation of hand propulsion forces at four swimming techniques using pressure measurement and underwater motion capture. *24th Annual Congress of the European College of Sport Science* (p. Abstract). Prague, Czech Republic: European College of Sports Science.

Vanhatalo, A., & Jones, A. (2009). Influence of prior sprint exercise on the parameters of the 'all-out critical power test' in men. *Experimental Physiology*, 94(2): 255-263.

Vanhatalo, A., Black, M., DiMenna, F., Blackwell, J., Schmidt, J., Thompson, C., . . . Jones, A. (2016). The mechanistic bases of the power-time relationship: muscle metabolic responses and relationship to muscle fiber type. *Journal of Physiology*, 594(15): 4407-4423.

Vanhatalo, A., Doust, J., & Burnley, M. (2007). Determination of Critical Power Using a 3-min All-out Cycling Test. *Medicine and Science in Sports and Exercise*, 39(3): 548-555.

Vanhatalo, A., Doust, J., & Burnley, M. (2008). Robustness of a 3 min all-out cycling test to manipulations of power profile and cadence in humans. *Experimental Physiology*, 93(3): 383-390.

Vanhatalo, A., Fulford, J., DiMenna, F., & Jones, A. (2010). Influence of hyperoxia on muscle metabolic responses and the power-duration relationship during severe-intensity exercise in humans: a 31P magnetic resonance spectroscopy study. *Experimental Physiology*, 95(4): 528-540.

Vucetic, V., Mozek, M., & Rakovac, M. (2015). Peak Blood Lactate Parameters in Athletes of Different Running Events During Low-Intensity Recovery After Ramp-Type Protocol. *Journal of Strength and Conditioning Research*, 29(4): 1057-1063.

Wakayoshi, K., Ikuta, K., Yoshida, T., Udo, M., Moritani, T., Mutoh, Y., & Miyashita, M. (1992). Determination and validity of critical velocity as an index of swimming performance in the competitive swimmer. . *European Journal of Physiology and Occupational Physiology*, 64(2): 153-157.

Wakayoshi, K., Yoshida, T., Udo, M., Harada, T., Moritani, T., Mutoh, Y., & Miyashita, M. (1993). Does critical swimming velocity represent exercise intensity at maximal lactate steady state? *European Journal of Applied Physiology and Ocuppational Physiology*, 66(1): 90-95.

Walsh, M., & Bannister, E. (1988). Possible Mechanisms of the Anaerobic Threshold. *Sports Medicine*, 5(5): 269-302.

Wasserman, K., Whipp, B., Koyal, S., & Beaver, W. (1973). Anaerobic threshold and respiratory gas exchange during exercise. *Journal of Applied Physiology*, 35(2): 236-243.

Yarar, H., Barug, D., Bostan, A., Kaya, A., & Aydin, E. (2021). Influence of Physical and Anthropometric Properties on Sprint Swimming Performance. *Pakistan Journal of Medical & Health Sciences*, 15(2): 814-818.

Zacca, R., & Castro, F. (2010). Critical Swimming Speed Obtained by the 200-400 Meters Model in Young Swimmers. *Biomechanics and Medicine in Swimming XI* (pp. 307-309). Oslo: Norwegian School of Sports Science.

Zacca, R., Azevedo, R., Chainok, P., Vilas-Boas, J., Castro, F., Pyne, D., & Fernandes, R. (2020). Monitoring Ag-Group Swimmers Over a Training Macrocycle: Energetics, Technique, and Anthropometrics. *Journal of Strength and Conditioning Research*, 34(3): 818-827.

Zacca, R., Azevedo, R., Peterson-Silveira, R., Vilas-Boas, J., Pyne, D., Castro, F., & Fernandes, R. (2019). Comparison of Incremental Intermittent and Time Trial Testing in Age-Group Swimmers. *Journal of Strength and Conditioning Research*, 33(3): 801-810.

Zacca, R., Fernandes, R., Pyne, D., & de S Castro, F. (2016). Swimming Training Assessment: The Critical Velocity and the 400-m Test for Age-Group Swimmers. *Journal of Strength and Conditioning Research*, 30(5): 1365-1372.

Zarzeczny, R., Kuberski, M., Deska, A., Zarzeczna, D., & Rydz, K. (2013). The Evaluation of Critical Swimming Speed in 12-Year-Old Boys. *Human Movement*, 14(1): 35-40.

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