5-2020

Bilateral Muscle Oxygenation Kinetics In Response To Repeat Sprint Cycling In Strong And Weak Individuals

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A dissertation
presented to
the faculty of the Department of Sport, Exercise, and Kinesiology
East Tennessee State University

In partial fulfillment
of the requirements for the degree
Doctorate of Philosophy in Sport Physiology and Performance

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by
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May 2020

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Keywords: Near-Infrared Spectroscopy, Repeat-Sprint Ability, Isometric Mid-Thigh Pull, Near Infrared Spectroscopy

ABSTRACT

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Repeat sprint ability has been investigated thoroughly, however optimal training methodology to improve RSA remains elusive. Both kinetic and physiological viewpoints have been used to scrutinize aspects of RSA including, initial sprint performance (anaerobic power), maximal cardiorespiratory fitness (VO_{2max}), lactate threshold, anaerobic capacity (mean power), muscle activation (EMG), and local muscle oxygenation kinetics. To our knowledge no study has utilized maximal strength levels as a separate factor among a homogenous group of cardiorespiratory fitness individuals (as determined by peak VO_2 during RSA). The purpose of this study was to better understand the relationship between maximal strength, muscular characteristics, and cycling RSA- respective to muscle oxygenation responses. Fifteen participants completed fifteen 10-second maximal effort sprints on a cycle ergometer interspersed with 30-seconds passive recovery. Respiratory, muscle oxygenation, and kinetic responses were monitored continuously and evaluated relationships with maximal strength and muscular architecture as determined by isometric mid-thigh pull and ultrasonography respectively. A series of 2 x 15 mixed design, group x time, ANOVA's were used to evaluate the effects of group and or sprint on muscle oxygenation kinetics. Strong individuals were found to have significantly greater levels of muscle oxygenation usage, recovery and the respective rates; $p = 0.01$, $p = 0.02$, $p < 0.01$, $p = 003$. In conjunction, stronger individuals displayed

significantly greater anaerobic power and capacity throughout fifteen consecutive sprints. Lastly, linear regression with stepwise selection, found muscular strength and size to account for 73% of the variance of RSA, removing muscular pennation angle and VO_{2max}. The results suggest that maximal strength is influential to RSA and should be an area of focus for repeat sprint ability training.

ACKNOWLEDGEMENTS

Words cannot express the gratitude I have for all of those who have allowed me to stand on their shoulders to pursue my educational and professional goals. To the friends, family, and colleagues who have been readily by my side, I extend the greatest appreciation for your assistance in augmenting my academic experience. Without the support of them all, this culminating project would never have come to fruition.

To my family, Karen, Bob, Jean, Drew and Lolly have provided me with a wealth of knowledge and experience that allow me stand where I do today, and will continue to propel me along a career path. A special bond will forever last with Jean as we routinely shared our wins and losses as we progressed through the road to our terminal degrees. To my family I thank you for all you have done and hope to be able to provide the same support to others in my future.

To my Committee, Dr. Michael Stone, Dr. Michael Ramsey, Dr. Michael Joyner, and Dr. Kevin Carroll, without you this opportunity and project would not be possible. Your relentless challenges, support, and past experiences have allowed me to grow as a student, researcher, and practitioner. The lessons you have instilled upon me will be forever lasting and spread where ever the path may lead me.

To my mentors, Dr. Brad DeWeese and Meg Stone who shared their knowledge, experience and expertise. Your integrity, resiliency, and desire for excellence has reshaped my philosophy on academia, training, and so much more. The knowledge and experiences that you made possible for me stay close to heart and continue to help me succeed.

To my friends who stood by my side through the challenges of this journey and provided the best of support in times of need. In particular, I must recognize and thank Kaela, who stood by my side through thick and thin along our doctoral process.

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CHAPTER 1. INTRODUCTION

Muscle oxygenation, measured via Near Infrared Spectroscopy (NIRS), has been used as a non-invasive measure of muscle metabolism as early as 1977 (Jöbsis, 1977). Until recently, the use of NIRS devices in sport was impractical due to the complexity and cost of the instrumentation. Advancements in technology have allowed the production of portable, wireless devices utilizing light emitting diodes (LED) at a consumer level. Companies such as Artinis, MOXY, and HUMON produce devices that can used by athletes and researchers alike. Since Jöbsis initial investigation, a plethora of research has been conducted on muscle oxygenation kinetics, oxygen usage and recovery and respective rates, during graded exercise test and steady-state submaximal work (Buchheit, Abbiss, Peiffer, & Laursen, 2012; Iannetta, Qahtani, Mattioni Maturana, & Murias, 2017; Miura, Araki, Matoba, & Kitagawa, 2000; A. Subudhi, A. Dimmen, & R. Roach, 2007; van Der Zwaard et al., 2016). More recently, practical applications of NIRS and muscle oxygenation has become a topic of substantial interest among exercise and sport scientists, for example in repeat sprint ability (RSA), resistance training, freediving, and rock climbing (Buchheit et al., 2012; Dupont, Millet, Guinhouya, & Berthoin, 2005; Pereira, Gomes, & Bhambhani, 2007; Perrey & Ferrari, 2017; Racinais et al., 2007).

The ability to perform multiple repetitions of sprint or other high-intensity movements, with limited rest intervals is paramount for field and court sports. Successful repeated sprint performance is dependent on a balance of conflicting components of physical fitness, strength-power and muscular-cardiovascular endurance (Girard, Mendez-Villanueva, & Bishop, 2011). Field and court sports have a requisite degree of endurance capacity to participate, however scoring opportunities are commonly created with repeated bouts of high intensity efforts. Faude, Koch, and Meyer (2012) established that professional football players created successful scoring opportunities with a combination of powerful movements, of which 61% included near maximal straight sprinting. The importance of repeat sprint ability (RSA) is widely accepted, and a wealth of literature is available on RSA performance, limitations, training, and testing procedures (Buchheit et al., 2012; Girard et al., 2011; Nikolaidis & Knechtle, 2016; Smith & Billaut, 2010). Much debate exist about optimal training strategies to optimize RSA in athletes, though the literature is in agreement of limiting factors of RSA (D. Bishop, Girard, & Mendez-Villanueva, 2011). Repeat sprint ability can be diminished by: 1) neural fatigue, 2) depleted energy supply including alterations to the phosphocreatine adenosine triphosphate system, anaerobic glycolysis, and oxidative metabolism, 3) Metabolite accumulation, 4) Decreased muscle excitation (D. Bishop, Lawrence, & Spencer, 2003; Girard et al., 2011; Karatzaferi, De Haan, Van Mechelen, & Sargeant, 2001; McGawley & Bishop, 2008; Soderlund & Hultman, 1991; Yoshida & Watari, 1993). Therefore, improving those factors may prolong the onset of detrimental effects resulting from fatigue. Fatigue has been found to reduce work production, compromise cognitive processing, and alter movement mechanics (Almonroeder, Tighe, Miller, & Lanning, 2018; Bushnell & Hunter, 2007; Mendez-Villanueva, Hamer, & Bishop, 2007). These factors are related to training adaptations, such as maximal strength, power, and cardiorespiratory fitness, in which can be evaluated for their interaction with repeat sprint ability.

Researchers have used NIRS to assess muscle oxygenation in repeat sprint activities to identify oxygen usage and recovery trends, differences in recovery duration and condition, responses to training, and in relation to pulmonary oxygen uptake (Buchheit et al., 2012; Jones, Hamilton, & Cooper, 2015; Ohya, Aramaki, & Kitagawa, 2013). No literature exists comparing muscle oxygenation responses between individuals of differing maximal strength levels. Only one study to the authors knowledge investigated bilateral asymmetry of muscle oxygenation response to activity (Hesford, Laing, Cardinale, & Cooper, 2012). No research is available evaluating changes in movement mechanics in response to RSA procedures.

The purpose of this dissertation is to evaluate muscle oxygenation kinetics during a RSA protocol. In particular, to examine muscle oxygenation kinetic differences between individuals of differing strength levels. The primary purpose of this study is to determine if strength is a factor that contributes to a more desirable performance in conjunction with muscle oxygenation kinetics which could provide evidence supporting the addition of strength training to improve RSA performance. A secondary purpose of this dissertation is to identify trends muscle oxygenation asymmetry in response to a RSA protocol. With more evidence regarding bilateral muscle oxygenation kinetics, practitioners could likely implement NIRS as a monitoring tool to assess acute fatigue and recovery within athletes.

CHAPTER 2. COMPREHENSIVE REVIEW OF THE LITERATURE

Physiological Basis for Oxygenation

Hemoglobin and Myoglobin

Oxygen is required for cellular respiration and energy production. Oxygen becomes available for diffusion, via mechanical ventilation, from atmospheric air through creating imbalances in air pressure between the atmosphere and the thoracic cavity. These differences in pressure draw atmospheric air into the lungs until the pressure within the lungs and atmosphere equalize. As musculature, such as the diaphragm and intercostals relax the thoracic cavity collapses to its resting state. This relaxation compresses the lungs which increases the pressure within the lungs beyond the pressure of the atmosphere which results in an outward flow of air. The mechanical ventilation process is highly regulated by the autonomic nervous system however can be overridden through somatic activation.

Henry's law states that gasses dissolve into liquid in proportion to their partial pressure (Brooks, Fahey, & Baldwin, 2005). When atmospheric air enters the lungs and into alveoli, the partial pressures (summation) of individual gasses drive external respiration, the transport of gas from within the lung across a shared basal membrane into capillaries, and vice versa. The partial pressure of oxygen is depressed, roughly 40 mmHg as compared to the atmospheric pressure of 105 mmHg, within venous blood and drives the movement of oxygen molecules from within the alveoli into the capillaries. The opposite is true of carbon dioxide (CO_2), which partial pressure is elevated in venous blood and dissolves out of the blood stream into the alveoli to be exhaled.

Oxygen is travels through the body in two methods simultaneously, dissolved in plasma and bound to hemoglobin. Of the two methods, hemoglobin is the primary method of oxygen transport. Hemoglobin is a protein consisting of 4 sub-units, four Globulin chains and four heme groups. Each molecule of hemoglobin carries for molecules of gas, either O_2 or CO_2. Hemoglobin's affinity for Oxygen is dependent on the partial pressure of oxygen, temperature, blood pH, and presence of 2-3 diphosphoglycerate. These four components collectively affect how much oxygen is bound to hemoglobin.

Exercise increases the demand for energy in the form of adenosine triphosphate(ATP). A small quantity of ATP is available floating freely within cells, however the remainder of the demanded ATP is produced from one of the following systems: ATP-PCr, Anerobic Glycolysis, or Oxidative metabolism. All the systems create a physiological imbalance that is restored utilizing oxygen-dependent energy pathways.

Exercise increases the demand for energy in the form of adenosine triphosphate (ATP). A small quantity of ATP is available floating freely within cells, however the remainder of the demanded ATP is produced from one of the following systems: ATP-PCr, Anerobic Glycolysis, or Oxidative metabolism. Oxygen is not innately required for ATP to be produced via ATP-PCr or Anerobic Glycolysis though the restoration of homeostasis occurs primarily aerobically (Brooks et al., 2005). After the cessation of exercise, respiration remains elevated, this phenomenon is known as excessive post oxygen consumption(Gaesser & Brooks, 1984; Schaun, Alberton, Ribeiro, & Pinto, 2017). Oxygen is vital for the restoration of homeostasis including resynthesis of PCr and glycogen, temperature management, and hormone balancing (Gaesser & Brooks, 1984; Schaun et al., 2017). Phosphocreatine resynthesis occurs during moments of rest, inter-repetition or after cessation of activity, only if O_2 is available (McMahon & Jenkins, 2002).

When O_2 is not available PCr recovery is entirely suppressed, though as O_2 becomes available PCr recovery occurs (Harris et al., 1976). The demand for O_2 is increased after just 1 sprint to assist in the restoration of the above mentioned. The increased demand of oxygen for restoration, in combination with increased temperatures, decreased pH, and accumulation of 2,3 DPG all reduce the hemoglobin's affinity for oxygen. These principles are best described by the Bohr Effect (Brooks et al., 2005).

Near Infrared Spectroscopy: Design, Principles and Limitations

Near Infrared Light and Chromophores

Near infrared reflectance spectroscopy (NIRS) has gained popularity since its first implementation over 35 years ago, and is used for/in research and sold to consumers as a tool to monitor exercise intensity, fitness status and progression (Perrey & Ferrari, 2017). Near infrared spectroscopy devices are comprised of light emitting diodes or laser photodiodes and photodetectors. Due to the complexity of biological tissue, several techniques have been developed to quantify changes in light absorption. Most simplistically single distance CW NIRS devices use a single light source to emit incident light (I_O) into biological tissue. The intensity of the light is reduced as it travels through the tissue and emergent light (I), that light that leaves the tissue, is received by the photodetector. Light intensity is reduced due to two main factors, absorption by chromophores such as; hemoglobin, myoglobin, and cytochrome c oxidase, and loss due to tissue scattering (Owen-Reece, Smith, Elwell, & Goldstone, 1999). Oxygenation status of hemoglobin and cytochrome c oxidase alters the absorption spectrum which allows for the distinction between individual concentrations of oxygenated hemoglobin (HbO_2) and deoxygenated hemoglobin (HHb)(Bakker, Smith, Ainslie, & Smith, 2012). Cytochrome c oxidase attenuation signal is ten times less than hemoglobin and not thought to have a significant effect on measurements (Madsen & Secher, 1999).

The Beer-Lambert Law

Analysis of substances using spectroscopy rely on the Laws of Lambert and Beer, which are typically combined in the relation of Equation 1.

Equation 1. *The Beer-Lambert Equation*

$$A = \log\left(\frac{I_o}{I}\right) = \alpha \cdot c \cdot d$$

Total Attenuation of a chromophore is equal to the ratio of incident light to emergent light. This ratio is dependent on the relationship between the concentration of a chromophore, *c,* its extinction coefficient, α, and the path length of light (Owen-Reece et al., 1999). This basic form the Beer-Lambert equation is more readily used in colorimetry, in which a path length is determinable. In biological tissue path length determination is infeasible. Biological tissue is a considered a highly scattering medium and directs light away from its original linear path. The Beer-Lambert equation considers the path length to be the distance between optodes, however due to scattering, photons travel a mean distance that is far greater than *d* (Delpy, 1988). The modified Beer-Lambert equation incorporates a differential path length factor (*DPF*) and a geometry dependent factor, Equation 2 (Bakker et al., 2012; Delpy, 1988).

Equation 2. *Modified Beer-Lambert Equation*

$$A = \log\left(\frac{I_o}{I}\right) = \alpha \cdot c \cdot d \cdot DPF + \mathrm{G}$$

The Modified Beer-Lambert equation accounts, to some extent, for scattering however when *d* and *DPF* are assumed to be constant, changes in chromophore concentration can only be described qualitatively. Several techniques, including second derivative, spatially resolved, and time resolved, are available for estimation of path length. When these techniques are used relative changes, not absolute measures, can be measured over time.

Validity and Reliability of Near Infrared Spectroscopy

Jöbsis (1977) was the first to demonstrate the ability to monitor the chromophore concentration response in biological tissue to alterations in oxygen availability. Through a series of experiments within cats and humans, NIRS was found to be an effective, non-invasive method to monitor Hb-HbO_2 steady states, and blood volume. Many years later an extensive evaluation of NIRS derived measured was completed to validate the use of these measures during exercise. Mancini et al. (1994) conducted a series of in-depth experiments to better understand if NIRS was a valid tool to monitor muscle oxygenation and blood volume during exercise. Several of the concerns of Mancini et al. included light attenuation due to skin blood flow, the correlation between changes in attenuation and invasive venous oxygen saturation, and attenuation-based measure with changes in blood flow. Skin blood flow was artificially altered by exposing the participant to hot and cold environments then participants performed forearm exercise. When temperature was modified alterations in skin blood flow occurred however no change in light attenuation was noted until the exercise commenced. These findings suggest that NIR light attenuation is not altered by increases or decreases in skin blood flow. To better understand the changes in forearm muscular blood flow, nitroprusside and norepinephrine, potent vasodilator and vasoconstrictors were intravenously administered. Both at rest and with exercise both chemical alterations significantly affected light attenuation. Changes in light attenuation and venous saturation share a significant linear relationship, $r = 0.82\text{-}0.97$. This finding is in agreement with R. Belardinelli, T. J. Barstow, J. Porszasz, and K. Wasserman (1995b) who also reported a strong correlation, $r = 0.99$. Increased blood flow and reduced muscle oxygenation was observed with the integration of nitroprusside whereas the opposite was true with norepinephrine. NIRS was found to be an acceptable, non-invasive tool to measure muscle tissue oxygenation. While strong relationships are observed between NIRS derived measures and venous saturations, several limitations exist that prevent absolute measures from being derived As previously discussed, path length in muscle could not be accurately determined , although there are several techniques to assist in estimating path length though tissue scattering makes this nearly impossible (Ferrari, Mottola, & Quaresima, 2004; Owen-Reece et al., 1999). However, qualitative data based on relative changes is still valuable. To increase the value of measured relative changes, a blood flow conclusion protocol is suggested to calibrate the changes to minimal and maximal values.

For a device to be practical and useful, validity and reliability are important factors to determine, arguably more so reliability. Researchers have attempted to identify breaking points in muscle oxygenation during graded exercise test, that are thought to be associated with an athletes lactate threshold (Austin et al., 2005). Test-retest reliability of muscle oxygenation at metabolic thresholds as determined via known physiological measures was found to be high (R= 0.87 at lactate threshold and 0.88 at VO_{2max} (Austin et al., 2005).

Muscle Oxygenation and Sport

Since its initial evaluation in 1977, NIRS measurements have been used in investigating biological tissue, often in response to exercise. Increased practicality due to technological advancements that allow devices to be small, lightweight, and wireless promote the ecological validity of NIRS, particularly as it pertains to exercise and sport. Muscle oxygenation has gained practical popularity due to the relationship it shares with oxygen consumption, metabolite production, phosphocreatine resynthesis , and muscle activation (Y. N. Bhambhani, 2004; Ihsan, Abbiss, Lipski, Buchheit, & Watson, 2013; McCully et al., 1994). Graded exercise test and submaximal endurance exercise have been extensively used to evaluate the relationship of muscle oxygenation and its association with measures such as resting and submaximal exercise values for VO_2, VO_{2max}, and metabolic thresholds such as lactate and ventilatory measures. Resistance training has also been used as a model to evaluate muscle oxygenation responses, in particular the relationship between duration of deoxygenation and hypertrophy and strength adaptations (Kacin & Strazar, 2011; Pereira et al., 2007). Lastly, several researchers have attempted to identify relationships between muscle oxygenation recovery and Pi-PCR kinetics. There is plentiful information about acute responses to the above-mentioned modalities however little discussion on practical application to sport exist in the literature. Each modality discussed above provides insight on certain aspects of sport however the combination of all those responses best describes the typical demands of field or court sports.

Graded Exercise Test and Muscle Oxygenation

Incremental exercise and graded exercise test are used to assess cardiopulmonary fitness, biochemical response, and biomechanical economy. These tests are often used to determine an athletes VO_{2max} and pace or power output at lactate threshold. Extensive literature exist that demonstrates the relationship between graded exercise test variables, pulmonary and local muscle oxygenation responses.

Muscle oxygenation during incremental exercise tends to follow a four-phase response : 1) initial increase in saturation to meet the metabolic demand, 2) a linear decrease in oxygen saturation with increasing workloads, 3) an exponential decrease in oxygen saturation above a certain intensity possibly associated with a metabolic threshold, 4) a rapid increase in muscle oxygenation after the cessation of activity culminating in a super compensatory over-shoot in oxygenation (R. Belardinelli, Thomas J. Barstow, Janos Porszasz, & Karlman Wasserman, 1995a; Belardinelli, Georgiou, & Barstow, 1995; Y. N. Bhambhani, 2004; Y. N. Bhambhani, Buckley, & Susaki, 1997; Chance, Dait, Zhang, Hamaoka, & Hagerman, 1992)

The transition from a linear to exponential decrease is thought to be related to a metabolic threshold and or a ventilatory threshold. Depending on the variable, a clear breaking point that initiates the exponential decrease is not always easily identifiable (Shibuya & Tanaka, 2003). Wang et al. (2006) reported that all their participants demonstrated visual break points in the concentration of HHb and TOI, however in the same sample only 11 out of 15 participants displayed break points in HbO_2. Certain break points in NIRS derived measures have been found to have statistically significant correlations(Gaitanos, Williams, Boobis, & Brooks, 1993) with ventilatory and lactate threshold measures (Wang et al., 2006).

Submaximal Exercise

Submaximal exercise is a staple for endurance athletes. These workouts vary in duration but in some scenarios last up to 24 hours for ultra-endurance competitors (Chlíbková, Knechtle, Rosemann, Zákovská, & Tomásková, 2014). Coaches and athletes alike evaluate the physiological response to the implied workload and compare them to previous workouts to gauge the stress level of the athlete. For example, an athlete may typically perform 30 minutes of cycling at 250 watts and exhibit a heart rate of 160, if the athletes heart rate is lower over time at the same workload, the athlete has likely progressed. The opposite is true as well, if the athlete's heart rate is elevated the athlete is likely in a more physiologically stressed or fatigued state. Muscle oxygenation decreases in response to increasing workloads and is inversely proportional to integrated EMG. If at a given load, post training intervention, an athlete maintains a higher muscle oxygenation level, it is likely the athlete has increased their efficiency and activate working muscles to a smaller degree. At workloads beneath lactate threshold, muscle oxygenation steady state is achieved rapidly, approximately 1 minute, however above lactate threshold no steady state is achieved (Y. N. Bhambhani, 2004). Furthermore, strong relationships exist between the global response of VO_2 and muscle oxygenation (Belardinelli, Barstow, et al., 1995b; Y. Bhambhani, Buckley, & Susaki, 1999; Y. N. Bhambhani, 2004).

Repeat Sprint Activities

Relevance to Sport

Success, particularly for field and court sports requires a multifactorial training approach. Sports such as soccer, basketball, American football have undergone extensive time motion analysis with GPS or video. A requisite specific endurance capacity is required to participate in such sports. Successful athletes playing at all levels demonstrate the ability to perform high intensity burst of powerful movements such as straight and multidirectional sprinting, jumping, and kicking actions. Physiologically, a high demand is placed on the neuromuscular system to produce high power muscular contractions, glycolytic metabolism to meet the energetic demands necessary to prolong the burst of high-intensity movements, and lastly aerobic metabolism to meet the long-term energy demands of low intensity efforts as well as assist in recovery between high intensity efforts.

Markers of Performance

Repeat sprint ability is commonly assessed using a standardized protocol consisting of several repetitions, 5-15, of maximal or near maximal exertion with limited rest, 10-30 seconds, that promote performance degradation from repetition to repetition. It is important to note the difference between repeat sprint and intermittent sprint which include much longer rest intervals with minimal performance decrement from repetition to repetition. Commonly evaluated markers of performance for RSA test include, maximal work rate, mean work rate, total work, and a measurement of change in performance from initial to final sprint. Fatigue index (FI) can is calculated as the difference between the best and worst performance relative to the best performance (equation 3).

Equation 3. *Fatigue Index*

$$\mathrm{FI} = 100 \times \frac{(S_{best} - S_{worst})}{Sbest}$$

Limiting Factors

Fatigue accumulates at varying degrees though no clear mechanism is evident. Fatigue is attributed to a culmination of factors including but not limited to: energy supply, metabolite accumulation, and neural factors.

Notable interest has been directed toward the initial sprint and substantial decreases in performance after the first sprint (Girard et al., 2011). It is common to observe more drastic decreases in performance, from the first sprint to successive sprints. Strong positive correlations have been reported between initial sprint mechanical performance and performance decrement (D. Bishop et al., 2003; Girard et al., 2011; Hamilton, Nevill, Brooks, & Williams, 1991). It is important to clarify that the connection between initial sprint performance and performance decay is likely to be attributed to the energy suppling metabolic pathways, rather than the absolute force itself (Gaitanos et al., 1993; Girard et al., 2011). This finding indicates that muscular strength is more likely to be a limiting factor compared to the supporting metabolic pathways. Considering the potential effects of force production in maintaining performance creates implications for training programs that bolster adaptations that increase both strength and supporting metabolism.

Metabolic pathways that support energy demand and inter-repetition rest are the ATP-PCr, anaerobic glycolysis, and oxidative metabolism. Each system providing energy is unique, but works synergistically with other systems to meet exercise demands and promote recovery. Within muscle the muscle cell free ATP and the ATP-PCr provide ATP at the highest rates (Brooks et al., 2005). This extremely rapid delivery of ATP is prominently found within fast twitch muscle fibers. Phosphocreatine availability limits the energy contribution (Gaitanos et al., 1993). To produce ATP, PCr donates its phosphate to free ADP (Brooks et al., 2005). As this system decays from PCr depletion the rate at which energy is produced also decays and is exhibited as a reduction of work rate. Typically the ATP-PCr system is capable of providing energy for up to ten seconds (Brooks et al., 2005). Thus RSA has greater dependence upon the phosphagen system, particularly the first few (Gaitanos et al., 1993; Girard et al., 2011). Primarily training the phosphagen system requires high intensities and relatively long recovery intervals (Forbes, Slade, & Meyer, 2008).

Simultaneously, anaerobic glycolysis is upregulated and provides up to 40% of the energy required for a single sprint (Gaitanos et al., 1993). Glycolysis produces ATP at a slower rate slower than the phosphagen system, however is heavily reliant on biochemical pathways that increase metabolic acidosis. With successive sprints the contribution of energy production from glycolysis can decrease up to 8-fold (Gaitanos et al., 1993). There is confusion in the literature upon the best practices for training glycolytic mechanisms. Two main findings appear to be contradictory when recommending training for improvement. First participants tend to have greater performance decrements with greater glycolytic rates during the first sprint (Bogdanis, Nevill, Boobis, Lakomy, & Nevill, 1995). Secondly, those who had greater glycolytic rates have greater initial sprint performance with a strong correlation with final and total sprint performance (David Bishop, Edge, & Goodman, 2004). This paradigm is widely accepted, though caution should be used when it is interpreted. While, those with greater initial sprint performance display a more rapid decay in achieved work, they are also likely to continue to produce more work than inferior initial sprint performers over a number of sprints (David Bishop et al., 2004; D. Bishop et al., 2003; Bogdanis et al., 1995).

During a single maximal sprint a small percentage, approximately 10%, of energy production occurs aerobically. With successive sprints the aerobic contribution increases to nearly 50% (McGawley & Bishop, 2008). The oxidative pathway is upregulated when the concentration of ADP and AMP become elevated and remains upregulated until a balance of energy is restored. Unlike the other systems the ability to create energy aerobically does not appear to decay with repeated sprints. Conversely, muscle oxygen recovery can be affected by increased demands and decreased affinity. Oxygenation recovery is a limitation, as reduced recovery with successive sprints culminates a progressive deoxygenation. Oxygen availability is crucial for maintenance of energy production and performance, when oxygen availability is reduced from either increased demand or other biochemical interactions such as the Bohr effect, the ability to produce work is negatively impacted.

Muscle Oxygenation Kinetics

Muscle oxygenation responses to repeat sprint activities have been reported to have two major characteristics. After the initial sprint muscle oxygenation decreases rapidly, with successive sprints muscle oxygenation plateaus. Oxygen utilization during repeated sprints is thought to be unaffected with multiple repetitions, thought this may not be the case for recovery. With repetition, oxygenation recovery diminishes and results in a progressive deoxygenation across multiple sprints. This interaction leads to what may be considered maximal oxygen utilization. Contrarily, when oxygen availability is artificially limited by a hypoxic environment individuals use more oxygen compared to normoxic conditions (Brocherie, Girard, Faiss, & Millet, 2017; Subudhi, Dimmen, & Roach, 2007). This finding is interesting as it promotes an inquiry into central or neural factors, regulating performance. While inquisitive in nature, literature pertaining to the topic is still emerging and beyond the scope of this project.

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CHAPTER 3. BILATERAL MUSCLE OXYGENATION KINETICS IN REPONSE TO REPEAT SPRINT CYCLING IN STRONG AND WEAK INDIVIDUALS

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Bilateral Muscle Oxygenation Kinetics In Response To Repeat Sprint Cycling In Strong and Weak Individuals

Abstract

Repeat sprint ability (RSA) is a large component to field and team sports. Enhancing RSA has been shown to improve physical and on-field performance; assessments and training typically consist of short duration, less than 15s, maximal sprint efforts, with incomplete rest, less than 45s. The use of resistance training to augment RSA has been investigated however these training programs target primarily metabolic adaptations, especially in trained individuals. Resistance training intended to develop maximal strength has been shown to improve several of the limiting factors associated with RSA. The first study demonstrated that individuals of differing strength levels have unique responses to RSA. The purpose of this study was to evaluate if individuals with differing levels of strength respond uniquely to an extensive RSA assessment. Sixteen participants completed a series of evaluations including: maximal strength (isometric mid-thigh pull), muscular architecture, and kinetic and physiological response to the RSA assessment. The RSA protocol was completed on a cycle ergometer consisted of fifteen maximal effort sprints of a 10 second duration separated by 30 seconds of passive recovery. Very large, statistical relationship existed between maximum strength and muscle oxygenation usage and rate of usage; $r = 0.75$ $p < 0.01$, $r = 0.73$ $p < 0.01$, respectively. Participants were then separated by strength level into 2 groups. Strong participants produced statistically greater peak and mean power, both absolute and relative to body mass. Strong participants also exhibited greater magnitudes and rates of muscle oxygenation usage and recovery through out the duration of the RSA assessment. Our findings provide evidence that maximal strength is associated with greater RSA performance and greater muscle oxygenation kinetics. This evidence suggest that athletes should perform resistance training with the intention to increase maximal strength to augment RSA performance.

Keywords: Muscle Oxygenation, Repeat Sprint Ability, Team Sport, Resistance Training

Introduction

To better assist athletes in performing repeated high intensity sprint activities, it is vital to understand physiological and biomechanical components that promote success. Repeat sprint ability (RSA) is a requirement to be an effective team sport athlete. The ability of an athlete to sprint repetitively is often measured during free running, treadmill running, or cycle ergometry. Athletes' proficiency at such task is measured by comparing performance decrement, total work accomplished, or initial sprint performance. It is clear that repeated high-intensity sprints with limited recovery intervals engenders decreases in performance, however the mechanisms of fatigue remain elusive. Girard et al. (2011) highlighted muscular and neural factors such as: muscle excitability, limitations in energy supply, metabolite accumulation, neural drive, and muscle recruitment strategies. Each of these pillars are complex and require thorough examination to better understand how their interactions with fatigue development.

Repeat Sprint Ability test are typically graded for performance decay within an athlete though scores such as percent decrement or fatigue index do not account for magnitude of work accomplished. For example, an athlete may have a greater percent decrement from first sprint to last sprint, however produce more work than an athlete with a lesser decrement (Pyne, Saunders, Montgomery, Hewitt, & Sheehan, 2008). When considering best training practices to increase RSA it is important to train both maximal strength and anaerobic metabolism in conjunction with aerobic metabolism. Boosting the ability of these three characteristics will increase an athlete's ability to: produce greater forces at faster rates (more economical), sustain higher force outputs (increased anerobic fuel production), and lastly increase the ability to recover and maintain long term elevated energy demand. Coaches and practitioners rely upon higher volume/ lesser intensity resistance training for its metabolic stress and negate the importance of low volume/ high strength and the neural and muscular adaptations (D. Bishop et al., 2011). The benefits of strength training on running performance, economy, and metabolic alterations is plentiful, but greater clarification is needed to support the importance of muscular strength for RSA. The purpose of this study is to evaluate physiological and biomechanical responses, such as heart rate, muscle oxygenation, power output, and power percent decrement, to repeated sprint exercise between strong and weak individuals.

Methods

Participants

Sixteen recreationally trained individuals volunteered to participate in the study, however one participant was unable to complete the protocol and was removed from the study (12 male, 4 female, 26.5±5.2 yrs, 73.5±9.1 kg, 172±8.2 cm, 13.5±8.2 %BF). All participants were required to have participated in at least 6 months of consistent training for: team sport, repeat sprint exercise, resistance training, and or endurance training. Furthermore, participants were required to be free of musculoskeletal injury and have a resting blood pressure less than 140/90mmHg. Participants were excluded if they had current musculoskeletal injuries, known cardiovascular distress or injury, were less than 18 years of age, pregnant, and or those with known health conditions including bleeding disorder, cardiovascular disease, hypertension greater than 140/90, or diabetes. All subjects read and signed an informed consent document prior to participating in the study, as approved by the university's Institutional Review Board.

Experimental Design

Participants underwent two testing sessions in the laboratory twice. During the first session, participants were assessed for resting blood pressure, hydration status, bilateral ultrasonography of the vastus lateralis, and maximal strength through an isometric mid-thigh pull. During the second visit, participants were assessed for their hydration status, performed the repeat sprint ability test on the cycle ergometer. During the RSA protocol participants wore a chest mounted heart rate strap, NIRS devices bilaterally superficial to the vastus lateralis, and gas exchange was monitored continuously through a metabolic cart. After the RSA protocol was complete, participants underwent a 3-minute blood flow occlusion to assess minimal and maximal rebound muscle oxygenation levels.

Ultrasonography

Measurements: vastus lateralis for muscle thickness (MT), adipose tissue thickness (AT), cross sectional area (CSA), and pennation angle (PA of the right vastus lateralis (VL) in a standing posture, bilaterally, using ultrasonography (LOGIQ P6, General Electric Healthcare, Wauwatosa, WI, USA)(Wagle et al., 2017). The measurement site was determined as 5 cm medial of half the distance between the greater trochanter and lateral epicondyle, bilaterally (Wagle et al., 2017). All measurement sites for all participants were determined by a single practitioner, and images were collected in a repeated measures manner, and therefore any potential error would be systematic (Wagle et al., 2017).

Isometric Mid-Thigh Pull

Participants completed a standardized general warm up before the maximal isometric mid-thigh pull (IMTP) assessment (Sha, 2014). Isometric mid-thigh pull testing was performed standing on dual force plates (Rice Lake Weighing Systems, Rice Lake, WI, USA) sampling at 1000Hz, inside a custom power rack that allows specific bar height adjustments. Participants assumed a mid-thigh pull position in which the participant's torso was vertical and knees were positioned at 125 ± 5 degrees, measured by a handheld goniometer. Once bar height and mid-thigh pull position was confirmed, 2 warm up attempts were completed at 50% and 75% maximal effort. After the 50% effort the participant's hands were secured to the bar using lifting straps and athletic tape. Participants were instructed "pull as fast and hard as possible" for 2-3 maximal trials separated by 120 seconds rest (Hornsby, 2010). For each maximal trial participants were instructed to assume the mid-thigh pull position, apply steady tension on the bar, and a "3,2,1 pull" with loud verbal encouragement until force application plateaued. The force-time curves were analyzed by the same investigator using custom designed lab view software (National Instruments, Austin, TX, USA). The mean of the best two attempts for peak force and peak force application symmetry were considered for data analysis.

Near Infrared Spectroscopy measurements and analysis

Two MOXY monitors were used to monitor SMO_2 bilaterally during the RSA testing protocol. MOXY monitors use 2 light emitting diodes, near-infrared light waves between 670 and 810nm, and one photodetector, to detect changes in light absorbency within muscle tissue. MOXY uses a proprietary algorithm based on the modified beer-lambert law to provide an estimation of muscle oxygen saturation (SMO_2). Muscle oxygen saturation as defined by Fortiori Design is the ratio of the sum of oxygenated hemoglobin and myoglobin compared to the sum of oxygenated and deoxygenated hemoglobin.

Equation 4. *Muscle Oxygen Saturation (SMO_2)*

$$\frac{Oxygenated\ Hemoglobin + Oxygenated\ Myoglobin}{Total\ Hemoeglobin\ and\ Myoglobin}$$

MOXY monitors were placed bilaterally 5 cm medial of half the distance between the greater trochanter and lateral epicondyle, superficial of the vastus lateralis. Each monitor was placed within a polyurethane skirt to block outside light sources from interfering with the device measurements. The unit and skirt were held in place with custom adhesive patches. The device was then covered by the participants athletic compression garments. Data was recorded at 2 Hz and stored on each device continuously throughout the duration of the RSA protocol. Data was also wirelessly transmitted to a laptop for live feedback utilizing PeriPedal software, during the occlusion protocol. Data was downloaded and analyzed in RStudio (Version 1.2.1335).

Post RSA, participants were assessed for minimal and maximal SMO_2 via blood flow occlusion. The process took place in a supine position; a pneumatic tourniquet was placed around the one thigh. The tourniquet was inflated to 10 mmHg above the participants systolic blood pressure and increased by 10 mmHg until occlusion was reached, but not exceeding 250mmhg. Occlusion was defined by a sustained decrease in muscle oxygenation. The occlusion was released when either a minimal plateau of SMO_2 for 30 seconds was observed, a maximal duration of 3 minutes, or by request. Minimal SMO_2 was defined as the lowest value recorded during the occlusion. Maximal SMO_2 was defined as the highest value recorded during super compensatory recovery period after the release of the occlusion.

Cardiorespiratory Measures

During the repeat sprint cycling protocol respiratory gas exchange were continuously measured (TrueOne 2400, ParvoMedics, UT, USA). Gases of a known concentration and a 3L syringe were used to calibrate gas sensors and the flow meter.

Repeat Sprint Cycling

After 24 hours of rest, each participant was familiarized with the cycle ergometer (Velotron, Quarq, SD, USA). The cycle ergometer was adjusted to each participant to allow for a maximal knee extension angle of 30 ± 5 degrees.(Silberman, Webner, Collina, & Shiple, 2005) Participants performed a 5 minute warm-up at 100 watts. Before the repeat cycling protocol began, participants were instrumented with a chest mounted heart rate strap (Garmin Ltd, KS,USA) , metabolic cart headgear, and NIRS sensors (MOXY Monitor, Fortiori Design LLC, MN, USA).

The participants completed two 5 second submaximal sprints in order to become familiar with the starting position and determine their lead foot. Cycle exercise began seated, with the preferred foot forward with the crank at 45 degrees. Participants received a 5 second count down before the initiation of the sprint. The rest intervals were completed seated and passive.

Data Analysis

Raw data from the MOXY devices was downloaded and processed using RStudio. Data from each leg was calibrated to the respective minimal and maximal SMO_2 recorded during occlusion and post occlusion. Data was smoothed with a 10-point moving average. Maximal SMO_2 ($SMO_{2\ maximal}$) values were defined as the maximal SMO_2 recorded prior to the start of each sprint. Minimal SMO_2 ($SMO_{2\ minimal}$) values were defined as the minimal SMO_2 recorded after to the end of each sprint. Muscle oxygen usage ($SMO_{2\ usage}$) was calculated as the difference between $SMO_{2\ maximal}$ and $SMO_{2\ minimal}$, for sprints 1 through 15. Muscle oxygen recovery ($SMO_{2\ recovery}$) was calculated as the absolute difference between $SMO_{2\ minimal}$ and the following $SMO_{2\ maximal}$, for sprints 1-14. A recovery protocol after the 15th sprint was self-selected and therefore excluded from analysis. Rates of oxygen usage ($SMO_{2\ rate\ of\ usage}$) and recovery ($SMO_{2\ rate\ of\ recovery}$) were calculated by dividing the change in SMO_2 by the duration between maximal and minimal SMO_2 values. Lastly, symmetry index scores were calculated for $SMO_{2\ usage}$ and $SMO_{2\ recovery}$ per sprint

Statistical analysis was performed using JASP (Version 0.10.2). In attempt to evaluate the differences in strength, the strongest and weakest 6 individuals were chosen for analysis. Pearson Product-Moment correlations were used to evaluate if a relationship existed between maximal strength and muscle oxygenation kinetics. A series of 2x15 mixed design, group x time, measures analysis of variance (ANOVA) were used to compare $SMO_{2\ usage}$, $SMO_{2\ recovery}$, $SMO_{2\ rate\ of\ usage}$, $SMO_{2\ rate\ of\ recovery}$ between strong and weak participants and across sprint repetitions. Tukey post hoc analysis were computed to determine differences when a statistical interaction effect was detected. Paired sample T-Test compared symmetry index scores for $SMO_{2\ usage}$, $SMO_{2\ recovery}$, $SMO_{2\ rate\ of\ usage}$, $SMO_{2\ rate\ of\ recovery}$, between strong and weak individuals. Relationships between maximal strength and muscle oxygenation kinetics 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, Batterham, Marshall, & Hanin, 2009). The level of significance was set at $p \leq 0.05$. Data are reported as mean ± SD.

Results

Physical and Performance Measurements

Anthropometric data from both groups is displayed in Table 1. To be expected the strong participants exhibited more muscle mass with greater pennation angles, two characteristics that are associated with greater strength and rates of force development, respectively (Wagle et al., 2017). No statistical difference was observed between participants VO_{2max}.

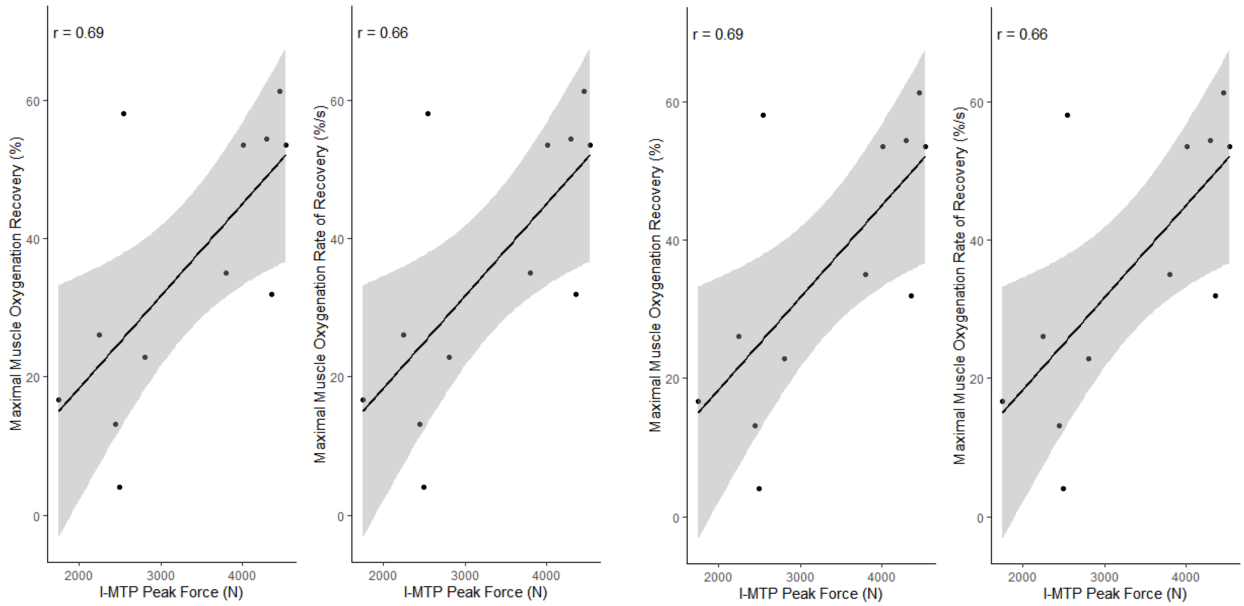
Table 1. Athlete Demographics

Group	Weak	Strong	Effect Size Difference (*d*)
Age (years)	24.49 ± 3.12	24.65 ± 3.26	0.05 (-1.08 – 1.18)
Height (cm)	165.98 ± 5.11	174.75 ± 6.89*	1.45 (0.13 – 2.712)
Weight (kg)	69.42 ± 8.40	76.42 ± 9.84	0.77 (-0.43 – 1.93)
ATT (cm)	0.99 ± 0.50	0.22 ± 0.12**	-2.07 (-3.481 – (-0.6))
CSA (cm^2)	2.97 ± 0.53	3.64 ± 0.59*	1.5 (0.16 – 2.77)
PA (degrees)	20.82 ± 3.41	23.02 ± 4.26**	2.3 (0.76 – 3.77)
MT (cm)	2.23 ± .036	2.95 ± 0.42	0.06 (-1.19 – 1.07)
Peak VO_2 (ml/kg/min)	37.15 ± 7.29	43.91 ± 9.99	0.77 (-0.424 – 1.94)

Table 1 displays anthropometric data: Age, Height, Weight, Adipose Tissue Thickness (ATT), Cross Sectional Area (CSA), Pennation Angle (PA), Muscle Thickness (MT), and relative Peak VO_2 as means and standard deviation. Effect sizes are reported with 95% confidence intervals. *,**,and *** indicates statistical differences respective to $p \leq 0.05$, 0.01, 0.001.

A very large, statistical relationship existed between maximum strength and muscle oxygenation usage and rate of usage; $r = 0.75$ $p < 0.01$, $r = 0.73$ $p < 0.01$, respectively. A large, statistical relationship existed between recovery and rate of recovery, $r = 0.69$ $p = 0.01$ and $r = 0.66$ $p = 0.66$. These relationships, displayed in Figure 1, suggest that stronger athletes can use more oxygen during aerobic exercise with enhanced recovery. To further explore this association participants were divided into strong and weak groups for comparison.

Figure 1. Relationships Between Strength and Muscle Oxygen Kinetics



Performance data is displayed in Table 2. Stronger athletes displayed greater measures of strength, anaerobic power, and anaerobic capacity both absolute and relative to body mass throughout the entire test, Figures 1-4. In both groups peak power performance decayed across the sprints, the strong groups fatigue index was moderately larger on average. Peak anaerobic capacity as described by mean power output was greater in strong participants however exhibited a moderately larger index of fatigue, though not statistically different. No statistical difference was found in symmetry index scores for I-MTP PF, or any muscle oxygenation kinetics.

Table 2. Performance Measures

Group	Weak	Strong	Effect Size Difference (*d*)
I-MTP PF (N)	2380.47 ± 359.49	4243.82 ± 281.63***	5.77 (3.02 – 8.48)
I-MTP PF_a ($N/BW^{2/3}$)	138.5 ± 12.34	233.5 ± 14.53***	7.05 (3.79 – 10.27)
Best Peak Power (W)	595 ± 131.28	874.83 ± 177.56**	1.79 (0.39 – 3.13)
Best Peak Power (W/kg)	8.18 ± 2.01	11.37 ± 1.21***	1.92 (0.49 – 3.30)
Peak Power Fatigue Index (%)	30.13 ± 19.7	44 ± 9.0	0.927 (-0.29 – 2.11)
Best Mean Power (W)	489.5 ± 107.37	715.83 ± 157.50*	1.68 (0.031 – 3.00)
Best Mean Power (W/kg)	6.72 ± 1.59	9.29 ± 1.16**	1.85 (0.43 – 3.21)
Mean Power Fatigue Index (%)	28.98 ± 18.70	43.99 ±9.93	1.00 (-0.23 – 2.192)

Table 2 displays strength and initial sprint performance variables as means and standard deviation. Isometric Mid-Thigh Pull peak force (I-MTP PF) and allometrically scaled (I-MTP PF_a) represent maximal strength levels. Absolute and relative peak power are indicatory of anaerobic power and capacity, respectively. *,**,and *** indicates statistical differences respective to $p \leq 0.05$, 0.01, 0.001.

Figure 2. Absolute Cycling Peak and Mean Power Output

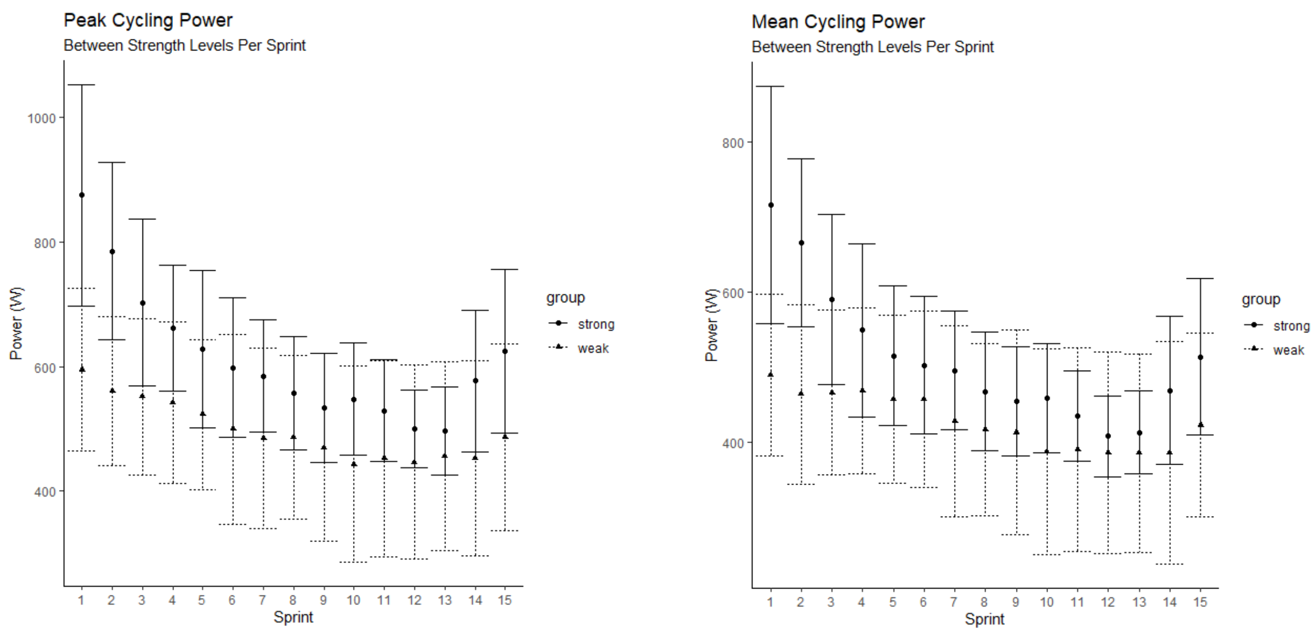
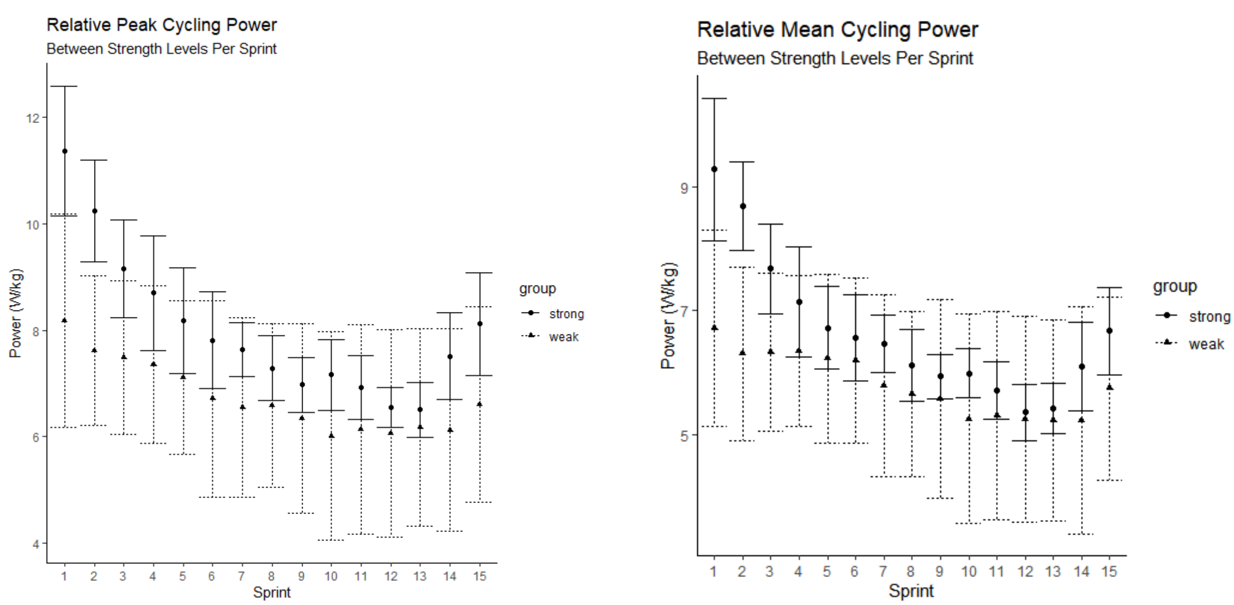


Figure 3. Relative Cycling Peak and Mean Power Output



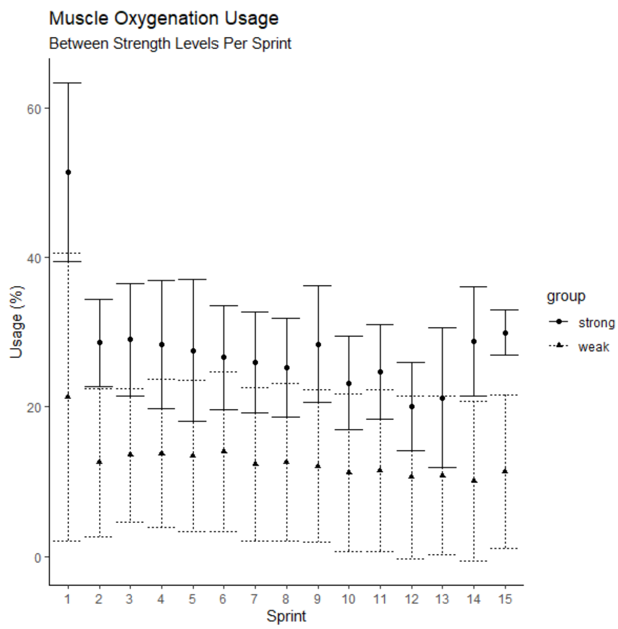
Muscle Oxygenation Usage

The $SMO_{2\ usage}$ values calculated for the RSA test are displayed in Figure 1. Statistical differences were observed between sprint, $F(14,140) = 18.79$, $p < 0.01$, strength groups $F(1,10) = 9.00$, $p = 0.01$, and the interaction of sprint and group, $F(14,140) = 4.87$, $p < 0.01$. Strong participants exhibited statistically greater $SMO_{2\ usage}$ compared to weak individuals; $p = 0.01$, $d = 0.87$. Regardless of strength level, the initial sprint showed a greater $SMO_{2\ usage}$ compared to recovery after all other sprints 1-14 $d = 1.68$-1.26.

A significant interaction between group and sprint was observed. Strong individuals $SMO_{2\ usage}$ during the first sprint was greater than all other sprints in both strength groups; $p \leq .01$ $d = 1.58 – 4.09$. Weak participants used less oxygen during the second sprint in comparison to the first sprint; $p = 0.03$, $d = 1.15$. A trivial increase in usage occurred from repetitions 2 - 6, $d = 0.12$-0.19. From sprint 6 to the end of the test $SMO_{2\ usage}$ decreased and remained statistically less than the 1st sprint $p = 0.01 – 0.04$ but not the 2nd.

Overall the strong participants used more oxygen on average, and during each sprint throughout the duration of the test. The weak participants usage remained steady, compared to the strong, but still had significant reductions in the latter sprints.

Figure 4. Muscle Oxygenation Usage Per Sprint and Group

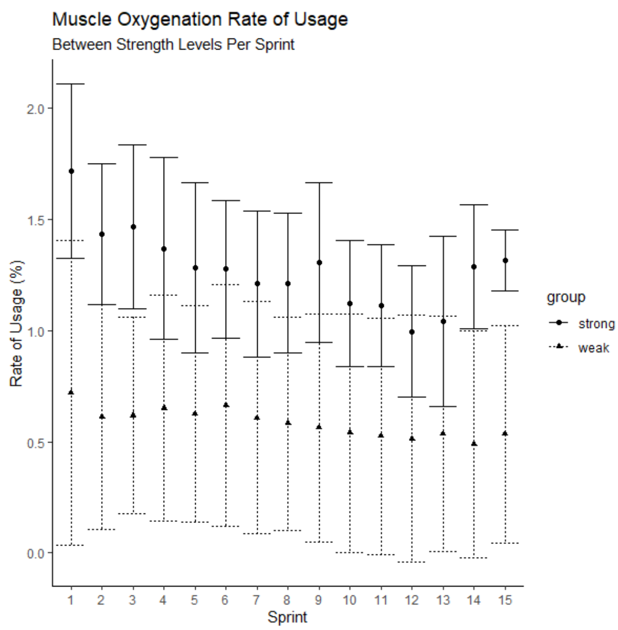


Rate of Muscle Oxygen Usage

The $SMO_{2\ rate\ of\ usage}$ values calculated for the RSA test are displayed in Figure 2. Statistical differences were observed between sprint, $F(14,140) = 7.14$, $p < 0.01$, strength groups $F(1,10) = 8.40$, $p < 0.01$, and the interaction of sprint and group, $F(14,140) = 2.60$, $p = 0.02$. Strong participants exhibited statistically greater $SMO_{2\ rate\ of\ usage}$ compared to weak individuals; $p = 0.02$, $d = 0.84$. Regardless of strength level, the initial sprint had a greater $SMO_{2\ rate\ of\ usage}$ compared to recovery after all other sprints 1-14 $d = 0.47$-1.15.

A significant interaction between group and sprint was observed. The strong participants exhibited a steeper decline in $SMO_{2\ rate\ of\ usage}$ however usage remained greater than the weak participants. This decay is evident as a statistical decrease in $SMO_{2\ rate\ of\ usage}$ compared to the first sprint from repetitions 4-15. The weak participants remained consistent, no statistical difference across all repetitions when compared to repetition 1 but moderately less than the strong group through all the repetitions.

Figure 5. Muscle Oxygenation Rate of Usage Per Sprint and Group

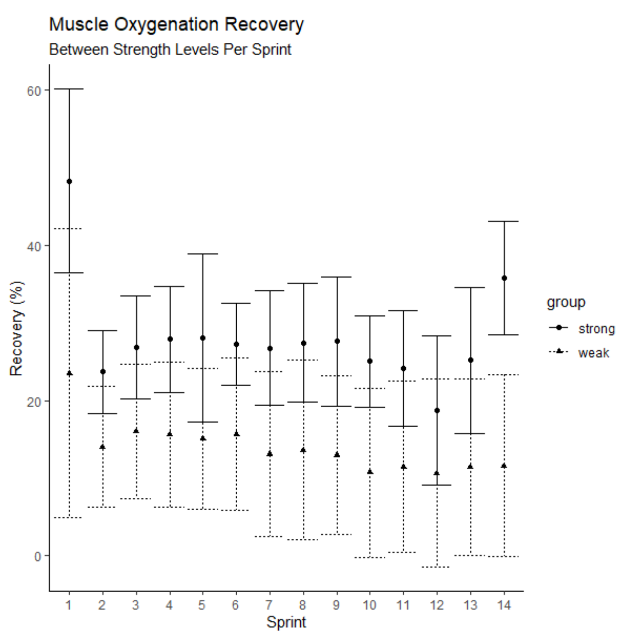


Muscle Oxygenation Recovery

The $SMO_{2\ recovery}$ values, the amount of muscle oxygen recovered between the lowest achieved value post sprint to the highest achieved value before the next sprint. calculated, as the amount for the RSA test are displayed in Figure 2. Statistical differences were observed between sprint, $F(13,130) = 14.55$, $p < 0.01$, strength groups $F(1,10) = 7.69$, $p = 0.02$, and the interaction of sprint and group, $F(13,130) = 3.55$, $p < 0.01$. Strong participants exhibited statistically greater $SMO_{2\ recovery}$ compared to weak individuals; $p = 0.02$, $d = 0.80$. Regardless of strength level, the initial sprint was followed with greater $SMO_{2\ recovery}$ compared to recovery after all other sprints 1-14 $d = 1.28$-1.80.

Lastly a significant interaction between group and sprint was observed. Strong individuals $SMO_{2\ recovery}$ after the first sprint was greater than all other sprints in both strength groups, besides the weak groups first sprint, $d = 1.42\text{-}3.36$. Statistical difference was not found between the groups recovery that followed the first sprint though a large difference was observed, $d = 1.27$. The weak group did not exhibit an exaggerated recovery after the first sprint, instead weak participants maintained a lesser extent of recovery that statistically decayed after the 6th sprint, $p \leq .01\text{-}.04$. Interestingly, the strong group recuperated the ability to recovery in the last three sprints, with the recovery that followed the 14th sprint being statistically greater compared to the second sprint; $p < 0.01$, $d = 1.38$.

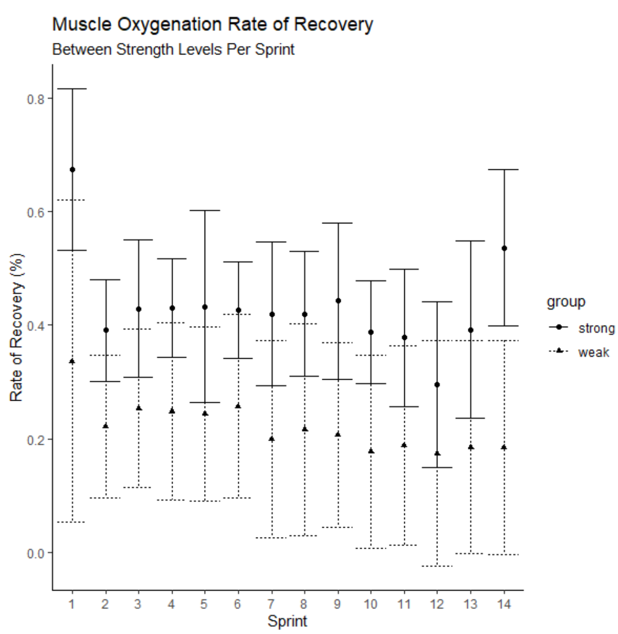
Figure 6. Muscle Oxygenation Recovery Per Sprint and Group



Rate of Muscle Oxygenation Recovery

Similar to recovery, the rate of recovery was statistically different between sprints, $F(13,130) = 9.34$, $p < 0.01$, strength groups, , $F(1,10) = 6.87$, $p = 0.03$, and an interaction between strength levels and sprint, , $F(13,130) = 2.46$, $p = 0.01$. The strong groups recovery rate was statistically greater than the weak group; $p = 0.03$, $d = 0.76$. Strong participants recovery, that following the first sprint, was statistically more rapid than all other sprints in both groups except for the first sprint of the weak group. A statistical difference was not observed between the strong and weak participants recovery following the first sprint but a moderate effect was noted between groups favoring the strong group; $p = 0.15$, $d = 1.09$.

Figure 7. Muscle Oxygenation Rate of Recovery Per Sprint and Group



Discussion

Elevated strength levels appear to provide greater RSA performance, when considering absolute and relative anaerobic power and capacity. Stronger athletes exhibit greater local muscle oxygenation kinetics such as usage, recovery and the respective rates, which appears to an advantageous characteristic to RSA. No statistical asymmetries appeared in either group during maximal strength or RSA testing. These findings support the use of strength training to augment RSA performance.

RSA and Fatigue Index

Repeat sprint ability performance has been defined as the ability to repeatedly produce maximum power output (Mendez-Villanueva et al., 2007). Fatigue index is commonly used to evaluate an athletes RSA, however this variable undermines the importance of the initial and final power output (D. Bishop et al., 2011). Da Silva, Guglielmo, and Bishop (2010) found that the strongest predictor of RSA was anaerobic power (maximal power produced) which accounted for 73% of the variance. In the present study, strong participants exhibited on average a moderately larger fatigue index but also continued to display greater anaerobic power and capacity (mean cycling power per sprint) in their most fatigued state. The association between strength levels and anaerobic power would bolster the concept of implementing a strength training regimen to augment RSA.

Muscle Oxygen Recovery and Rate of Recovery

Bishop et al. (2011) highlights two primary factors of RSA: initial sprint performance (maximal anaerobic power) and recovery between sprints. Recovery between sprints is discussed in three subfactors: PCr resynthesis, aerobic fitness, and muscle buffering. Aerobic fitness and PCr resynthesis are likely intertwined as the latter is completely dependent on oxygen availability(McCully et al., 1994). Furthermore, the rate of PCr resynthesis has been reported to be related to the rate of hemoglobin reoxygenation (Di Prampero & Margaria, 1968; McCully et al., 1994). Phosphocreatine stores can be depleted rapidly, as much as 45-65% after a 6-second maximal sprint (Gaitanos et al., 1993). A complete recovery of PCr stores can last more than 5 minutes, so only partial recovery may occur typical RSA rest intervals. Based on the previous connection of reoxygenation and PCr resynthesis it would appear a faster rate of reoxygenation ($SMO_{2\ \text{Rate of Recovery}}$) would be advantageous replenishing PCr stores.

Strength training often requires use of set and repetition programs that stress the phosphagen and glycolytic systems and has been shown to enhance anaerobic power and capacity; thus metabolic aspects of strength training may have been a factor in the outcomes of this study (Bazyler et al., 2017). Indeed, the results of this study are supported by those of Nagasawa (2013) who found that individuals with exposure to glycolytic intensive training, aka sprinters, had greater rates of muscle oxygenation recovery as compared to those of endurance trained counterparts during short, high-intensity sprints, 30 second Wingate.

Stronger individuals had moderately faster rates of oxygenation compared to weaker individuals. Individual's strength levels are most easily improved through a periodized resistance training program (DeWeese, Hornsby, Stone, & Stone, 2015). High intensity training that led to increases in strength are also characterized by drastic reduction and post exercise supercompensation of muscle oxygenation (Tanimoto & Ishii, 2006). Resistance training, particularly low-intensity, is reported to increase hypoxia inducible factor-1 alpha and several other genes associated with muscle adaptation (Drummond et al., 2008). A well-constructed resistance training plan utilizing block periodization and phase potentiation targets a spectrum of intensities with desired acute and chronic adaptations. Recently, intensity and effort level during resistance training have been shown to elicit different muscle oxygenation responses. Greater magnitudes of intensity and effort produce the most drastic alterations in muscle oxygenation (Gómez-Carmona et al., 2019). The similarity of muscle oxygenation kinetics found by Gomez-Carmona et al. and the current study suggest commonalities between higher intensity resistance training and successful RSA.

Conclusion

Stronger individuals produced advantageous RSA traits such as greater anaerobic power and capacity when compared to weak individuals of similar cardiorespiratory fitness (VO_{2max}). Strength levels are largely related to muscle usage and recovery which encourages the use of resistance training to augment muscle oxygenation kinetics. Resistance training should focus on intent and a spectrum of intensities organized in a logical sequenced manor, as both are influential in regards to muscle oxygenation kinetics, quality of strength gains, and transference to performance (DeWeese et al., 2015; Gómez-Carmona et al., 2019). Athletes, coaches, and practitioners should emphasize maximal strength gains to augment RSA performance.

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CHAPTER 4: RELATIONSHIP BETWEEN MUSCULAR STRENGTH, MUSCULAR SIZE AND PHYSIOLOGICAL AND BIOMECHANICAL ASPECTS OF A CYCLING BASED RSA ASSESSMENT

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Relationship Between Muscular Strength, Muscular Size, Physiological and Biomechanical Characteristics Of A Cycling Based Repeat Sprint Ability Assessment

Abstract

Repeat sprint ability (RSA) is a large component to field and team sports. Enhancing RSA has been shown to improve physical and on-field performance; assessments and training typically consist of short duration, less than 15s, maximal sprint efforts, with incomplete rest, less than 45s. The use of resistance training to augment RSA has been investigated however these training programs target primarily metabolic adaptations, especially in trained individuals. Resistance training intended to develop maximal strength has been shown to improve several of the limiting factors associated with RSA. The first study demonstrated that individuals of differing strength levels have unique responses to RSA. The purpose of this study was to determine the most influential factors associated with maximal sprint speed, a predictor of RSA. Sixteen participants completed a series of evaluations including: maximal strength (isometric mid-thigh pull), muscular architecture, and kinetic and physiological response to the RSA assessment. The RSA protocol was completed on a cycle ergometer consisted of fifteen maximal effort sprints of a 10 second duration separated by 30 seconds of passive recovery. A linear regression with stepwise selection revealed that maximal strength and muscle cross sectional area were the most accurate predictors for maximal sprint performance, adjusted $R^2 = 0.73$. It is apparent that initial sprints of greater magnitude are often accompanied by greater fatigue. However our previous study supports that those with greater initial sprint performance retained the ability to outperform those of lesser sprint performances throughout the entirety of the assessment. Therefore, increases in maximal strength and to an extent muscular cross-sectional area are likely to be beneficial for RSA performance.

Keywords: Muscle Oxygenation, Repeat Sprint Ability, Team Sport, Resistance Training

Introduction

To better assist athletes to be able to better perform repeated high intensity burst of sprint activities, it is vital to understand physiological and biomechanical components that promote success. Repeat sprint ability is a requirement to be an effective team sport athlete. The ability of an athlete to sprint repetitively is often measured during free running, treadmill running, or cycle ergometry. Athletes proficiency at such task is measured by comparing performance decreases from their best or initial sprint to their last or worst sprint. It is clear that repeated high-intensity sprints with limited recovery intervals engenders decreases in performance however the mechanisms of fatigue remain elusive. Girard et al. (2011) highlighted muscular and neural factors such as: muscle excitability, limitations in energy supply, metabolite accumulation, neural drive, and muscle recruitment strategies. Each of these pillars are complex and require thorough examination to better understand how their interactions with fatigue development.

Study One of this dissertation demonstrated that participants of similar training backgrounds and cardiorespiratory fitness had significantly different responses to RSA testing. Stronger people, as determined by I-MTP PF, had significantly greater muscle oxygenation kinetics as compared to weak people in response to short high intensity sprints. These results are supported by Nagasawa (2013), which demonstrated that sprinters had significantly greater muscle oxygenation recovery in response to short high intensity sprints than endurance trained counterparts. The literature has previously described that greater cardiorespiratory augmented muscle oxygenation rates of recovery, however those works primarily examined the response after the cessation of long duration lesser intensity exercise (Hamaoka, 1992; Ichimura et al., 2006). During short, high intensity exercise these findings do not appear to be supported.

The purpose of this study is to evaluate participants characteristics associated with RSA performance maximal sprint power such as: VO_{2max}, maximal strength, vastus lateralis cross sectional area, and vastus lateralis pennation angle.

Methods

Participants

Sixteen recreationally trained individuals volunteered to participate in the study, however one participant was unable to complete the protocol and was removed from the study. (12 male, 4 female, 26.5±5.2 yrs, 73.5±9.1 kg, 172±8.2 cm, 13.5±8.2 %BF). All participants were required to participate in at least 6 months of consistent participation in: team sport, repeat sprint exercise, resistance training, and or endurance training. Furthermore, participants were required to be free of musculoskeletal injury and have a resting blood pressure less than 140/90mmHg. Participants were excluded if they had current musculoskeletal injuries, known cardiovascular distress of injury, less than 18 years of age, pregnant, and or those with known health conditions including bleeding disorder, cardiovascular disease, hypertension greater than 140/90, or diabetes. All subjects read and signed an informed consent document prior to participating in the study, as approved by the university's Institutional Review Board.

Experimental Design

Participants underwent two testing sessions in the laboratory twice. During the first session, participants were assessed for resting blood pressure, hydration status, bilateral ultrasonography of the vastus lateralis, and maximal strength through an isometric mid-thigh pull. During the second visit, participants were assessed for their hydration status, performed the repeat sprint ability test on the cycle ergometer. During the RSA protocol participants wore a chest mounted heart rate strap, NIRS devices bilaterally superficial to the vastus lateralis, and gas exchange was monitored continuously through a metabolic cart. After the RSA protocol was complete, participants underwent a 3-minute blood flow occlusion to assess minimal and maximal rebound muscle oxygenation levels.

Ultrasonography

Measurements: cross sectional area (CSA), and pennation angle (PA of the right vastus lateralis (VL) in a standing posture, bilaterally, using ultrasonography (LOGIQ P6, General Electric Healthcare, Wauwatosa, WI, USA)(Wagle et al., 2017). The measurement site was determined as 5 cm medial of half the distance between the greater trochanter and lateral epicondyle, bilaterally (Wagle et al., 2017). All measurement sites for all participants were determined by a single practitioner, and images were collected in a repeated measures manner, and therefore any potential error would be systematic (Wagle et al., 2017).

Isometric Mid-Thigh Pull

Participants completed a standardized general warm up before the maximal isometric mid-thigh pull (IMTP) assessment (Sha, 2014). Isometric mid-thigh pull testing was performed standing on dual force plates (Rice Lake Weighing Systems, Rice Lake, WI, USA) sampling at 1000Hz, inside a custom power rack that allows specific bar height adjustments. Participants assumed a mid-thigh pull position in which the participant's torso was vertical and knees were positioned at 125 ± 5 degrees, measured by a handheld goniometer. Once bar height and mid-thigh pull position was confirmed, 2 warm up attempts were completed at 50% and 75% maximal effort. After the 50% effort the participant's hands were secured to the bar using lifting straps and athletic tape. Participants were instructed "pull as fast and hard as possible" for 2-3 maximal trials separated by 120 seconds rest (Hornsby, 2010). For each maximal trial participants were instructed to assume the mid-thigh pull position, apply steady tension on the bar, and a "3,2,1 pull" with loud verbal encouragement until force application plateaued. The force-time curves were analyzed by the same investigator using custom designed lab view software (National Instruments, Austin, TX, USA). The mean of the best two attempts for peak force and peak force application symmetry were considered for data analysis.

Repeat Sprint Cycling

After 24 hours of rest, each participant was familiarized with the cycle ergometer (Velotron, Quarq, SD, USA). The cycle ergometer was adjusted to each participant to allow for a maximal knee extension angle of 30 ± 5 degrees.(Silberman et al., 2005) Participants performed a 5 minute warm-up at 100 watts. The participants completed two 5 second submaximal sprints in order to become familiar with the starting position and determine their lead foot. Participants, while seated, placed their preferred foot forward with the crank at 45 degrees. Participants received a 5 second count down before the initiation of the sprint. The rest intervals completed seated and passive.

Data Analysis

Data are reported as means ± standard deviation (sd). Statistical significance was set at $p \leq 0.05$. The Shapiro-Wilk test was used to assess the normality of distribution. Relationships between cycling peak power during the first sprint and maximal VO_2, maximal strength, vastus lateralis cross sectional area, and vastus lateralis pennation angle were assessed with Pearson product-moment correlations. Relationships between cycling peak power and other 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. Multiple linear regression was used to determine which characteristics could predict RSA success.

Results

The predictive variables of the 15 participants are displayed in Table 3. The relationships between performance characteristics to cycling peak power are represented in figure 5. Peak power shared very large, significant relationships with VL CSA ($r = 0.72$, $p < 0.01$), and I-MTP peak force ($r = 0.79$, $p <0.01$). No correlation was observed between cycling peak force and VO_{2max} ($r = 0.38$, $p = 22$, or pennation angle ($r = 0.29$, $p = 0.37$).

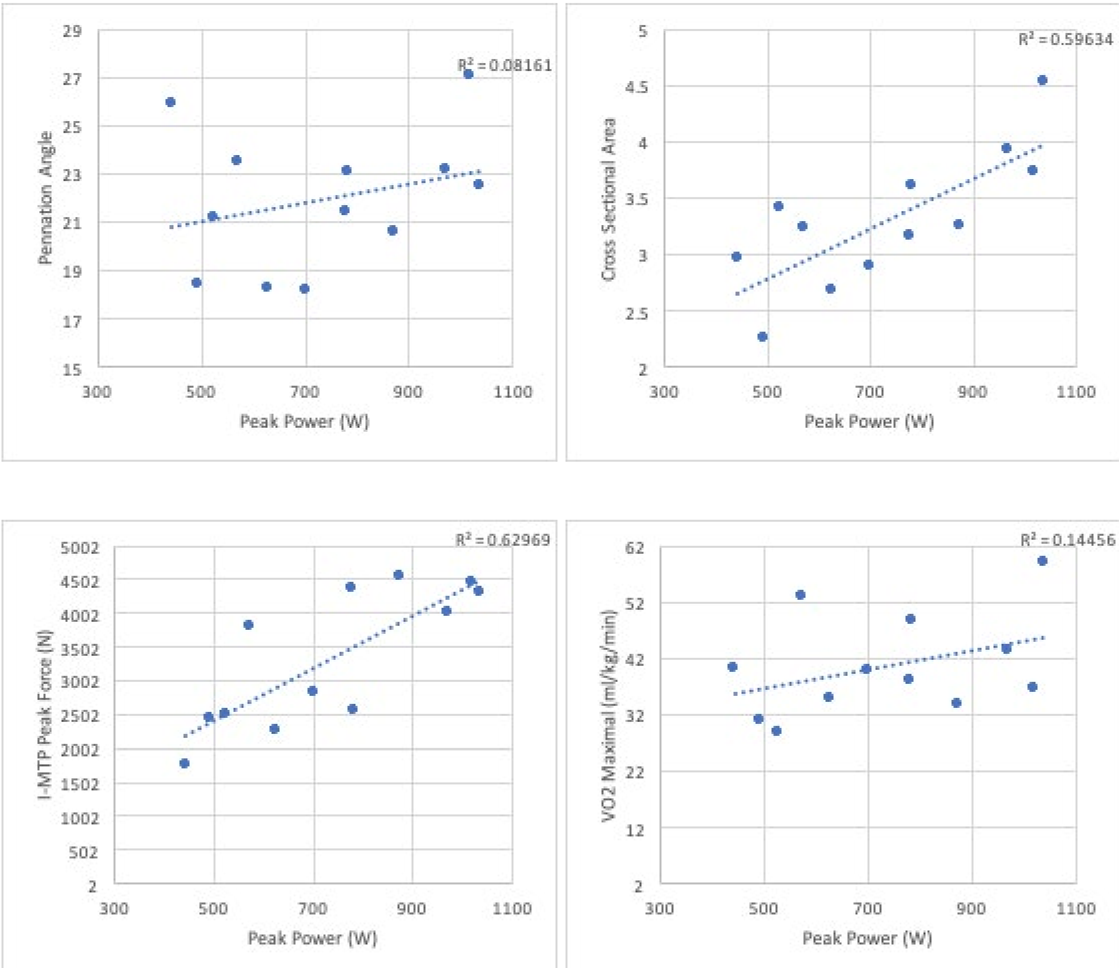
A multiple linear regression with stepwise elimination was performed to assess how much variance in cycling peak force, a major predictor of RSA, could be explained by relative

VO_{2max}, maximal strength (I-MTP PF), muscular size (VL CSA), and muscular characteristics (VL PA). The resulting model included maximal strength and muscular size which accounted for 73% of the variance for cycling peak power. The resulting equation can significantly predict peak cycling power, Peak Power = -159.71 + (0.11* I-MTP PF) + (163.782 * VL CSA), $F(2,11) = 15.95$, $p < 0.01$, adjusted $R^2 = 0.73$.

Table 3. Participant Performance Characteristics

Peak Cycling Power (W)	VO_{2max} (ml/kg/min)	I-MTP PF (N)	VL CSA (cm2)	VL PA
734.9 ± 208.6	40.53 ± 9.05	3312 ± 1021	3.30 ± 0.60	21.92 ± 2.863

Figure 5. Muscular Strength and Cardiorespiratory Fitness Relationships with Peak Power



Discussion

Repeat sprint ability performance has been strongly related to maximal power performed during the initial sprint. Previous work has demonstrated that individuals of different magnitudes of strength have different physiological and mechanical responses to the same RSA protocol. This study attempted to better understand the contribution of physical characteristics: muscular strength, muscular size, muscular architecture, and VO_{2max}, to peak power production during a RSA test. Approximately 73% of the variance of peak power can be explained by muscular strength and size. Resistance training is thought to be beneficial for RSA performance though the literature demonstrates skepticism that resulting strength is to be responsible for improvements (D. Bishop et al., 2011; Hill-Haas, Bishop, Dawson, Goodman, & Edge, 2007).

Studies that have evaluated resistance training fail to provide ecologically valid training programs (Hill-Haas et al., 2007). Most of these studies use high volume, lesser intensity programs which likely elicit work capacity adaptations more like repeat sprint exercise. Recently, Gomez-Carmona et al. (2019) demonstrated that training intensity and intent alter muscle oxygenation responses. Further investigation of muscle oxygenation kinetic responses to acute and chronic resistance training will strengthen the rationale for resistance training paradigm selection, such as phase potentiation. Furthermore, muscle oxygenation kinetics have not been monitored throughout combined resistance and aerobic training programs.

Conclusion

Repeat sprint ability performance is often analyzed by assessing total work accomplished or amount of fatigue accumulated. A misleading concept that is often not addressed is that greater levels of fatigue accumulation do not necessarily mean lesser performance compared to other individuals. Our previous work established that stronger individuals exhibit greater anaerobic work and capacity compared to weaker individuals of similar VO_2 peaks. Initial sprint performance has been associated with more successful RSA performance, therefore we evaluated what was most impactful for this predictor variable. Maximal strength and vastus lateralis cross sectional area account for 73% of the variance of maximal peak force. While there is a requisite amount of low intensity endurance and high intensity exercise endurance, increasing maximal strength will likely improve RSA.

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CHAPTER 5. CONCLUSION

Repeat sprint ability is required in team and field sports. Several limiting factors to RSA have been evaluated and training recommendations have been provided in the literature. As a whole, a lack of clarity exists upon the optimal method to analyze RSA between: total work accomplished, fatigue decrement, or fatigue index. Total work accomplished appears to be the best indication of applicability to sport performance, while improvement of fatigue index maybe a better monitoring measure per individual. The importance of maximal strength and the characteristics it provides, such as rates of force development, postural control, and improved musculotendinous stiffness, are widely accepted in strength power sports. The appreciation of these qualities does not appear to be unanimously accepted in team and field sports. Maximal strength levels do positively affect RSA and muscle oxygenation kinetics. This study is not meant to undermine the importance of high intensity exercise endurance training, but to suggest the incorporation of a logically sequenced resistance training program that elicits gains in maximal strength.

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