MECHANICAL EFFICIENCY IS LOWER AFTER CYCLING COMPARED TO AFTER RUNNING IN TRAINED TRIATHLETES

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by
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Abstract

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Abstract

Triathlon involves swimming, cycling, and running. Mechanical Efficiency of running (ME_R) has been investigated in many previous studies. However, no known studies have examined ME_R after a cycling stimulus. **PURPOSE:** To examine whether a 40-km cycling stimulus alters running economy (RE) and ME_R in trained triathletes. **METHODS:** Eight competitive triathletes (7 males, 1 female; 21.0±1.5 yrs; height 1.8±0.1 m; weight 73.9±8.2 kg; VO_2max 59.2±7.6 mL•kg^{-1}•min^{-1}) with a minimum of one-year experience competing in triathlon distances ranging from Olympic to Ironman participated in this study. Subjects reported to the lab for three separate visits (separated by ≥ 48 hrs). At visit one, subjects completed the informed consent, a VO_2max test, anthropometric measures, and baseline performance testing [isometric squat maximal voluntary contraction (MVC) and countermovement jump (CMJ)]. During the second visit, RE and ME were measured during running after subjects completed 5k run non-cycling exercise stimulus (NCS). For visit three, RE and ME were measured during running after subjects completed 40-km cycling stimulus (CS40K) using a Computrainer®. MVC, CMJ, and Muscle Glycogen values were measured before and after the exercise bout on visit two and three. **RESULTS:** ME_R after CS40K was significantly lower than ME_R after completing a NCS (CS40K: 48.4±5.7%, NCS: 53.7±3.5%; p=0.004). RE, as a percentage of VO_2max (CS40K: 74.8±9.3%, NCS: 74.1±7.8%; p=0.771) or as absolute VO_2 (CS40K: 6.5±1.3 $L \bullet min^{-1}$, NCS, 6.4±1.2 $L \bullet min^{-1}$; p=0.804) was not significantly different between CS40K and NCS. Blood lactate (CS40K: 5.5±1.2 $mmol \bullet L^{-1}$, NCS: 4.2±1.3 $mmol \bullet L^{-1}$; p=0.055), respiratory exchange ratio (RER; CS40K: 0.93±0.11, NCS: 0.88±0.05; p=0.260), and work (CS40K: 61,380±6,176 joules, NCS: 64,094±5,554 joules; p=0.137) were not significantly different between CS40K and NCS. Also, there were no significant differences in the percent decrease in glycogen (CS40K: 14.3±10.1%, NCS: 15.0±8.0%; p=0.879), percent decrease in CMJ (CS40K: 10.9±9.2%, NCS: 10.1±12.9%; p=0.885), or percent decrease in MVC (CS40K: 15.3±9.8%, NCS: 15.9±16.9%; p=0.923). **CONCLUSION:** The lower value for ME_R observed following cycling in this study might be due to the combined effect of slightly higher blood lactate values, slightly higher RER, and slightly lower external mechanical work performed. A lower value of ME_R after cycling may hinder run performance and thereby increase time to completion. However, the exact mechanisms for the observed lower value of ME_R after CS40K are unclear. Future investigations should examine additional physiological and biomechanical variables that might impact ME_R, such as variations in running form after cycling.

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Introduction

Triathletes are required to alter movement patterns while maintaining intensity during the swim, cycle, and run phases of competition. Their ability to do this efficiently is dependent on a combination of physiological and biomechanical factors. However, for many triathletes, the run phase after cycling is characterized by decreased performance, compared to running alone (Bonacci, Chapman, Blanch, & Vicenzino, 2009; Vleck & Alves, 2011). Determining the cause for the decline in performance is essential for improving success (Bonacci et al., 2009). To date, only running economy (RE) after cycling has been studied in triathletes. RE, defined as the oxygen uptake at a given intensity/speed, has been used extensively to measure the efficiency of running in various populations (Conley & Krahenbuhl, 1980; Helgerud, Støren, & Hoff, 2010) and is often used as an important measure of performance in trained runners (Saunders, 2005; Shaw, Ingham, Fudge, & Folland, 2013). For example, when comparing collegiate runners, matched for VO_2max, RE was the metric correlated best with 10k finishing times (Conley & Krahenbuhl, 1980). Various studies since have further validated the importance of running economy to athletic success and running performance (Helgerud et al., 2010; Nummela et al., 2006); however, studies investigating changes in RE after cycling have provided conflicting results (Bonacci, Green, et al., 2010; Bonacci, Saunders, Alexander, Blanch, & Vicenzino, 2011; Bonacci, Vleck, Saunders, Blanch, & Vicenzino, 2013). Perhaps the discrepancies are due to the fact that RE only considers oxygen consumption, while running performance is dependent on a multitude of factors, including but not limited to blood pH, external mechanical work, fuel utilization, fatigue, and oxygen consumption (Gregoire, Millet, & Vleck, 2000; Kohrt, Morgan, Bates, & Skinner, 1987; van Rensburg, Kielblock, & van der Linde, 1986).

Mechanical efficiency during running (ME_R) evaluates multiple aspects of performance and thus may be a more suitable assessment of an individual's running efficiency than RE alone (Ito, Komi, Sjoedin, Bosco, & Karlsson, 1983). ME_R, defined as the ratio of mechanical work to energy expenditure (both anaerobic and aerobic), provides a more thorough assessment of performance than running economy (Cavagna & Kaneko, 1977; Ito et al., 1983; Kyrolainen & Komi, 1995; McBride et al., 2015). McBride et al. recently demonstrated that during a hopping protocol, competitive and recreational runners have similar external mechanical work values, however recreational runners have significantly higher aerobic and anaerobic energy expenditures, and thus lower mechanical efficiency during hopping, compared to competitive runners (McBride et al., 2015). Despite the importance of mechanical efficiency in athletic performance, only one study has previously reported the inverse relationship between relative running intensity and mechanical work and energy expenditure, resulting in decreased ME_R (Ito et al., 1983).

No known previous research has measured ME_R after cycling; therefore, the purpose of this study is to evaluate changes in ME_R and RE after a cycling stimulus, compared to non-cycling exercise stimulus, in trained triathletes.

Statement of the Problem

Triathletes are believed to experience negative changes in run performance when transitioning from the cycle to run leg of a triathlon. These impairments impact performance though the feeling of heavy legs, change in stride turnover, and overall slower finishing times. No known previous research has measured ME_R after cycling; therefore, the purpose of this study is to evaluate changes in ME_R and RE after a cycling stimulus, compared to non-cycling exercise stimulus, in trained triathletes.

Thus the purpose of this research is to investigate changes in running economy and mechanical efficiency after a bout of cycling compared to a bout of independent running and attempt to determine why this change in economy and efficiency is occurring.

Hypothesis

I hypothesize that running economy and mechanical efficiency will be lower after cycling than after running alone.

Significance of Study

This research will give a better understanding of how mechanical efficiency and running economy are affected with varying activity. Further, triathletes will benefit from this study by gaining valued insight on what is influencing performance during the run leg of the triathlon.

Review Of Literature

Introduction

Success in endurance events depends a variety of physiological and biomechanical factors; some are alterable while others depend greatly on genetic predisposition (Saunders, 2005). Although success is multifactorial, past and recent literature suggests that there is a positive strong correlation between running economy, defined by energy use at a given intensity of exercise, and endurance success (Franch, Madsen, Djurhuus, & Pedersen, 1998; Helgerud et al., 2010; Santos-Concejero, Granados, Irazusta, et al., 2013; Saunders, 2005; Shaw et al., 2013). Also, more recent literature done reviewing changes in muscle mechanical characteristics, termed mechanical efficiency and defined as the ratio between work performed to energy expenditure suggests similar findings (McBride et al., 2015). Research findings suggest that preservation of these two metrics can greatly increase the time to fatigue and improve performance. Further, researches and coaches have adopted various training modalities to improve these metrics for single sport athletes. Triathletes however, believed to be due highly to their multisport focus, experience impaired running performance during the run phase of triathlon. Previous research has been done in an attempt to understand why running performance is impacted, but little progress has been made in this area, thus it seems appropriate to look at how running economy and mechanical efficiency are being altered in running after a cycling bout. Thus the purpose of this research is to investigate changes in running economy and mechanical efficiency after a bout of cycling compared to a bout of independent running and attempt to determine why this change in economy and efficiency is occurring. This review of literature will aim to assess factors that improve endurance performance, fatigue, and the effects of multisport training and racing performance.

Factors Effecting Performance

Research has investigated various physiological and biomechanical factors that contribute to athletic endurance success. Results of these studies have given rise to various conflicting findings stressing a greater importance on improving certain factors over others. However, years of refining and reviewing have led researchers and athletes alike to what appears to be reliable conclusions. The majority of this research has suggested that major factors that influence performance are VO_2max, lactate/ventilatory threshold, and movement patters/ economy of movement.

VO_2 Max

VO_2 max is an individual's ability to consume and deliver oxygen to the working muscles. Seminal papers reviewing this aspect of physiology suggested that it is essential for endurance athletes and it sets the upper limit for performance, thus the greater an individual's VO_2max the greater performance (Butts, Henry, & McLean, 1991; Foster, Costill, Daniels, & Fink, 1978). In fact, a study done in well-trained endurance athletes suggests that VO_2max was more highly correlated to performance than muscle fiber type, and succinate dehydrogenase activity (Foster et al., 1978). Further, some research completed in untrained populations has shown that this metric can be improved through training which will theoretically improve aerobic capacity and performance (Legaz, Serrano, Casajus Mallen, & Munguia Izquierdo, 2005). Finally, the importance of VO_2max has been reviewed countless times by various researchers with findings showing that generally, more elite endurance athletes possess a higher ability to consume and utilize oxygen when compared to sub elite athletes (Astorino, 2008; Hale, 2008; Kenny, Wilmore, & Costill, 2012; Ortiz, Greco, de Mello, & Denadai, 2006; Puthucheary et al., 2011).

Although the idea of a high VO_2max has for some time been the gold standard for endurance performance, this view has become somewhat antiquated over time. While this correlation remains true for heterogeneous populations, i.e. comparing sub elite to elite runners, the dichotomy of this relationship increases greatly as the athletic population becomes more homogenous (Legaz et al., 2005). Previous research done on elite athletes measuring the same VO_2max have been reported to have vast differences in performance (Astorino, 2008). Further, longitudinal studies comparing improvements in performance and VO_2max have shown that improvements in performance are independent of VO_2max, and further, that in some cases VO_2max may actually decrease to some degree while performance will increase (Bragada et al., 2010; Legaz et al., 2005; Ortiz et al., 2006). Interestingly, a longitudinal study done on trained 3000 meter runners showed that VO_2max was not correlated to changes in performance (Bragada et al., 2010). Of course this does not mean that a high VO_2max constitutes a negative factor, because it does offer a physiological aerobic ceiling for athletes. Further, the data can't be denied that generally elite athletes do have higher VO_2max values than sub-elite counterparts. However, one cannot refute the fact that there are other, seemingly loftier, physiological factors at play. More recent research has attempted to elucidate these factors and they will be discussed below.

Blood pH

Another section of an endurance athlete's physiology that influences performance is avoiding metabolite accumulation and decreases in blood pH levels. Past literature has shown that metabolite accumulation can result in a decrease in force output from the muscle and can alter muscle contractile characteristics (Cairns, 2006). This has been proven with, studies done on skinned rat skeletal muscle suggests that a decrease in pH can change contractile properties of the muscle leading to a decrease in force production (Fabiato & Fabiato, 1978). This change in blood pH is the result of an increased release of hydrogen atoms from the breakdown of ATP for energy. Normally, at lower intensity's the hydrogen atoms are buffered by other metabolic processes resulting is a negligible change in blood pH and no change in performance (Cairns, 2006). However, as the intensity begins to increase, which normally occurs during racing, the bodies buffering capacity is exceeded causing an increase in hydrogen ions, a decrease in pH resulting in decreased performance. (Cairns, 2006; Tanaka & Matsuura, 1984). Therefore, the aptly named Lactate threshold (LT) or the onset blood lactate accumulation (OBLA) is a point that endurance athletes should seek to avoid. Ever since researchers understood the negative effects metabolite accumulation has on performance, there has been an interest in determining how to alter this lactate threshold to improve performance (Buchheit & Laursen, 2013; Jakeman, Adamson, & Babraj, 2012; Kohn, Essén-Gustavsson, & Myburgh, 2011). Multiple methods such has HIIT, lactate threshold training, and various other coined terms have been employed and are currently practiced by many endurance athletes to increase the ability to tolerate blood pH changes (Carte, Jones, & Doust, 1999). Of course maintaining an intensity below lactate threshold is vital for maintaining intensity. Thus literature has suggested that economy might be a vital means of maintaining intensity and performing during training and racing.

Exercise Economy

Exercise economy, an individual's ability to utilize energy at a given intensity, has often been a sought after variable to improve athletic performance. Recent research has considered this metric to be more valuable than individuals VO_2max. For example, when comparing athletes of a similar VO_2max, running economy and cycling economy was the determining factor for 5k running and 40k cycling finishing times (Bini, Diefenthaeler, & Carpes, 2011; Bonacci et al., 2009; Conley & Krahenbuhl, 1980; Jones & Carter, 2000). Upon realizing its importance, researchers have come to various conclusions as to what aspects of physiology impact this metric. These metrics include not only the previously discussed physiological factors VO_2max and lactate threshold, but also substrate availability, maximum aerobic running velocity, and running mechanics (Jones & Carter, 2000; Paavolainen, Hakkinen, Hamalainen, Nummela, & Rusko, 1999; Santos-Concejero et al., 2014; Saunders, 2005). Thus, similar to many aspects of physiology there is most likely some sort of dynamic interplay between all these factors.

Fortunately for athletes, regardless of what factors influence this, it appears to be highly adaptable though training (Paavolainen et al., 1999). Since this discovery, multiple studies on running economy have attempted to determine what aspects of physiology and biomechanics are improved through training, including decreased co-activation of muscle, decreased amplitude and duration of muscle activity, lowering variability of movement, improving substrate utilization, and improving mechanical muscle characteristics, and contact time (Bonacci et al., 2009; Bonacci, Green, et al., 2011; Bonacci, Green, et al., 2010; Bonacci, Saunders, et al., 2011; Bonacci et al., 2013; Ettema, 2001; D. A. Jones, de Ruiter, & de Haan, 2006; Petersen, Hansen, Aagaard, & Madsen, 2007; Pratt et al., 2013; Rabita, Couturier, Dorel, Hausswirth, & Le Meur, 2013). From a performance standpoint, improving running economy allows athletes to exercise at the same intensity at a lower oxygen or energy cost, or increase intensity to match the oxygen cost from pre training. Of Course, the opposite can be said when running economy diminishes, which generally happens with detraining and fatigue. While detraining can for the most part be avoided or planned for, fatigue is always a concern for endurance athletes. In fact, fatigue is the one aspect of physiology that is known to cause negative outcome on running economy.

While there is some ambiguity on what factors improve exercise economy, the one common theme associated with impairment of all the factors that influence running economy is fatigue. These mechanisms will be discussed later in more detail, fatigue does appear to impair running economy by decreasing the amount of economical work done by the muscle and thereby negatively impacts performance. Further, since this is such a vital aspect of performance, understanding it is vital for athletes. Unfortunately, small sample sizes and methodology issues have limited this type of research on endurance athletes, (Amann, 2011; Burgess & Lambert, 2010; Conceição, Silva, Barbosa, Karsai, & Louro, 2014; Noakes, 2000; Petersen et al., 2007; Shei & Mickleborough, 2013).

Mechanical Efficiency

Mechanical Efficiency is defined by a ratio of work performed to energy used and is in fact a product of running economy. Work is a product of force produced and displacement;

while energy, as mentioned above, is related to ATP broken down or oxygen consumed. This allows the researcher to gain a more direct look at an individuals economy of movement, rather than looking an individuals gross economy like with running economy. Previous researchers have indicated mechanical efficiency depends on the mechanical characteristics of the muscle including: tension, relaxation speed, contraction strength, ground force reactions, and actin myosin relationship; along with things such as running form, stride angle, stride length, moment arm length, and contact time (Ettema, 2001; Keir, Zory, Boudreau-Larivière, & Serresse, 2012; Kumari & Ramana, 2010; McBride et al., 2015; Petersen et al., 2007; Santos-Concejero et al., 2014; Tartaruga et al., 2013). Previous methods have used frame-by-frame analysis to calculate the amount of work completed, this required very careful measures and a very large time investment. However, more recent methods look at ground reaction forces and O_2 consumption (Cavagna & Kaneko, 1977; McBride et al., 2015). Previous studies done reviewing mechanical efficiency in recreational vs competitive runners found little significant difference in VO_2max, however did observe measurable difference in mechanical efficiency being 34% and 44% respectively (McBride et al., 2015). Similar to running economy, improved mechanical efficiency has an impact of a variety of performance factors including increased maximal running speed, increase time to fatigue, and improve overall endurance performance (Ettema, 2001; Harris, Debeliso, & Adams, 2003; Keir et al., 2012; Kumari & Ramana, 2010; McBride et al., 2015; Petersen et al., 2007; Santos-Concejero et al., 2014; Tartaruga et al., 2013). As would be expected, elite runners were found to have enhance mechanical efficiency compared to their sub-elite counterparts (McBride et al., 2015). Thus the importance of this factor, like running economy, appears to be necessary for endurance success (Saunders, 2005). However, similar to an athletes exercise economy, as fatigue occurs, there is a notable regression in mechanical efficiency (Petersen et al., 2007; Shei & Mickleborough, 2013). Previous research has been completed looking at differences in mechanical efficiency in elite vs non-elite athletes, and on how this metric is influenced by changes in speed, however no literature has reviewed how fatigue effects this or how varying successive activity may effect this metric in running.

Fatigue

An endurance athlete's ability to resist fatigue is perhaps one of the most vital characteristics for maintaining performance. Fatigue, whether it is exhausting energy substrates, an increase in blood and muscle metabolites, a change in muscle mechanical characteristics, or a alteration in neuron firing rate/ muscle recruitment, all result in decreased ability to maintain intensity (Amann, 2011; Barnes & Kilding, 2015; Farrell, Wilmore, Coyle, Billing, & Costill, 1993; Guezennec, Vallier, Bigard, & Durey, 1996; Ražanskas, Verikas, Olsson, & Viberg, 2015; Riddell et al., 2003). Researchers have divided fatigue based on its characteristics into central and peripheral components. Central fatigue is related to motivation, central nervous system signal transmission, and the ability for the motor unit to be recruited upon receiving signal and has the potential to reduce the force producing capability of the muscle (Shei & Mickleborough, 2013). Peripheral fatigue however deals with the availability of energy substrates, blood and muscle metabolite buildup, and muscles mechanical characteristics; thereby influencing the actin myosin ability to cause muscle contraction (Shei & Mickleborough, 2013). Further, both divisions are believed to contribute in some way to endurance performance, but how each one impacts performance is still a contested topic. Thus its vital to differentiate these two divisions of fatigue and how training, exercise intensity, mode of exercise and genetics effect performance.

Peripheral Fatigue

Peripheral fatigue is best described the body's inability to meet the muscles need for fuel due to substrate depletion. In other words, it results in a decrease in the muscles ability to buffer (hydrogen ions) metabolites resulting in a change in the contractile proteins of the muscle. Although, there have been other proposed aspects of this fatigue, the focus will remain on the more well understood aspects of fatigue (Amann, 2011; Ražanskas et al., 2015; Riddell et al., 2003).

Perhaps the best understood mechanism of peripheral fatigue is a decrease in substrate availability. Substrate utilization involves three major fuel sources consisting of carbohydrates, fats, and protein. These fuel sources are not created equally and contribute at different intensities, with the greatest contribution coming from carbohydrates (glycogen) at higher intensity's, Free Fatty Acids (FFA) at low intensity, and proteins when all stored fuels are exhausted (Ortenblad, Westerblad, & Nielsen, 2013; Riddell et al., 2003). Thus, during endurance exercise there is generally a joint contribution from fats and glucose, with a higher focus being on glucose (Riddell et al., 2003). These fuels are able to be stored in the liver and muscle, and exhausting them has caused drastic negative effects in past research. In particular, depletion of this fuel source has been known to result in decreased force production, therefore making relative intensity seem higher than it was pre-fatigue (Petersen et al., 2007; Shei & Mickleborough, 2013). Although this only seems to occur for very long endurance events greater than two hours, or for individuals exercising at a intensity just below lactate threshold for an extended amount of time. Research done on elite marathoners showed that post marathon, force production was deceased significantly and was slow to recover in the days following the marathon (Petersen et al., 2007). Often times, to compensate, athletes relative O_2 consumption will increase to maintain intensity resulting in increased energy expenditure and a decreased time to fatigue, creating a vicious cycle for athletes.

The second piece of peripheral fatigue is the increase in metabolite production and the inability for the body to buffer the metabolites being produced (Farrell et al., 1993; Shei & Mickleborough, 2013). Research has long since shown that as lactate and Hydrogen ions begin to accumulate in the blood, oxygen consumption increases which similar to glycogen depletion causes an increase in relative intensity (Farrell et al., 1993; Santos-Concejero, Granados, Bidaurrazaga-Letona, et al., 2013; Shei & Mickleborough, 2013). Furthermore, very similar to substrate depletion, an accumulation in hydrogen ions has been seen to result in decreases in force of contraction in human and animal models (Horita & Ishiko, 1987; Shei & Mickleborough, 2013). Thus, maintaining intensity below the level of lactate accumulation, but still at a high enough intensity to perform is essential for performance. Training interventions have been implemented to train this system by pushing the lactate steady state towards a high intensity thus allowing athletes to work at a higher relative intensity before crossing the threshold. Again, this training is highly specific to the sport making it difficult for multisport athletes to see large benefits.

Multisport Events: Challenges and Changes

Discussed briefly above, multisport events come with their own set of challenges that must be overcome by athletes. Further, although not fully understood as to how, both central and peripheral fatigue contributes to performance decrements. Furthermore, changes in substrate availability, metabolite accumulation, motor recruitment or the fatigue of motor neurons can alter kinetics, exercise economy, and cause greater injury rates during training and racing (Bonacci et al., 2009). For single sport athletes, many of these adaptations occur to a much higher degree, helping to slow a number of these fatigue factors. However, due to their multisport discipline, many of these positive adaptations to central and peripheral fatigue are blunted or altered in triathletes while the negative aspects are amplified and therefor impairing performance of these athletes.

Single Sport Versus Multisport

For single sport athletes, recruitment patterns, improvements in efficiency, economy, and ways to prevent fatigue are generally well adapted through repeated practice of their skill (Bini et al., 2011; Bonacci, Blanch, Chapman, & Vicenzino, 2010; Bonacci et al., 2009). However, to be competitive, even elite triathletes can’t devote as much time to any one sport compared to their matched single sport athletes (Bonacci et al., 2009). Research measuring leg EMG activity in cyclists and triathletes suggested that trained triathletes had decreased motor recruitment patterns through increased muscle co-activation, amplitude of contraction, and variability of movement (Chapman, Vicenzino, Blanch, & Hodges, 2007). This decreased control could potentially decrease time to fatigue in these athletes and decrease performance and increase injury rates (Chapman, Vicenzino, Blanch, Dowlan, & Hodges, 2008; Chapman et al., 2007; Chapman, Vicenzino, Blanch, & Hodges, 2008; Conley & Krahenbuhl, 1980).

One could also propose that substrate utilization may be impacted by the both way these athletes must alter activity during training and racing. Single sport athletes can gain various adaptions through training; one seemingly essential one is improved economy of movement. Of course, this idea has been highly correlated with specificity of sport. Studies reviewing cycling economy in triathletes and trained cyclists showed that cyclists had much greater economy of movement than triathletes. Meaning that higher trained runners, cyclists, and swimmers are more economical than their subpar counterparts. This idea presents nothing novel, however, what does appear to hold stock is the lacking potential for triathletes to benefit from these vital adaptions from economy. Notably, decreased economy of movement results in greater muscle recruitment, which results in increased work per contraction, and therefore an increase in fuel utilization. This should come as no surprise, but it does help to give an insightful look as to why performance may be impeded during the run in triathlon. Thus, finding out why and if fatigue is influencing performance could shape future research avenues.

Neuromuscular overwriting

There is a belief that some positive neuromuscular recruitment changes my be lost when combining multiple sports in sequence, or with minimal recover time (Bonacci et al., 2009). Due to limitations such as athlete tracking, it is unknown if these effects are recognized in experienced athletes, or to what degree long-term training may attenuate this overwriting effect. However, short term studies on altering motor control with varying tasks suggests that neuronal adaptations are inhibited in the task preformed first, and are biased toward the learning of the second task (Karniel & Mussa-Ivaldi, 2002; Shadmehr & Brashers-Kreg, 1997). Unfortunately, these studies were done outside of an athletic setting and on varying individuals, but the findings present an interesting look at motor training and motor recruitment. Triathletes generally train more than one discipline a day, and often perform workouts to mirror race conditions in an attempt to train specifically for racing (Bonacci et al., 2009). Thus, while the literature is sparse, it provides evidence current training methods may further impair neuromuscular recruitment patterns in triathletes. Further studies need to be done on a multisport athletic population to better understand these results.

Altered Recruitment Patterns

Additionally recent research suggests that motor recruitment patterns are altered when transitioning from the cycle to the run leg of a triathlon. These changes could decrease performance by altering running economy and heightening injury rates because of altered kinematics and biomechanics (Bonacci et al., 2009). Some research done reviewing this topic has shown that there is little to no change in recruitment patterns during this transition (Bonacci, Blanch, et al., 2010; Bonacci, Green, et al., 2010), and only actually cause impairments in 7% of triathletes (Bonacci, Blanch, et al., 2010). However, these studies use small sample sizes and review the effects of easy to moderate cycling and running over a short time frame. Thus, they don't represent the longer duration or higher intensity strategies that are generally represented in training or racing by triathletes. Further, other research that has done similar investigations applying a more race and training specific methodology found increased negative effects on neuromuscular recruitment. The literature suggests that these neuromuscular changes can alter exercise economy, increase the energy cost of activity, impair kinematics of running, and could increase injury rates (Chapman, Hodges, Briggs, Stapley, & Vicenzino, 2010; Chapman, Vicenzino, Blanch, Dowlan, et al., 2008; Lepers, Hausswirth, Maffiuletti, Brisswalter, & Van Hoecke, 2000). These negative outcomes can negate the proposed benefits that can occur with improved neuromuscular recruitment and cause a reduced performance.

Substrate Utilization: Effects of Localized fatigue

Mentioned above, budgeting energy throughout endurance events is vital for success, and if not done properly, the impact on race performance can be great. When glycogen stores become exhausted, even with the availability of other substrates, muscle function is decreased and the intensity of exercise is greatly hindered (Ortenblad et al., 2013). Fortunately, as mentioned above, athletes can adapt to this by improving economy and efficiency through skill repetition. However, since triathletes have multiple sports to focus on, improvements in economy aren’t as great (Moro et al., 2013). This means that energy stores (primarily glycogen) are generally exhausted sooner when training and racing.

Furthermore, studies done on trained cyclists, suggests that there is a localized fatigue in the quadriceps during an all out cycling protocol (Dingwell, Joubert, Diefenthaeler, & Trinity, 2008). As would be expected, this localized fatigue led to impaired muscle function, increased recruitment of non-fatigued muscle to compensate, and a change in cycling kinematics, leading to an overall change in efficiency (Dingwell et al., 2008). Trained cyclists are able to compensate for this very well to maintain intensity throughout the remainder or the cycling bout. Of course, based on previous data, one would expect to see similar or even greater changes in triathletes during cycling because of the time they must spread amongst multiple sports. Furthermore, one might also infer that effects of this localized fatigue will likely be experienced in the run that may lead to a change in mechanics and efficiency. Although there have been attempts, no studies have been able to determine why performance is impacted so greatly. Further, although it seems very possible no studies have looked at substrate fatigue in the triathlete as a possible reason for decreased performance during the run.

Conclusion

As stated above, energy cost of running is elevated post bike much greater than post run, possibility due to changes in recruitment patterns, localized fatigue, and kinematic changes which may alter economy of movement (Chapman et al., 2010; Chapman, Vicenzino, Blanch, Dowlan, et al., 2008; Guezennec et al., 1996). Further, the run has been considered to be the most important portion of this race because of its increased difficulty compared to running under normal conditions (Guezennec et al., 1996). Since this leg is after a high intensity cycle swim and cycle, it is likely that athletes are becoming fatigued and effecting race performance (Guezennec et al., 1996; Riddell et al., 2003). Future research should focus on reviewing what metrics of run performance are changing and further review possible mechanisms as to what may be causing these changes.

Methods

Study Design

Eight competitive triathletes (7 males, 1 female; 21.0±1.5 yrs; height 1.8±0.1 m; weight 73.9±8.2 kg; VO_2max 59.2±7.6 mL•kg^{-1}•min^{-1}), with a minimum of one-year experience competing in triathlon distances ranging from Olympic to Ironman, participated in this study. Subjects reported to the lab for three separate visits each separated by ≥ 48 hours. During visit one, subjects completed the informed consent, health screening questionnaire, anthropometric measures, baseline performance testing [isometric squat maximal voluntary contraction (MVC) and countermovement jump (CMJ)], and a VO_2max test.

During the second visit, before any activity, resting muscle glycogen levels were measured using MuscleSound® ultrasound technology (MuscleSound; Denver, CO) though a method validated previously (Hill & Millan, 2014; Nieman, Shanely, Zwetsloot, Meaney, & Farris, 2015). After obtaining baseline resting metabolic data (VO_2, VCO_2, RER, and V_E; Parvo Medics 2400; Sandy, UT), subjects performed a non-cycling exercise stimulus (NCS) 5k run on a Bertec instrumented treadmill (Bertec; Columbus, OH) at a competitive triathlon race pace; intensity of the run was ensured by measuring heart rate through a chest strap heart rate monitor (Polar Fit One; Kempele, Finland). The purpose of this NCS was to remove the athletes from a resting state to help account for possible fatigue that might occur in mechanical efficiency of running (ME_R) and running economy (RE) after cycling. Immediately after completing NCS, subjects performed the MVC and CMJ tests, then returned to the treadmill for mechanical efficiency of running ME_R and running economy RE data collection. Time between the end of NCS and start of the ME_R test ranged from 60-90 seconds, which simulates a typical triathlon transition. Finally, post-glycogen measures were obtained using MuscleSound® to observe changes in muscle glycogen content.

For visit three, ME_R and RE were measured during running again, but this time after completing 40 km of cycling on their own personal bicycles using a Computrainer® system (RacerMate; Seattle, WA). After obtaining resting glycogen and metabolic values (same as in visit two), subjects cycled for 40 kilometers (CS40K) at a competitive race pace while wearing a chest strap heart rate monitor to ensure intensity. Upon completion of CS40K, subjects performed the MVC and CMJ tests, before moving to the Bertec treadmill for ME_R and RE measurements (same as in visit two). Finally, post-muscle glycogen levels were also obtained at the conclusion of the ME_R and RE data collection periods.

VO_2max Test Protocol

Subjects performed a graded exercise test to volitional exhaustion on the Bertec treadmill to assess individual maximal oxygen consumption. After obtaining baseline resting metabolic data, subjects were disconnected from the metabolic cart and asked to complete a 10-minute warm-up at a self-selected pace (no incline). Subjects were then reconnected to the metabolic cart to obtain exercise metabolic data. Subjects were instructed to begin at a self-selected pace and that the treadmill speed would increase 0.4 $m \cdot s^{-1}$ (no incline) for each successive stage until volitional exhaustion. Stages one through three were 4 minutes long, and every successive stage thereafter was 2 minutes long. Heart rate was recorded via a chest strap heart rate monitor.

Mechanical Efficiency Of Running Overview

For the ME_R test, subjects were asked to run at their competitive triathlon pace for four minutes to ensure steady state data collection began during the final two minutes of the four-minute stage. Forces from the footstrikes, and O_2 consumption and respiratory exchange ratio (RER) were measured to gain external mechanical work and aerobic energy expenditure, respectively. Immediately after the 4-minute stage, blood lactate was taken by means of finger prick using a Lactate Plus portable lactate analyzer (Nova Biomedical; Waltham, MA) to gain anaerobic energy expenditure.

Energy Expenditure for Mechanical Efficiency of Running

During the two ME_R and RE data collection periods, baseline/resting metabolic data were obtained before any activities were performed. During the resting data collection period, the cart was placed next to the treadmill and total O_2 consumed in liters was recorded for two minutes to measure aerobic energy expenditure in kJ•L of O_2^{-1} (Kyrolainen & Komi, 1995; McBride & Snyder, 2012; McCaulley et al., 2007). Energy expenditure was also calculated from changes in RER through a linear equation (kJ•L of O_2^{-1} = 5.254* RER+ 15.986) created by Zuntz and Schumburg (Zuntz & Schumburg, 1901). Total O_2 consumed for the data collection time period [Δtime (min)*VO_2 (L•min^{-1})] was then multiplied by the kJ•L of O_2^{-1} calculated from RER to provide energy produced. The sum of kJ of energy produced from the RER and total O_2 consumed was considered baseline aerobic energy expenditure. The baseline aerobic energy expenditure was subtracted from the kJ of energy produced from the RER and total O_2 consumed during the exercise data collection period to gain changes in aerobic energy expenditure (E_{Aer}). Anaerobic energy expenditure was measured through changes in blood lactate. A resting lactate value was obtained during baseline metabolic data collection and subtracted from the lactate taken immediately after the exercise protocol. The change in lactate was then converted to O_2 equivalents as 3 mL of $O_2 \bullet kg^{-1} \bullet mM^{-1}$ and multiplied by 21.1 kJ•L of O_2^{-1} (Di Prampero et al., 1993; DiPrampero, 1972; Margaria, Cerretelli, Diprampero, Massari, & Torelli, 1963).

Mechanical Work for Mechanical Efficiency of Running

To calculate external mechanical work (W_e), vertical and horizontal center of mass (COM_b) velocities (v) and displacements (h) were calculated from integration of acceleration values obtained via the force plates mounted within the Bertec treadmill (Cavagna & Kaneko, 1977). The energy-time curve of the COM_b was provided by the summation of the potential (E_p = mgh) and kinetic energies ($E_k = ½mv^2$), where m is the mass of the subject and g is acceleration due to gravitational force ($9.81\ m \bullet s^{-2}$). Thus, W_e is represented by the incremental summation of this curve ($W_e = mgh + ½mv^2$) (Willems, Cavagna, & Heglund, 1995). W_e was calculated as the positive work completed from each foot strike during the final two minutes of the four-minute stage to obtain steady state values (Ito et al., 1983; Kyrolainen & Komi, 1995; McBride & Snyder, 2012; McCaulley et al., 2007). During the two-minute time period, every 15th footstrike was analyzed resulting in an average of 22 analyzed footstrikes at the subject's race pace velocity. Then, the total number of footstrikes analyzed was multiplied by the average positive work to obtain work values. Mechanical efficiency (ME) was then calculated as the ratio between W_e and E_n ($ME = W_e / E_n$), in accordance with previously published methods (Kyrolainen & Komi, 1995; McBride et al., 2015; McBride & Snyder, 2012; McCaulley et al., 2007).

Isometric Squat Maximal Voluntary Contraction

MVC force was measured during baseline testing on day one and immediately following NCS and CS40K trials. Subjects stood feet flat on a force plate (Advanced Mechanical Technology Inc, Watertown, MA), with knee angle at 90 degrees and an immovable bar resting on their shoulders. Subjects were instructed to perform a 5-second duration maximal effort isometric squat. For analysis, the body mass of each subject was subtracted from the force-time curve with peak force in Newtons (N) analyzed.

Countermovement Jump

A Vertec Jump Training System (Vertec; Columbus, OH) was used to measure countermovement jump (CMJ) height. Subjects were asked to stand directly under the system with dominant arm outstretched above their head as high as possible. Standing height was set based on each individual's standing reach. Subjects were then asked to preform one stationary maximal CMJ. Standing reach height was subtracted from CMJ height to obtain total jump height. CMJ was taken at the same time points as the MVC.

Muscle Glycogen Ultrasound Measure

Muscle glycogen levels were obtained using the MuscleSound® ultrasound system, according to previous validation studies (Hill & Millan, 2014; Nieman et al., 2015). Subjects were asked to lay supine while glycogen levels were measured in rectus femoris muscle of the left leg in each subject before and after activity on visits two and three. A mark was made at half the distance from the patella to the inguinal crease to enable pre to post measurements at the same location. Four images were obtained and ultrasound gel was used to improve image quality.

Statistical Analyses

A Repeated Measures AVOVA was used to compare changes in ME, RE, lactate, RER, work, glycogen, MVC, and CMJ values after CS40K and NCS. Significance was set at $p \leq 0.05$. All statistical analyses were completed with the SPSS program (IBM: Version 21.0. Armonk, NY).

Results

ME_R after 40-km of cycling (CS40K) was significantly lower than ME_R after completing a 5-km treadmill run (NCS) (CS40K: 48.4±5.7%, NCS: 53.7±3.5%; p=0.004; Figure 1). However, RE as a percentage of VO_2max (CS40K: 74.8±9.3%, NCS: 74.1±7.8%; p=0.771; Figure 2) or as absolute VO_2 (CS40K: 3.2 ± 0.6 $L \bullet min^{-1}$, NCS, 3.2 ± 0.6 $L \bullet min^{-1}$; p=0.804; Figure 3), was not significantly different between CS40K and NCS. Blood lactate tended to be higher after CS40K, compared to NCS (CS40K: 5.5±1.2 $mmol \bullet L^{-1}$, NCS: 4.2±1.3 $mmol \bullet L^{-1}$; p=0.055). Respiratory exchange ratio (CS40K: 0.93±0.11, NCS: 0.88±0.05; p=0.260) and work (CS40K: 61,380±6,176 joules, NCS: 64,094±5,554 joules; p=0.137) were not significantly different between CS40K and NCS (Table 1).

There were no significant differences in the percent decrease in glycogen (CS40K: 14.3±10.1%, NCS: 15.0±8.0%; p=0.879), percent decrease in CMJ (CS40K: 10.9 ± 9.2%, NCS: 10.1±12.9%; p=0.885), or percent decrease in MVC (CS40K: 15.3±9.8%, NCS: 15.9±16.9%; p=0.923), suggesting that both protocols resulted in the same amount of fatigue (Table 2). Average heart rate (HR) was 180 (8) bpm, while time to completion was 22.1 (3.29) min for the 5k run. Average heart rate (HR) was 153 (13) bpm, while time to completion was 75.6 (7.46) min for the 5k run (Table 3).

Total external mechanical work values were estimated for cycling 40 kilometers and for running 5 kilometers. Work values were calculated from computrainer metrics by multiplying [(Power (Watts) * Revolutions per minute (RPM)) * Time (Minutes)]. Work values for running were measured by utilizing work values collected during the mechanical efficiency test. NCS 490,067 ± 40136 Joules 1,164,311 ± 158098 Joules (p=.000009).

Discussion

The main finding of this study was that mechanical efficiency of running, but not running economy, significantly decreased after a 40 km bout of cycling, in trained triathletes. While blood lactate concentrations tended to be higher after cycling, we observed no other significant differences in respiratory exchange ratio, external work, glycogen levels, or the performance measures (maximal isometric squat or countermovement jump) compared to control. These findings are novel in that, for the first time, we report a possible mechanism for the observed declines in running performance after cycling in triathletes. We have related the observed declines in performance to a lower value of ME_R after cycling.

Our results indicate that running economy is not different after cycling in triathletes. This is consistent with previous literature reporting that RE does not increase after cycling, compared to after running in trained triathletes (Bonacci, Saunders, et al., 2011). However, it has been suggested that mechanical efficiency may provide a better assessment of running performance than running economy because of the multitude of performance variables factored into calculating mechanical efficiency (Ito et al., 1983), compared to solely oxygen consumption as with running economy. Variables considered for calculating mechanical efficiency include: oxygen consumption and energy expenditure, respiratory exchange ratio, blood lactate concentration, and work (McBride et al., 2015). The significant decrease in running mechanical efficiency after an acute bout of cycling might be attributed to minor alterations in several of these factors. We observed slight, but non-significant increases in energy expenditure and decreases in work after cycling. Although these minor changes in energy expenditure and work were not statistically significant, they may be considered physiologically significant when calculating mechanical efficiency and warrant further investigation.

When considering each of the variables included in calculating ME_R, small changes in any of these variables could result in significant changes in performance. We observed blood lactate levels were on average was 1.3 mmol•L^{-1} higher after cycling, compared to control. Previous research suggests that increases in blood lactate can negatively influence performance (Farrell et al., 1993; Santos-Concejero, Granados, Bidaurrazaga-Letona, et al., 2013). Research conducted by Nelson and Fitts suggests that increases in blood lactate and/or decreases in pH can impair the muscle's ability to function. In particular, they found that decreases in pH caused a decrease in Ca^{2+} sensitivity thereby decreasing the muscles ability to produce force (Nelson & Fitts, 2014). Further, since muscular work is directly related to force production, this helps to explain why work decreased after cycling, compared to control. Further, the slight increase in RER after cycling is indicative of an increased reliance on carbohydrates for fuel, which might signify an increase in running intensity after cycling, compared to control (Williamson et al., 2012). Unfortunately, our study only offers a glimpse of RER values, however if these values were to stay elevated or continued to rise during competition, it could further impact performance over a triathlon run by exhausting carbohydrate stores (McGawley, Shannon, & Betts, 2012).

Fatigue might also play an important role in decreased running performance after cycling in triathletes. Our results suggest that, although indicators of fatigue (glycogen levels, maximal isometric squat, and countermovement jump) were all significantly different from pre-exercise levels in both trials, they were not statistically different between trials. These results suggest that fatigue did not play a role in the decreased mechanical efficiency after cycling. Previous research completed on trained triathletes and cyclists suggests that pedaling rate, power, and total work of cycling can influence energy expenditure (Bernard et al., 2003; Cámara, Maldonado-Martín, Artetxe-Gezuraga, & Vanicek, 2012; Sargeant, 1994). For trained cyclists, having the ability to sustain a high power output while minimizing energy expenditure for the duration of a race is ideal (Jeukendrup, Craig, & Hawley, 2000). In running, much like cycling, mechanical efficiency might play the largest role in performance when the athlete is able to produce optimal power while conserving energy (Reger, Peterman, Kram, & Byrnes, 2013). For triathletes who must run after cycling, conserving energy becomes even more vital for success (Diefenthaeler, Coyle, Bini, Carpes, & Vaz, 2012; Kohrt et al., 1987); however, the opposite generally occurs. Higher power outputs are generally associated with disproportional increases in energy expenditure, which may increase lactate, RER, and overall energy expenditure (Chapman et al., 2007; Diefenthaeler et al., 2012). Furthermore, higher cycling cadence is associated with a glycogen sparing effect when compared to a lower cycling cadence (Beneke & Alkhatib, 2015). Previous research suggests that lower cycling cadences causes greater overall muscle activation and results in athletes working at a higher percent of maximum, therefore increasing overall energy expenditure (Bonacci et al., 2009). For triathletes, who typically have lower absolute power outputs than trained cyclists, high force and work outputs may decrease successive run performance (Diefenthaeler et al., 2012). Mechanical work values for the NCS were estimated for our present study. For our present study, total work during each trial was not measured, but it was estimated for both the NCS and CS40K. Total work for the NCS was less than the total work for CS40K. It is possible that if total work were equal between the two trials, then mechanical efficiency may not have changed.

In conclusion, we report that modest changes in multiple variables associated with ME_R were enough to cause a significant decline in ME_R after cycling. This supports the hypothesis that multiple physiological and biomechanical variables can influence athletic performance. Further, a lower value of ME_R after cycling may hinder run performance and thereby increase time to completion. However, the exact mechanisms for the observed lower value of ME_R after cycling are unclear. Future investigations should examine additional physiological and biomechanical variables that might impact ME_R, such as variations in running biomechanics after cycling, work of cycling, and cycling efficiency in triathletes.

References

Amann, M. (2011). Central and peripheral fatigue: Interaction during cycling exercise in humans. *Medicine and Science in Sport and Exercise, 43*(11), 2039-2045.

Astorino, T. A. (2008). Changes in running economy, performance, VO2max, and injury status in distance runners running during competitive. *Journal of Exercise Physiology Online*, *11*(6), 56-66.

Barnes, K. R., & Kilding, A. E. (2015). Running economy: measurment, norms, and determining factors. *Sports Medicine*, *1*(8), 1-15.

Beneke, R., & Alkhatib, A. (2015). High cycling cadence reduces carbohydrate oxidation at given low intensity metabolic rate. *Biology of Sport*, *32*(1), 27-33.

Bernard, T., Vercruyssen, F., Grego, F., Hausswirth, C., Lepers, R., Vallier, J., & Brisswalter, J. (2003). Effect of cycling cadence on subsequent 3 km running performance in well trained triathletes... including commentary by Vleck V. *British Journal of Sports Medicine, 37*(2), 154-159.

Bini, R., Diefenthaeler, F., & Carpes, F. P. (2011). Lower limb muscle activation during a 40km cycling time trial: Co-activation and pedalling technique. *International SportMed Journal*, *12*(1), 7-16.

Bonacci, J., Blanch, P., Chapman, A. R., & Vicenzino, B. (2010). Altered movement patterns but not muscle recruitment in moderately trained triathletes during running after cycling. *Journal of Sports Sciences, 28*(13), 1477-1487.

Bonacci, J., Chapman, A., Blanch, P., & Vicenzino, B. (2009). Neuromuscular adaptations to training, injury and passive interventions implications for running economy. *Sports Medicine, 39*(11), 903-921.

Bonacci, J., Green, D., Saunders, P. U., Franettovich, M., Blanch, P., & Vicenzino, B. (2011). Plyometric training as an intervention to correct altered neuromotor control during running after cycling in triathletes: A preliminary randomised controlled trial. *Physical Therapy in Sport, 12*(1), 15-21.

Bonacci, J., Green, D., Saunders, P.U., Blanch, P., Franettovich, M., Chapman, A. R., & Vicenzino, B. (2010). Change in running kinematics after cycling are related to alterations in running economy in triathletes. *Journal of Science & Medicine in Sport, 13*(4), 460-464.

Bonacci, J., Saunders, P. U., Alexander, M., Blanch, P., & Vicenzino, B. (2011). Neuromuscular control and running economy is preserved in elite international triathletes after cycling. *Sports Biomechanics, 10*(1), 59-71. doi: 10.1080/14763141.2010.547593

Bonacci, J., Vleck, V., Saunders, P. U., Blanch, P., & Vicenzino, B. (2013). Rating of perceived exertion during cycling is associated with subsequent running economy in triathletes. *Journal of Science & Medicine in Sport*, *16*(1), 49-53.

Bragada, J. A., Santos, P. J., Maia, J. A., Colaço, P. J., Lopes, V. P., & Barbosa, T. M. (2010). Longitudinal study in 3,000 m male runners: relationship between performance and selected physiological parameters. *Journal of Sports Science & Medicine, 9*(3), 439-444.

Buchheit, M., & Laursen, P. (2013). High-intensity interval training, solutions to the programming puzzle. *Sports Medicine, 43*(10), 927-954. doi: 10.1007/s40279-013-0066-5

Burgess, T. L., & Lambert, M. I. (2010). The effects of training, muscle damage and fatigue on running economy. *International SportMed Journal, 11*(4), 363-379.

Butts, N. K., Henry, B. A., & McLean, D. (1991). Correlations between VO2max and performance times of recreational triathletes. / Correlations entre le VO2 max et la performance des triathletes de loisirs. *Journal of Sports Medicine & Physical Fitness, 31*(3), 339-344.

Cairns, S. P. (2006). Lactic acid and exercise performance: culprit or friend? *Sports Medicine, 36*(4), 279-291.

Cámara, J., Maldonado-Martín, S., Artetxe-Gezuraga, X., & Vanicek, N. (2012). Influence of pedaling technique on metabolic efficiency in elite cyclists. *Biology of Sport, 29*(3), 229-233.

Carte, H., Jones, A. M., & Doust, J. H. (1999). Effect of 6 weeks of endurance training on the lactate minimum speed. *Journal of Sports Sciences, 17*(12), 957-967. doi: 10.1080/026404199365353

Cavagna, G. A., & Kaneko, M. (1977). Mechanical work and efficiency in level walking and running. *Journal of Physiology, 268*(2), 467-481.

Chapman, A. R., Hodges, P. W., Briggs, A. M., Stapley, P. J., & Vicenzino, B. (2010). Neuromuscular control and exercise-related leg pain in triathletes. *Medicine & Science in Sports & Exercise, 42*(2), 233-243.

Chapman, A. R., Vicenzino, B., Blanch, P., Dowlan, S., & Hodges, P. W. (2008). Does cycling effect motor coordination of the leg during running in elite triathletes? *Journal of Science & Medicine in Sport, 11*(4), 371-380.

Chapman, A. R., Vicenzino, B., Blanch, P., & Hodges, P. W. (2007). Leg muscle recruitment during cycling is less developed in triathletes than cyclists despite matched cycling training loads. *Experimental Brain Research, 181*(3), 503-518. doi: 10.1007/s00221-007-0949-5

Chapman, A. R., Vicenzino, B., Blanch, P., & Hodges, P. W. (2008). Patterns of leg muscle recruitment vary between novice and highly trained cyclists. *Journal of Electromyography & Kinesiology, 18*(3), 359-371. doi: 10.1016/j.jelekin.2005.12.007

Conceição, A., Silva, A. J., Barbosa, T. M., Karsai, I., & Louro, H. (2014). Neuromuscular fatigue during 200 M breaststroke. *Journal of Sports Science & Medicine, 13*(1), 200-210.

Conley, D. L., & Krahenbuhl, G. S. (1980). Running economy and distance running performance of highly trained athletes. / Economie de course et performance en course de fond d ' athletes tres bien entraines. *Medicine & Science in Sports & Exercise, 12*(5), 357-360.

Di Prampero, P. E., Capelli, C., Pagliaro, P., Antonutto, G., Girardis, M., Zamparo, P., & Soule, R. G. (1993). Energetics of best performances in middle-distance running. *Journal of Applied Physiology, 74*(5), 2318-2324.

Diefenthaeler, F., Coyle, E. F., Bini, R. R., Carpes, F. P., & Vaz, M. A. (2012). Muscle activity and pedal force profile of triathletes during cycling to exhaustion. *Sports Biomechanics, 11*(1), 10-19. doi: 10.1080/14763141.2011.637125

Dingwell, J. B., Joubert, J. E., Diefenthaeler, F., & Trinity, J. D. (2008). Changes in muscle activity and kinematics of highly trained cyclists during fatigue. *IEEE Transactions on Biomedical Engineering*, *54*(11), 2666-2674.

DiPrampero, P. E. (1972). Energetics of muscular exercise. *Journal de Physiologie*, *65*(1, Suppl), 51A-51A.

Ettema, G. J. C. (2001). Muscle efficiency: The controversial role of elasticity and mechanical energy conversion in stretch-shortening cycles. *European Journal of Applied Physiology*, *85*(5), 457-465.

Fabiato, A., & Fabiato, F. (1978). Effects of pH on the myofilaments and the sarcoplasmic reticulum of skinned cells from cardiace and skeletal muscles. *The Journal Of Physiology*, *276*, 233-255.

Farrell, P. A., Wilmore, J. H., Coyle, E. F., Billing, J. E., & Costill, D. L. (1993). Plasma lactate accumulation and distance running performance. / Accumulation de lactate plasmatique et performance en course de fond. *Medicine & Science in Sports & Exercise*, *25*(10), 1091-1097.

Foster, C., Costill, D. L., Daniels, J. T., & Fink, W. J. (1978). Skeletal muscle enzyme activity, fiber composition and VO2 max in relation to distance running performance. / Activite enzymatique du muscle squelettique, composition des fibres et consommation maximale d ' oxygene en relation avec la performance en course de distance. *European Journal of Applied Physiology & Occupational Physiology, 39*(2), 73-80.

Franch, J., Madsen, K., Djurhuus, M. S., & Pedersen, P. K. (1998). Improved running economy following intensified training correlates with reduced ventilatory demands. *Medicine & Science in Sports & Exercise, 30*(8), 1250-1256.

Gregoire, P., Millet, & Vleck, V. E. (2000). Physiological and Biomechanical Adaptations to the Cycle to Run Transition in Olympic triathlon: review and practical recommendations for training. *British Journal of Sports Medicine, 34*(5), 384-390.

Guezennec, C. Y., Vallier, J. M., Bigard, A. X., & Durey, A. (1996). Increase in energy cost of running at the end of a triathlon. / Augmentation du cout energetique de la course a la fin d ' un triathlon. *European Journal of Applied Physiology & Occupational Physiology, 73*(5), 440-445.

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.

Harris, C., Debeliso, M., & Adams, K. J. (2003). The effects of running speed on the metabolic and mechanicial energy costs of running. *Journal of Exercise Physiology Online, 6*(3), 28-37.

Helgerud, J., Støren, Ø., & Hoff, J. (2010). Are there differences in running economy at different velocities for well-trained distance runners? *European Journal of Applied Physiology, 108*(6), 1099-1105.

Hill, J. C., & Millan, I. S. (2014). Validation of musculoskeletal ultrasound to assess and quantify muscle glycogen content. A novel approach. *The Physician And Sports Medicine, 42*(3), 45-52.

Horita, T., & Ishiko, T. (1987). Relationships between muscle lactate accumulation and surface EMG activities during isokinetic contractions in man. *European Journal of Applied Physiology & Occupational Physiology, 56*(1), 18-23.

Ito, A., Komi, P. V., Sjoedin, B., Bosco, C., & Karlsson, J. (1983). Mechanical efficiency of positive work in running at different speeds. / L' efficience mecanique du travail positif pour differentes vitesses de course. *Medicine & Science in Sports & Exercise, 15*(4), 299-308.

Jakeman, J., Adamson, S, & Babraj, J. (2012). Extremely short duration high-intensity training substantially improves endurance performance in triathletes. *Applied Physiology, Nutrition & Metabolism, 37*(5), 976-981.

Jeukendrup, A. E., Craig, N. P., & Hawley, J. A. (2000). The bioenergetics of world class cycling. *Journal of science and medicine in sport / Sports Medicine Australia, 3*(4), 414-433. doi: 10.1016/s1440-2440(00)80008-0

Jones, A. M., & Carter, H. (2000). The effect of endurance training on parameters of aerobic fitness. *Sports Medicine, 29*(6), 373-386.

Jones, D. A., de Ruiter, C. J., & de Haan, A. (2006). Change in contractile properties of human muscle in relationship to the loss of power and slowing of relaxation seen with fatigue. *Journal of Physiology, 576*(3), 913-922. doi: 10.1113/jphysiol.2006.116343

Karniel, A., & Mussa-Ivaldi, F.A. (2002). Does the motor control system use multiple models and context switching to cope with a variable environment? *Experimental Brain Research, 143,* 520-524.

Keir, D. A., Zory, R., Boudreau-Larivière, C., & Serresse, O. (2012). Mechanical efficiency of treadmill running exercise: Effect of anaerobic-energy contribution at various speeds. *International Journal of Sports Physiology & Performance, 7*(4), 382-389.

Kenny, L., Wilmore, J., & Costill, D. (2012). *Physiology of Sport and Exercise* (Fifth ed.). Champaign, IL: Human Kinetics.

Kohn, T. A., Essén-Gustavsson, B., & Myburgh, K. H. (2011). Specific muscle adaptations in type II fibers after high-intensity interval training of well-trained runners. *Scandinavian Journal of Medicine & Science in Sports, 21*(6), 765-772. doi: 10.1111/j.1600-0838.2010.01136.x

Kohrt, W. M., Morgan, D. W., Bates, B., & Skinner, J. S. (1987). Physiological responses of triathletes to maximal swimming, cycling, and running. / Reponses physiologiques de triathletes a l' exercice maximal de nage, de cyclisme, et de course. *Medicine & Science in Sports & Exercise, 19*(1), 51-55.

Kumari, M. V. L. S., & Ramana, Y. V. (2010). Effect of variations in training load on mechanical efficiency in athletes. *British Journal of Sports Medicine, 44*(S1), i19-i19.

Kyrolainen, H., & Komi, P. V. (1995). Differences in mechanical efficiency between power- and endurance-trained athletes while jumping. *European Journal of Applied Physiology & Occupational Physiology, 70*(1), 36-44.

Legaz, A., Serrano, E., Casajus Mallen, J. A., & Munguia, I. D. (2005). The changes in running performance and maximal oxygen uptake after long-term training in elite athletes. *Journal of Sports Medicine & Physical Fitness, 45*(4), 435-440.

Lepers, R., Hausswirth, C., Maffiuletti, N., Brisswalter, J., & Van Hoecke, J. (2000). Evidence of neuromuscular fatigue after prolonged cycling exercise. / Preuves de la fatigue neuromusculaire apres un exercice de pedalage prolonge. *Medicine & Science in Sports & Exercise, 32*(11), 1880-1886.

Margaria, R., Cerretelli, P., Diprampero, P. E., Massari, C., & Torelli, G. (1963). Kinetics and mechanism of oxygen debt contraction in man. *Journal of Applied Physiology, 18,* 371-377.

McBride, J. M., Davis, J. A., Alley, J. R., Knorr, D. P., Goodman, C. L., Snyder, J. G., & Battista, R. A. (2015). Index of mechanical efficiency in competitive and recreational long distance runners. *Journal of Sports Sciences, 33*(13), 1388-1395.

McBride, J. M., & Snyder, J. G. (2012). Mechanical efficiency and force-time curve variation during repetitive jumping in trained and untrained jumpers. *European Journal of Applied Physiology, 112*(10), 3469-3477 3469p.

McCaulley, G. O., Cormie, P., Cavill, M. J., Nuzzo, J. L., Urbiztondo, Z. G., & McBride, J. M. (2007). Mechanical efficiency during repetitive vertical jumping. *European Journal of Applied Physiology*(1), 115-124.

McGawley, K., Shannon, O., & Betts, J. (2012). Ingesting a high-dose carbohydrate solution during the cycle section of a simulated Olympic-distance triathlon improves subsequent run performance. *Applied Physiology, Nutrition & Metabolism, 37*(4), 664-671.

Moro, V. L., Ghedini Gheller, R., de Oliveira Berneira, J., Hoefelmann, C. P., Colussi Karasiak, F., Pereira Moro, A. R., & Diefenthaeler, F. (2013). Comparison of body composition and aerobic and anaerobic performance between competitive cyclists and triathletes. / Comparação da composição corporal, desempenho aeróbio e anaeróbio entre ciclistas e triatletas competitivos. *Brazilian Journal of Kineanthropometry & Human Performance, 15*(6), 647-655.

Nelson, C. R., & Fitts, R. H. (2014). Effects of low cell pH and elevated inorganic phosphate on the pCa-force relationship in single muscle fibers at near-physiological temperatures. *American Journal of Physiology-Cell Physiology, 306*(7), 670-678. doi: 10.1152/ajpcell.00347.2013

Nieman, D. C., Shanely, R. A., Zwetsloot, K. A., Meaney, M. P., & Farris, G. E. (2015). Ultrasonic assessment of exercise-induced change in skeletal muscle glycogen content. *BMC Sports Science, Medicine and Rehabilitation, 7*(1), 1-7. doi: 10.1186/s13102-015-0003-z

Noakes, T. D. (2000). Physiological models to understand exercise fatigue and the adaptations that predict or enhance athletic performance. *Scandinavian Journal of Medicine & Science in Sports, 10*(3), 123-146.

Nummela, A. T., Paavolainen, L. M., Sharwood, K. A., Lambert, M. I., Noakes, T. D., & Rusko, H. K. (2006). Neuromuscular factors determining 5 km running performance and running economy in well-trained athletes. *European Journal of Applied Physiology, 97*(1), 1-8.

Ortenblad, N., Westerblad, H., & Nielsen, J. (2013). Muscle glycogen stores and fatigue. *Journal of Physiology*, 4405-4413.

Ortiz, M. J., Greco, C. C., de Mello, M. T., & Denadai, B. S. (2006). Interval training at 95% and 100% of the velocity at VO2 max: Effects on aerobic physiological indexes and running performance. *Applied Physiology, Nutrition & Metabolism, 31*(6), 737-743. doi: 10.1139/H06-080

Paavolainen, L., Hakkinen, K., Hamalainen, I., Nummela, A., & Rusko, H. (1999). Explosive-strength training improves 5-km running time by improving running economy and muscle power. *Journal of Applied Physiology, 86*(5), 1527-1533.

Petersen, K., Hansen, C., Aagaard, P., & Madsen, K. (2007). Muscle mechanical characteristics in fatigue and recovery from a marathon race in highly trained runners. *European Journal of Applied Physiology, 101*(3), 385-396.

Pratt, S. J. P., Shah, S. B., Ward, C. W., Inacio, M. P., Stains, J. P., & Lovering, R. M. (2013). Effects of in vivo injury on the neuromuscular junction in healthy and dystrophic muscles. *Journal of Physiology, 591*(2), 559-570. doi: 10.1113/jphysiol.2012.241679

Puthucheary, Z., Skipworth, J. R. A., Rawal, J., Loosemore, M., Someren, K. V., & Montgomery, H. E. (2011). Genetic influences in sport and physical performance. *Sports Medicine, 41*(10), 845-859.

Rabita, G., Couturier, A., Dorel, S., Hausswirth, C., & Le Meur, Y. (2013). Changes in spring-mass behavior and muscle activity during an exhaustive run at V̇O2max. *Journal of Biomechanics, 46*, 2011-2017. doi: 10.1016/j.jbiomech.2013.06.011

Ražanskas, P., Verikas, A., Olsson, C., & Viberg, P. (2015). Predicting blood lactate concentration and oxygen uptake from sEMG data during fatiguing cycling exercise. *Sensors (14248220), 15*(8), 20480-20500. doi: 10.3390/s150820480

Reger, M., Peterman, J. E., Kram, R., & Byrnes, W. C. (2013). Exercise efficiency of low power output cycling. *Scandinavian Journal of Medicine & Science in Sports, 23*(6), 713-721.

Riddell, M. C., Partington, S. L., Stupka, N., Armstrong, D., Rennie, C., & Tarnopolsky, M. A. (2003). Substrate utilization during exercise performed with and without glucose ingestion in female and male endurance-trained athletes. *International Journal of Sport Nutrition & Exercise Metabolism, 13*(4), 407-421.

Santos-Concejero, J., Granados, C., Bidaurrazaga-Letona, I., Zabala-Lili, J., Irazusta, J., & Gil, S. M. (2013). Onset of blood lactate accumulation as a predictor of performance in top athletes. / Comienzo de la acumulación de lactato sanguíneo como predictor del rendimiento en atletas de élite. *Retos: Nuevas Perspectivas de Educación Física, Deporte y Recreación*(23), 67-69.

Santos-Concejero, J., Granados, C., Irazusta, J., Bidaurrazaga-Letona, I., Zabala-Lili, J., Tam, N., & Gil, S. M. (2013). Differences in ground contact time explain the less efficiency running economy in north african runners. *Biology of Sport, 30*(3), 181-187.

Santos-Concejero, J., Granados, C., Irazusta, J., Bidaurrazaga-Letona, I., Zabala-Lili, J., Tam, N., & Gil, S. M. (2014). Influence of the biomechanical variables of the gait cycle in running economy. / Influencia de variables biomecánicas del ciclo de paso en la economía de carrera. *RICYDE. Revista Internacional de Ciencias del Deporte, 10*(36), 95-108.

Sargeant, A. J. (1994). Human power output and muscle fatigue. *International Journal of Sports Medicine*, *15*(3), 116-121. doi: 10.1055/s-2007-1021031

Saunders, P. U. (2005). *Factors affecting running economy and performance in highly trained middle and long distance runners*. Retrieved from s3h database. RMIT University Melborn, Victoria.

Shadmehr, R., & Brashers-Kreg, T. (1997). Functional stages in the formation of human long-term motor memory. *The Journal of Neuroscience, 17*(1), 409-419.

Shaw, A. J., Ingham, St. A., Fudge, B. W., & Folland, J. P. (2013). The reliability of running economy expressed as oxygen cost and energy cost in trained distance runners. *Applied Physiology, Nutrition & Metabolism, 38*(12), 1268-1272.

Shei, R., & Mickleborough, T. (2013). Relative contributions of central and peripheral factors in human muscle fatigue during exercise: A brief review. *Journal of Exercise Physiology Online, 16*(6), 1-17.

Tanaka, B., & Matsuura, Y. (1984). Marathon performance, anaerobic threshold, and onset of blood lactate accumulation. *Journal of Applied Physiology, 57*(3), 640-643.

Tartaruga, M. P., Brisswalter, J., Mota, C. B., Alberton, C. L., Gomeñuka, N. A., & Peyré-Tartaruga, L. A. (2013). Mechanical work and long-distance performance prediction: The influence of allometric scaling. *Journal of Human Kinetics, 38*, 73-82.

van Rensburg, J. P., Kielblock, A. J., & van der Linde, A. (1986). Physiologic and biochemical changes during a triathlon competition. / Modifications physiologiques et biochimiques subies lors d' une competition de triathlon. *International Journal of Sports Medicine, 7*(1), 30-35.

Vleck, V., & Alves, F. (2011). Triathlon transition tests: Overview and recommendations for future research. *RICYDE. Revista Internacional de Ciencias del Deporte, 7*(24), 1-2.

Willems, P. A., Cavagna, G. A., & Heglund, N. C. (1995). External, internal and total work in human locomotion. *Journal of Experimental Biology, 198*, 379-393.

Williamson, Wilby, Fuld, Jonathan, Westgate, Kate, Sylvester, Karl, Ekelund, Ulf, & Brage, Soren. (2012). Validity of reporting oxygen uptake efficiency slope from submaximal exercise using respiratory exchange ratio as secondary criterion. *Pulmonary Medicine*, 1-8. doi: 10.1155/2012/874020

Zuntz, N. , & Schumburg, H. (1901). *Studien zu einer Physiologie des Marsches*. Berlin, Hirschwald.

Appendix A

Table 1: Mechanical efficiency (ME), running economy (RE; absolute and as % VO_2max), and other variables associated with ME after a 5k Run (NCS) and after 40k Cycling (CS40K) * - Mechanical efficiency was significantly lower after CS40K.

	Post Run	Post Cycle	P-Value
ME_R (%)	53.7 ± 3.5	46.8 ± 5.7*	0.004
RE (L/Min)	3.2 ± 0.6	3.2 ± 0.6	0.804
RE (% Max)	74.1 ± 7.8	74.8 ± 9.3	0.771
Work (Joules)	64,093 ± 5,554	61,380 ± 6,176	0.137
Lactate (mmol$\cdot$L^{-1})	4.2 ± 1.3	5.5 ± 1.2	0.055
RER	0.89 ± 0.05	0.93 ± 0.11	0.259
Energy Expenditure (Joules)	125,207 ± 23,699	137,972 ± 27,373	0.052

Table 2: Glycogen values, MVC, and CMJ after a 5k Run (NCS) and after 40k Cycling (CS40K).

	Percent Change From Baseline Run	Percent Change From Baseline Cycle	P-Value
Glycogen	-17.1 ± 8.0%	-16.3 ± 10.1%	0.86
MVC	-15.9 ± 16.9%	-15.3 ± 9.8%	0.92
CMJ	-10.1 ± 12.9%	-10.9 ± 9.2%	0.89

Table 3: Heart Rate and Time to Completion for 5k Run and 40k Cycle.

	Post Run	Post Cycle
Average Heart Rate (BPM)	180 ± 8	153 ± 13
Time to Completion (Minutes)	22.1 ± 3.3	75.6 ± 7.5

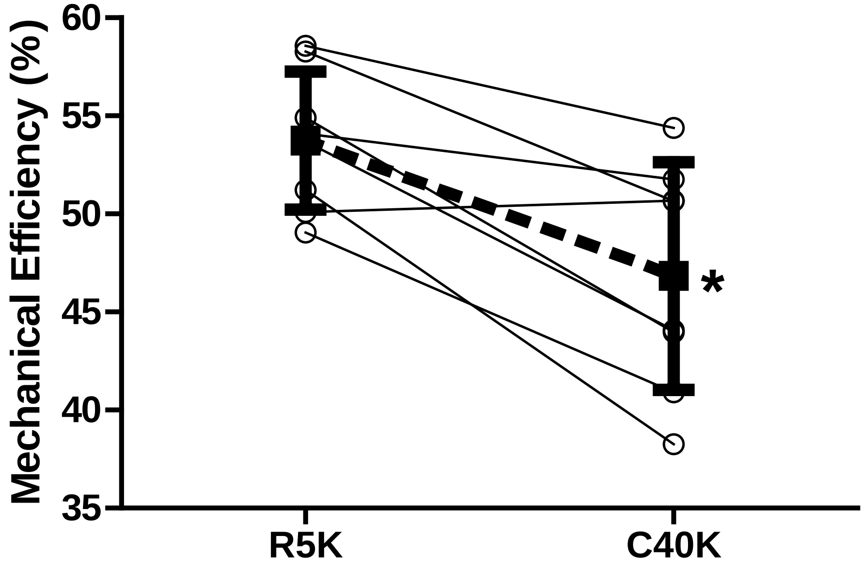

Figure 1: Mechanical efficiency after 5k Run (NCS) and 40k Cycling (CS40K). * - Mechanical efficiency was significantly lower after CS40K (P= 0.00375)

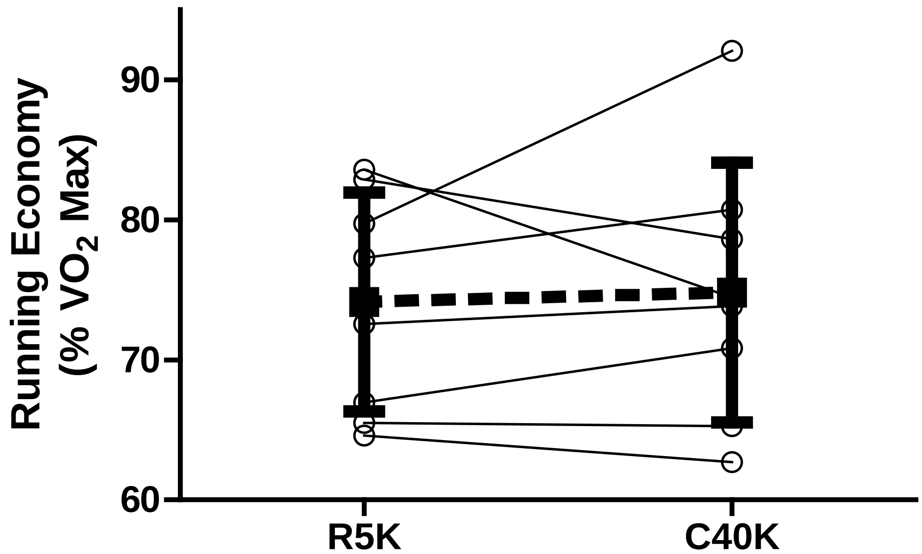

Figure 2: Running Economy as a Percent of VO_2max after a 5k Run (NCS) and after 40k Cycling (CS40K). There was no significant difference in RE between NCS and CS40K (P=0.771).

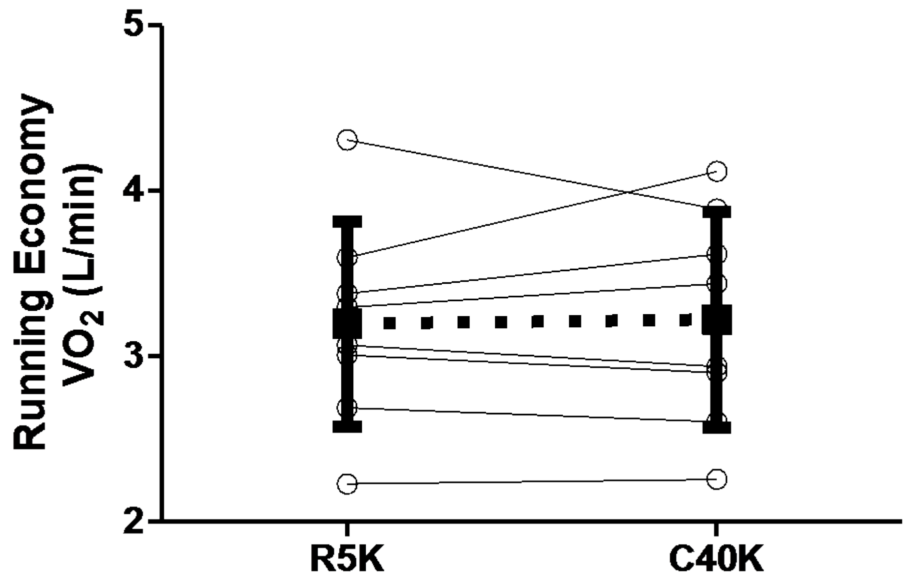

Figure 3: Running Economy as absolute oxygen consumption (L/min) after a 5k Run (NCS) and after 40k Cycling (CS40K). There was no significant difference in RE between NCS and CS40K (p=0.804).

Vita

Justin Albert Stewart was born in Lancaster, Virginia, to Cylde and Beth Stewart. He graduated from James Madison University in Virginia in May of 2013. In the fall of 2014 he started his Masters Degree at Appalachian State University where he began his research concentration. He plans on continuing his education and research by ultimately attaining his Ph.D in Exercise Physiology.