

UNIVERSITY OF WISCONSIN-LA CROSSE

Graduate Studies

A RELIABILITY ASSESSMENT OF A FOOTBALL-SPECIFIC REPEATED SPRINT  
TEST ON A NON-MOTORIZED TREADMILL

A Manuscript Style Thesis Submitted in Partial Fulfillment of the Requirements for the  
Degree of Master of Science – Human Performance

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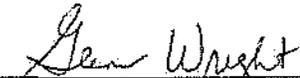
May, 2016

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We recommend acceptance of this thesis in partial fulfillment of the candidate's requirements for the degree of Master of Science -- Human Performance

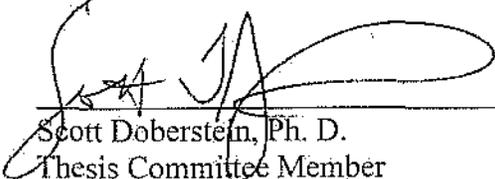
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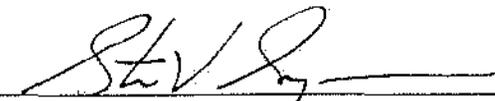
  
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## ABSTRACT

Lose, S.R. A reliability assessment of a football-specific repeated sprint test on a non-motorized treadmill. MS in Exercise & Sports Science – Human Performance, May 2016, 88pp. (G. Wright)

The purpose of this study was to determine the test-retest reliability of a football-specific repeated sprint test on a non-motorized treadmill as a way to assess anaerobic performance. Twenty-one NCAA DIII football players that played a non-line position completed the repeated sprint protocol (10 x 6-s maximal sprints, 25-seconds recovery) against a load equal to 15% of each subject's body weight on two separate occasions. Performance decrement, total mean power (MP) and mechanical load were analyzed for reliability for each test. No significant differences were found between the two trials for performance decrement and mechanical load ( $p > 0.05$ ). Reliability between the two trials was considered acceptable for performance decrement ( $r = 0.77$ ;  $CV = 14.26\%$ ), total MP ( $r = 0.90$ ;  $CV = 2.98\%$ ), and mechanical load ( $r = 0.85$ ;  $CV = 5.12\%$ ). Subjects achieved at least 90% of their age-predicted maximum heart rate at sprint 6 and maintained it for the remainder of the test. The results indicate that with adequate familiarization the football-specific repeated sprint test has acceptable reliability and can be used to assess anaerobic performance in American football players.

## ACKNOWLEDGEMENTS

I would like to express my sincerest thanks to everyone who has helped me along this journey. To Dr. Glenn Wright, who always asked for our best and inspired me to never give anything less. His passion for what he does and for the success of his students has not only pushed me throughout this journey but has also inspired me to do the same. He is a wonderful role model and has changed my perspective on school and life. Being the busiest person I know, he still always found time to meet with me and help me with everything. To the rest of my committee, Dr. Clayton Camic and Dr. Scott Doberstein, who have both helped me in their own unique ways not only in this thesis but also in my graduate school experience. To the participants and helpers, this whole study would not be possible without their willingness to take the time to be apart of the study. Lastly, to my family, I would not be where I am today without their love and support. Thank you for everything you have done for me.

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## INTRODUCTION

Performance testing of athletes is a chief feature in the evaluation and monitoring of athletes of all levels and disciplines. Anaerobic performance tests are used as predictors or measures of success in sports by estimating power and capacity of the anaerobic energy systems in a non-invasive manner. Common types of anaerobic testing include: stair tests (Margaria, Aghemo, & Rovelli, 1966; Hetzler et al., 2010), jump tests (Glencross, 1966; Seiler et al., 1990), cycling (Bishop, Spencer, Duffield, & Lawrence, 2001; Inbar, Bar-Or, & Sinner, 1996), and running (McLain et al., 2015; Pendleton, 1997; Zacharogiannis, Paradisis, & Tziortzis, 2004), with variations for both laboratory and field settings (Fitzsimmons, Dawson, Ward, & Wilkinson, 1993; Nummela, Hämmäläinen, & Rusko, 2007). To date, the Wingate Anaerobic Test (WAnT) has been the most popular and widely utilized anaerobic performance test. Its high reliability in assessing performance measures of peak power (PP) and mean power (MP) have helped enhance its popularity (Inbar et al., 1996; Patton, Murphy, & Frederick, 1985). Regardless of its popularity, the generalization of this test to all athletes can be questioned.

The specificity of a test in regards to the sport of the athlete being testing has been emphasized by many researchers (Bishop et al., 2001; Fitzsimmons et al., 1993). Thus, an obvious drawback to the WAnT and other cycle tests is in the modality itself. Most sports do not require cycling and accordingly, multiple studies have found that field athletes and runners perform better on running tests than cycling tests (Fitzsimmons et al., 1993;

Zemková and Hamar, 2004). Therefore, tests utilizing modalities seen in sports, such as running and jumping, offer a more functionally appropriate method of testing athletes. Bishop and colleagues (2001) emphasized the importance of selecting test protocols that are closely related to the actual distance or time period typically covered by athletes in match situations for the best results. A vast majority of sports require more than just a single effort. Field sports (i.e. American football, soccer, rugby, etc.) can typically be characterized by multiple, brief high-intensity work bouts combined with relatively short, low- to moderate-intensity recovery bouts (Glaister, 2005). Therefore, tests comprised of a single, maximal effort, such as the WAnT and jump tests, have questionable validity in estimating actual game performance for field sport athletes. It is the very nature of field sports that has led many coaches and researchers to use repeated sprint tests as a way of assessing and predicting an athlete's performance.

Although all field sports can be generalized this way, there are differences among them that make each unique for repeated sprint test purposes. For example, soccer has typical ratios of 4.4 seconds of work compared to 40 seconds between bouts during game play (Mayhew & Wenger, 1985), whereas Australian Rules football has a mean sprint time of 2.7 seconds and on average 73 seconds between bouts (McKenna, Patrick, & Chennells, 1988). Consequently, specific repeated sprint tests have been developed for sports, including soccer (Krustrup et al., 2003), rugby (Pendleton, 1997), and field hockey (Boddington, Lambert, Gibson, & Noakes, 2001). However, there appears to be no established repeated sprint test specific to American football, even though it is a widely popular sport and is, by definition, a sport that involves repeated sprints.

American football is characterized by brief, high-intensity work during the plays and short rest bouts between plays. On average, the duration of a single play in Division I (DI) college football is ~ 5.5 seconds (Iosia & Bishop, 2008; Rhea, Hunter, & Hunter, 2006), with the average recovery time between plays ranging from 18-30 seconds (Berkes, 2015). In addition, DI college football games average between six to seven plays per drive (Rhea et al., 2006). These characteristics lead to the combined contributions of the three energy systems. While it has been suggested that American football is predominantly fueled by the alactic system (Hoffman, 2008), evidence also shows a considerable contribution from the lactic system (Smith & Jackson, 1991; Zapiec & Taylor, 1979). As a result, American football players are commonly assessed for their strength and performance with the WAnT (Hoffman et al., 2005; Seiler et al., 1990), Margaria step test (Arnold, Brown, Micheli, & Coker, 1980; Seiler et al., 1990), vertical jump (Fry & Kraemer, 1991; Hoffman, Ratamess, & Kang, 2011; Seiler et al., 1990), broad jump (Seiler et al., 1990), and 40-yard dash (Arnold et al., 1980; Fry & Kraemer, 1991; Hoffman et al., 2011; Seiler et al., 1990). However, researchers have additionally stressed the importance of the aerobic energy system in American football for enhanced recovery between plays (Gleim, Witman, & Nicholas, 1981; Pincivero & Bompa, 1997). There is evidence showing that throughout repeated sprints there is an increased utilization of  $\dot{V}O_2$  with successive sprints (McGawley & Bishop, 2015). Thus, while the above tests are capable of distinguishing players' abilities and assessing single, maximal performance (Arnold et al., 1980; Seiler et al., 1990), they are unable to assess the athlete's ability to maintain repeated performance as is seen in competitive games.

A repeated sprint test that utilizes sprint running at work and rest intervals similar to that of an American football game would be more specific – metabolically and functionally – to football players. To our knowledge, there is no standardized repeated sprint test on a non-motorized treadmill used for assessing repeat sprint ability in American football players that has been assessed for its reliability. Therefore, the purpose of this study was to determine the test-retest reliability of a suggested football-specific repeated sprint test on a non-motorized treadmill as a way to assess the energy system development in American football players.

## **METHODS**

### **Experimental Approach to the Problem**

The study was conducted to examine the test-retest reliability of a proposed football specific repeated sprint protocol. All repeated sprint testing was performed on a non-motorized treadmill (NMT) capable of applying an electrical braking system to the treadmill belt (Woodway Force 2.0 treadmill, Woodway USA, Waukesha, WI). The repeated sprint protocol was developed to mimic the nature of a fast pace drive similar to a “2-minute period” during a football game. After a familiarization session, all subjects performed the repeated sprint protocol twice within seven days to assess test-retest reliability.

### **Subjects**

Twenty-one non-starters (age:  $19.3 \pm 1.1$  yrs; height:  $179.0 \pm 5.5$  cm; weight:  $85.5 \pm 6.9$  kg; body fat:  $11.2 \pm 2.7\%$ ) of a NCAA Division III football team were recruited to participate in the study. Linemen and players with lower limb injuries were excluded from the study. Before beginning the study, the university IRB committee approved all procedures. Subjects were individually informed of the procedures and risks involved and each individual provided written informed consent before participating in any aspect of the study. Subjects were asked to refrain from lower body strength training, sprint training, and the consumption of alcohol 24 hours prior to all testing and pre-workout supplements or caffeine consumption 12 hours prior to all testing. Subjects were prompted to stay well hydrated, refrain from skipping meals and to eat meals similar in

composition before each test. Prior to the first experimental trial (T1), subjects wrote down what they ate and drank that day. Subjects kept the food log and were instructed to mimic the food and drink consumption prior to the second experimental trial (T2). Food logs were not collected, but in order to confirm compliance, subjects verbally confirmed their hydration, meals, and activities within the 24 hours prior to T2 were similar to T1.

### **Procedures**

During the two weeks following the conclusion of the regular competitive football season, all subjects visited the Human Performance Laboratory at the University of Wisconsin – La Crosse three times for testing: one familiarization session and two experimental sessions. Each subject's sessions were completed at the same time of day and were separated by at least 48 hours and no more than 7 days.

The first session served as a familiarization session. Subjects' height, weight, and body composition were determined. Body composition was determined through 7-site skinfold measurements based on the procedures outlined by the American College of Sports Medicine (2010). Body density was estimated using the equation developed by Jackson & Pollock (1978). Body fat percentage was subsequently estimated from body density using the equation developed by Brozek et al. (1963). Subjects were then familiarized with sprinting on the NMT. During the familiarization, subjects practiced the sprint start from a split-stance position until the starts appeared consistent and the subject felt comfortable.

### **Sprint Protocol**

Subjects began each session with a standardized warm up consisting of 3 minutes of walking (4.02 kph) and 2 minutes of light jogging (8.05 kph) on a motorized treadmill,

followed by a dynamic warm up of five exercises. Subjects then performed 2-3 practice starts on the NMT. Following 5 minutes of passive rest in a chair, subjects were tethered to the back of the NMT with a fitted belt around their waist. The height of the belt was adjusted to a horizontal level based on the height of the subject. The repeated sprint test protocol for the experimental sessions was comprised of ten maximal 6-second sprints against a load equal to 15% of the subject's body weight, with 25 seconds of recovery. The familiarization session consisted of a similar protocol; however, only five sprints were performed. Subjects started from a stationary, split-stance position before each sprint and were instructed beforehand to try to reach maximum speed as soon as possible and continue to sprint as fast as possible for the entire duration of each sprint. Subjects were also instructed to make each sprint a maximal effort and to not pace. During the 25 seconds of recovery between sprints, subjects were instructed to keep their legs moving by slow marching in place to avoid blood pooling. Pre-recorded audio instructed the subjects when to sprint and when to stop in order to keep homogeneity between subjects and tests. The audio utilized verbal commands of "sprint" and "stop" to signal the beginning and end of each sprint. Before the start of each sprint, a 10-second warning was given and then a 3-second countdown to the start of the sprint. Strong verbal encouragement was given throughout each sprint. Following completion of the last sprint, subjects actively recovered by walking on a motorized treadmill at 4.02 kph.

During the two experimental sessions, fingertip capillary blood samples were taken 1 minute prior to the start of the test and 5 minutes after completion of the test. A Lactate Plus lactate analyzer (Lactate Plus, Waltham, Massachusetts) was used to analyze samples for blood lactate (BLa). Blood lactate data is reported as the difference between

pre and post samples. Subjects were also fitted with a monitor (Zephyr Technology, Annapolis, MD) on a chest strap to measure heart rate (HR) and mechanical load during all sessions. The overall peak HR achieved for the test ( $HR_{test}$ ), the highest HR achieved for each 31-second cycle (comprised of the 6-second sprint plus the following 25-second recovery period) ( $HR_{sprint}$ ), and the average HR achieved in the last 5-seconds of each 31-second cycle ( $HR_{5sAvg}$ ) were analyzed using the Zephyr Technology Software (PSM Training, Zephyr Technology, Annapolis, MD). Mechanical load is a metric that provides the volume and intensity of movements based on the accumulation of mechanical intensity over time. Mechanical intensity is an instantaneous measure of effort determined by the highest peak acceleration (g forces) in the x (vertical), y (lateral), and z (sagittal) axis of an internal accelerometer during each 1-second epoch sampled at 100Hz. During free sprinting, the peak acceleration is typically the acceleration of movement in the vertical axis, so sprinting on a NMT should not factor into the determination of the peak acceleration, and therefore, mechanical intensity.

Horizontal power output values, derived from velocity and force measurements, were calculated and recorded by the Pacer Performance Software (Innervations, Perth, Western Australia). Velocity was calculated by a tachometer on the NMT continuously recording distance traveled. A horizontally mounted force transducer attached to the subject by a waist belt and a fixed post allowed propulsive force to be measured. In order to determine MP values for each separate sprint, each sprint was analyzed individually. Within the software, a 6-second segment that correlated to the start of each sprint, based on the audio, was isolated by manually outlining and zooming in on the segment. When isolated, MP expressed as absolute values (Watts) was acquired for each individual

sprint. Mean power was defined as the average power output over the entire 6-second sprint. Performance decrement was used to represent the extent of fatigue during the test. Performance decrement was calculated as a percentage using the equation suggested by Glaister et al. (2008):

$$\text{Performance Decrement} = [100 \times (\text{total mean power} / \text{ideal mean power})] - 100$$

where total MP was defined as the sum of the MP values from each sprint and ideal MP was calculated by taking the highest MP from the entire test and multiplying it by the number of sprints. Mean power rather than PP was used because the researchers felt it was a better representation of overall sprint performance.

### **Statistical Analysis**

All data were analyzed using SPSS version 23.0 software (SPSS, Inc., Chicago, IL, USA). Means  $\pm$  standard deviations (SD) were determined for all variables. Test-retest reliability was analyzed for performance decrement, total MP, mechanical load, BLa, and HR<sub>test</sub> using Intraclass correlation coefficient (ICC), coefficient of variation (CV), and paired samples t-tests. An ICC equal to or above 0.70 was considered acceptable (Baumgartner & Chung, 2001). The CV was calculated by dividing the SD by the mean and then multiplying the value by 100. The mean CV was the average of the individual CVs calculated for each subject (Atkinson & Nevill, 1998). Paired samples t-tests were used to determine any significant changes in the mean between the sessions (Hopkins, 2000). The usefulness of the test was determined by comparing the typical error of the mean (TE) to the smallest worthwhile change (SWC) in performance for each test (Hopkins, 2004). The SWC was determined by multiplying the between-subject SD by either 0.2 (SWC<sub>0.2</sub>) (Hopkins, 2000), which is the typical small effect, or 0.5 (SWC<sub>0.5</sub>),

which is an alternate moderate effect. If the TE was below the SWC, the test was rated as 'good'; if the TE was similar to the SWC, the test was rated as 'OK'; and if the TE was higher than the SWC, the test was rated as 'marginal' (Hopkins, 2004).

Differences in MP output between sprints and trials were compared using analysis of variance (ANOVA) with repeated measures (trial and sprint). Mauchley's test of sphericity was used to evaluate the homogeneity of variance. When equal variance was not assumed, the Greenhouse-Geiser adjustment was used. Tukey's post-hoc analyses were used when significant F ratios were found. Alpha was set at 0.05 for all analyses to achieve statistical significance.

## RESULTS

Performance decrement, total MP, and mechanical load reliability data are found in Table 1. There were no significant differences in performance decrement or mechanical load between the two trials. The ICCs of all variables were above 0.70. Total MP and mechanical load had CVs less than 10%. The TE for performance decrement, total MP, and mechanical load was greater than the  $SWC_{0.2}$ . The TE for performance decrement and mechanical load was also greater than the  $SWC_{0.5}$ . The TE for total MP was less than the  $SWC_{0.5}$ . Blood lactate was not significantly different between trials ( $13.0 \pm 2.2$  vs.  $12.3 \pm 2.3$  mmol/L;  $p = 0.06$ ). The ICC value for BLa was 0.82 and the CV was 8.82%.

Table 1. Performance variables for football specific repeated sprint test on a NMT.

	<b>Performance Decrement (%)</b>	<b>Total MP (Watts)</b>	<b>Mechanical Load (AU)</b>
Trial 1	16.12 ± 4.34	8031 ± 732	9.44 ± 1.12
Trial 2	15.12 ± 4.28	8226 ± 700	9.40 ± 1.26
<i>p</i> value	0.23	0.04	0.84
ICC	0.77	0.90	0.85
TE	2.6	285.1	0.62
CV (%)	14.26	2.98	5.12
SWC <sub>0.2</sub>	0.87	146.48	0.22
Rating	Marginal	Marginal	Marginal
SWC <sub>0.5</sub>	2.17	366.20	0.56
Rating	Marginal	Good	Marginal

\*Values are expressed as means ± SD

\*\*Total MP = total mean power; ICC = intraclass correlation coefficient; TE = typical error; CV = coefficient of variation; SWC<sub>0.2</sub> = smallest worthwhile change (SD\*0.2); SWC<sub>0.5</sub> = smallest worthwhile change (SD\*0.5)

\*\*\*n = 21 for performance decrement and total MP; n = 17 for mechanical load

Mean power sprint data over the course of both trials are shown in Figure 1. There was a significant main effect between trials ( $F = 4.91, p = 0.039$ ). Total MP in T2 ( $8226 \pm 700W$ ) was higher than in T1 ( $8031 \pm 732W$ ). There was also a significant main effect between sprints ( $F = 127.36, p < 0.001$ ). When comparing the sprints individually against one another in both trials, the MP achieved in sprint 4 was significantly lower than the MP achieved in sprint 1. The remaining sprints (sprints 5-10) were also significantly

lower than sprint 1. No significant interaction of trial and sprints ( $F = 2.36$ ,  $p = 0.072$ ) was observed.

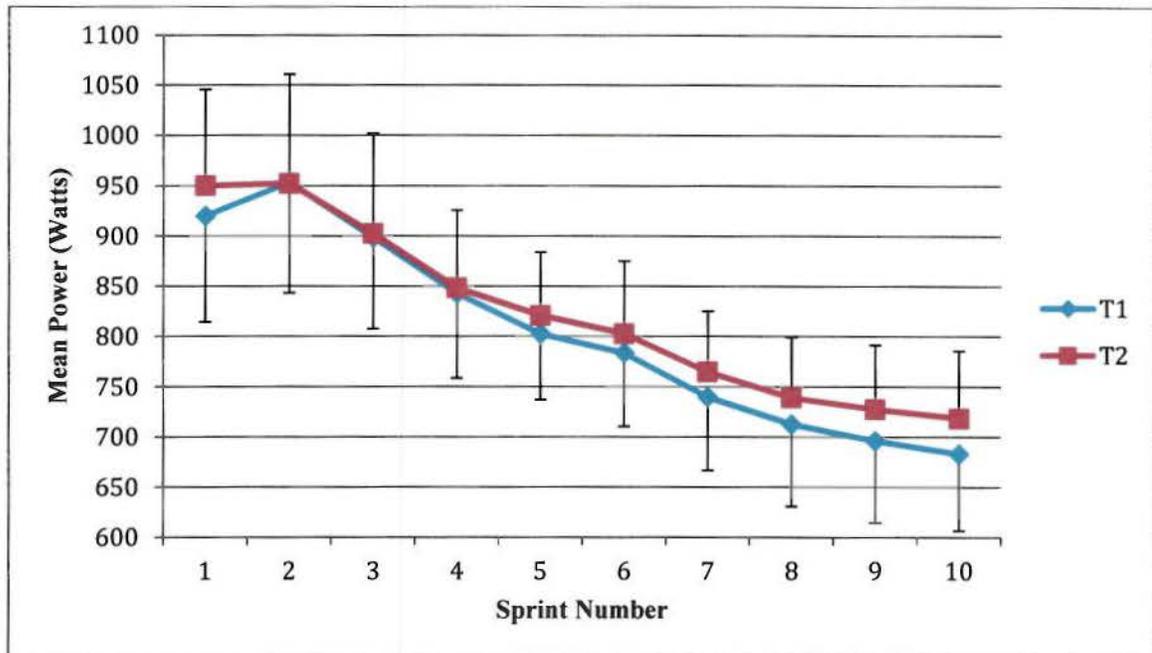


Figure 1. Mean power output for each sprint of trial 1 (T1) and trial 2 (T2).

Figure 2 shows the  $HR_{\text{sprint}}$  data throughout the course of the test for both trials. The  $HR_{\text{sprint}}$  was generally achieved between 7-15 seconds after the completion of the sprint, with  $HR_{5sAvg}$  commonly being lower than the  $HR_{\text{sprint}}$  achieved in that cycle. On average, the  $HR_{\text{test}}$  was reached at sprint 6 and maintained for the remainder of the test for both T1 and T2, respectively. During the trials, all subjects achieved over 90% of their age-predicted maximum HR (Tanaka et al., 2001). There was no significant difference in  $HR_{\text{test}}$  between trials (T1:  $192.4 \pm 14.2$  vs. T2:  $192.8 \pm 15.1$  bpm;  $p = 0.810$ ). The ICC and CV for  $HR_{\text{test}}$  were 0.92 and 1.6%, respectively. Heart rate and mechanical load data were only collected on 17 of the subjects due to technical difficulties in T2.

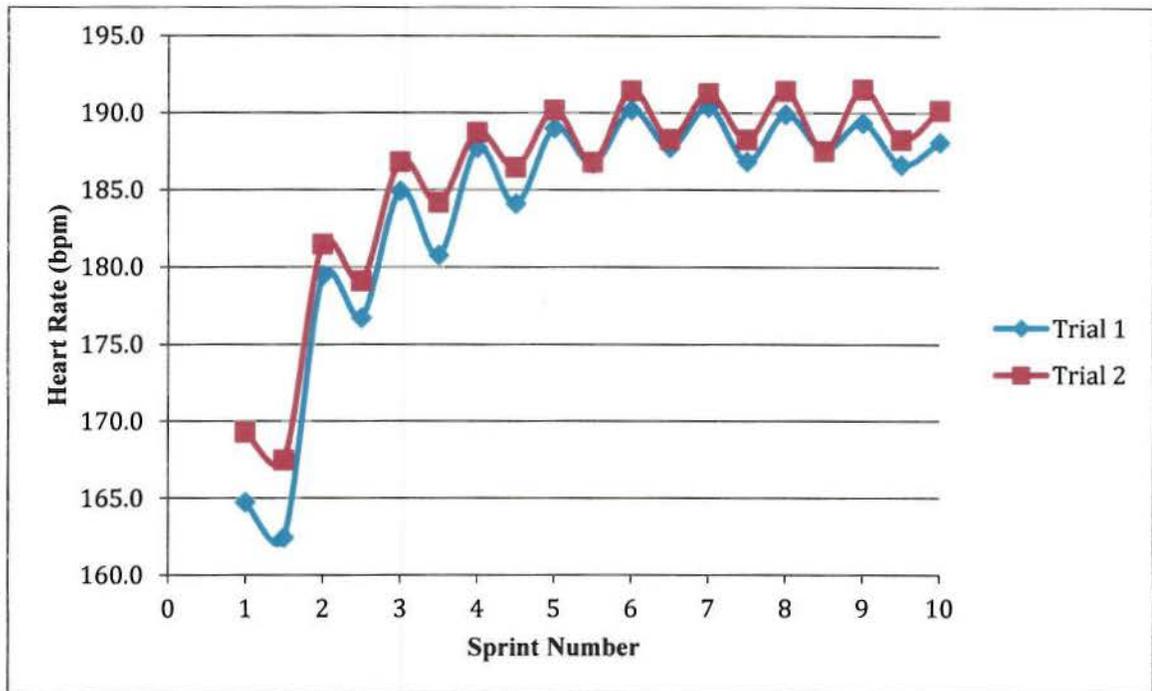


Figure 2. HR trend over the course of the repeated sprint test for T1 and T2 (n=10).  
 \*The data points in line with the sprint numbers represent  $HR_{sprint}$  (the highest HR achieved within that sprint's 31-second cycle). The data points between sprint numbers represent  $HR_{5sAvg}$  (the average HR in the last 5-seconds of that cycle).

## DISCUSSION

When developing new performance tests, it is important to first determine the reliability of the test protocol to confidently ensure that any changes seen in performance are due to differences in training status and not variability in the test itself (Atkinson & Nevill, 1998). Therefore, the main purpose of the study was to determine the test-retest reliability of a suggested repeated sprint protocol to assess football conditioning status. A major finding was that although both trials followed the same trend in the MP outputs of each sprint, there was a significant difference in the total MP output of the two trials. The MP of sprint 1 in T1 was noticeably lower than the MP of sprint 1 in T2 (see Figure 1). However, the MP of sprint 2 was almost identical in both T1 and T2. Furthermore, compared to the MP of sprint 1, the MP of sprint 2 was higher in T1 and the same in T2. This indicates that a possible learning effect may have occurred in T1 within the first two sprints. This learning effect may also explain why total MP of T2 was higher than T1. When excluding sprint 1 and comparing the total MP of sprints 2-10, there was no significant difference between T1 and T2 ( $p = 0.06$ ), supporting this hypothesis. Subjects were likely more acquainted with how to perform the test in T2 that they did not need the first sprint as extra familiarization. There have been differing reports on how much familiarization is necessary for repeated sprint tests. Researchers dealing with cycle ergometer tests have typically proposed two familiarization sessions are needed (McGawley & Bishop, 2006), whereas Hughes et al. (2006) reported one familiarization session was adequate on a NMT for athletes with no previous experience. Suggestions

from previous research, the strenuous nature of the protocol, and subject adherence were all taken into account when deciding to only complete half of the protocol in the familiarization session. However, our results suggest that more familiarization, possibly in the form of completing the whole protocol instead of only half, may be needed for athletes unfamiliar with running on a NMT in order to perhaps lead to more consistent performance.

Regardless, in both T1 and T2, MP in sprints 2 and 3 were not significantly different from sprint 1, suggesting any apparent fatigue did not occur until sprint 4. This is an important finding for football as it suggests that fatigue occurs early in a long drive. In other words, this test protocol demonstrated that these DIII football players would be able to maintain power performance for at least the first three plays of a 10-play drive; from there, performance may be diminished.

The overall trend of performance decrement in MP outputs is similar to that found by Holmyard et al. (1988) who tested university level rugby players on a NMT with a similar protocol (10 x 6-sec sprints, 30-sec recovery; no load mentioned). Our subjects achieved performance decrements of 15-16% compared to the MP performance decrements of approximately 12% reported by Holmyard et al. (1988). While we detected significant differences in MP after the third sprint compared to the first, they did not report differences until after the fifth sprint. In addition, the MP outputs achieved in the present study were also higher than those stated by Holmyard et al. (1988) (highest MP achieved: 953W vs. 716W). A combination of both of those factors, along with the slightly longer recovery time and no load to sprint against, may explain the slightly greater drop in MP seen in the present study compared to theirs. Phosphocreatine (PCr) is

the main energy substrate from the alactic energy system and therefore is predominantly utilized in short, maximal sprints (Gaitanos, Williams, Boobis, & Brooks, 1993). During the 25 and 30-second recovery periods, the fast phase of PCr resynthesis was occurring (Bogdanis, Nevill, Boobis, Lakomy, & Nevill, 1995; Harris et al., 1976). The extra 5 seconds of recovery given to the subjects in Holmyard et al. (1988)'s study could have thus allowed more resynthesis of PCr to be utilized in subsequent sprints, leading to greater maintenance of power. Moreover, in anaerobic performance tests, field or anaerobically trained athletes typically produce a greater power and speed (maximum performance) early in the test, but are unable to maintain a higher power output, indicated by a greater drop-off in performance throughout the test (Hamilton, Nevill, Brooks, & Williams, 1991; Inbar et al., 1996). Conversely, endurance or aerobically trained athletes do not generate the same degree of power or speed produced by their anaerobic counterparts, but they better maintain power and speed throughout the test, as shown by a lower decline in performance (Hamilton et al., 1991; Inbar et al., 1996). Therefore, this would indicate the subjects in the present study were slightly more anaerobically trained than the rugby players in Holmyard et al. (1988)'s study.

Both relative (ICC) and absolute (CV) reliability were determined for performance decrement, total MP, and mechanical load. Performance decrement is a relative variable that is not directly measured, but is calculated. It takes into account the maximum performance and the ability to match that maximum performance throughout the test (Fitzsimmons et al., 1993). Total MP is an absolute variable that is directly measured. It takes into account all of the sprints, however it does not relay any information as to the trend in performance. It simply implies how much power an

individual can produce over the 10 sprints (Fitzsimmons et al., 1993). For example, two individuals may have the same total MP, but different responses to the test. One individual may have a constant, moderate MP output for each sprint, whereas the other individual may have a higher MP output, but drop in performance throughout the test. Because both variables represent different aspects of the test, it is important to consider both when determining overall performance (Fitzsimmons et al., 1993).

Performance decrement, total MP, and mechanical load between the two trials were all shown to have acceptable relative reliability ( $ICC > 0.70$ ). Total MP and mechanical load were shown to have acceptable absolute reliability ( $CV < 10\%$ ), while performance decrement's CV was greater than 10%. It is common to find fatigue variables, such as performance decrement, to be less reliable than power or speed variables when performing anaerobic testing because of the combination of variables involved in its calculation (Austin, Gabbett, & Jenkins, 2013; Fitzsimmons et al., 1993; Hughes et al., 2006; Johnston & Gabbett, 2011; Wright, Isaacson, Malecek, & Steffen, 2015). Consequently, small changes in power can cause large changes in performance decrement. This is true for both single effort tests (Attia et al., 2014; McLain et al., 2015; Patton et al., 1985) and repeated sprint tests (Boddington et al., 2001; Fitzsimmons et al., 1993; Hughes et al., 2006; Zagatto, Beck, & Gobatto, 2009), regardless of the modality. As illustrated in our study, the noticeable difference in MP in sprint 1 of both trials may have caused a larger change in performance decrement between the two trials, leading to slightly lower reliability. There is a lack of studies determining reliability of repeated sprint tests on a NMT, so the comparability is limited. Fitzsimmons et al. (1993) reported a comparable performance decrement ICC of  $r = 0.75$  in a track-version of a repeated

sprint test. Other track-versions of differing repeated sprint tests have also reported similar ICC values ( $r=0.70-0.74$ ) for fatigue indices (Boddington et al., 2001; Zagatto et al., 2009). As consistent with other studies, our total MP variable ICC value was greater than performance decrement and comparable with ICC values of total work ( $r=0.97$ ) in a cycling repeated sprint test (Fitzsimmons et al., 1993), total distance covered ( $r=0.98$ ) in a field, repeated sprint running test (Boddington et al., 2001), and total time ( $r=0.90$ ) of a different field running repeated sprint test (Zagatto et al., 2009).

It is typical for a CV less than 10% to be considered appropriate (Atkinson & Nevill, 1998). The CVs for total MP (3%) and mechanical load (5%) fell below this cutoff. While our CV for performance decrement was higher than this, we still deemed it acceptable based on the proposal given by Glaister et al. (2008). They deemed the performance decrement equation was reliable in their study even though the ICCs were low (0.44-0.51) and the CVs were high (32-38%). Their reasoning was that even with the high CV, in relation to their mean, the variability accounted for by the CV still allowed for adequate evaluation of interventions. We credit this to the fact that, in their case, a 32-38% variation (i.e. the CV) from the mean was still less variation than that of the SD. This is true for our study as well. Although we discovered 14% test-retest variability, it is only half of the variability seen by the SD alone, based on our mean. In addition, our CV was comparably lower than that reported by Glaister et al. (2008) (32-38%) and Fitzsimmons et al., (1993) (18.5%).

Along with determining the reliability of a test, defining the usefulness is also important to consider. The usefulness of a test is a way of determining if the variability or error of the test itself will mask any worthwhile improvements or decrements (Hopkins,

2004). The TE of performance decrement and mechanical load was greater than both  $SWC_{0.2}$  and  $SWC_{0.5}$ , showing the usefulness of the test as “marginal” in regards to these variables. The usefulness of the test in regards to total MP is “good” at the moderate effect level ( $SWC_{0.5}$ ). This suggests that one can be confident in using this protocol to detect moderate changes in total MP. It has been proposed that homogeneous samples, such as in the present study, make it harder to find “good” usefulness than heterogeneous samples because of the smaller SDs seen in homogeneous samples (Lockie, Schultz, Callaghan, Jeffriess, & Berry, 2013).

The football-specific repeated sprint test was designed to be a reliable method of testing the strenuous nature of American football drives (series of plays) and the players’ anaerobic ability to perform this activity. The test demonstrated maximal effort with all subjects reaching a  $HR_{test}$  over 90% of their estimated maximum HR approximately six sprints into the test, respectively. Once reached, the subjects maintained this  $HR_{test}$  for the remainder of the test. This HR response was similar to that of rugby players completing a similar protocol (10 x 6sec; 30sec recovery) on a NMT (Holmyard et al., 1988) and that of soccer players completing twenty 5-second cycle sprints with 25 seconds of recovery (Billaut & Smith, 2010). It was also found that the  $HR_{sprint}$  was achieved about halfway through each 31-second cycle and the  $HR_{5sAvg}$  was commonly less than 5 bpm lower than the  $HR_{sprint}$  of the following cycle. This indicates that during 10 repeated sprints of 6-seconds with 25-seconds of recovery subjects achieve near maximal heart rates with little to no recovery or fluctuation. Blood lactate levels are an indication of the contribution of the lactic energy system during activity (Gaitanos et al., 1993). Thus, the high BLa levels achieved during both trials further suggest the highly anaerobic and maximal nature of

this test. During maximal sprinting, high BLa levels have been shown to be associated with higher power output values (Hamilton et al., 1991). Therefore, if the subjects gave a submaximal effort in one trial and a maximal effort in another, they would not achieve the same power outputs in the submaximal effort compared to the maximal effort because of the relative contributions from the energy systems. However, in our study a difference in effort seems to be unlikely as the “good” BLa reliability shown between trials ( $r = 0.82$  and  $CV < 10\%$ ) suggests that the lactic energy system was utilized similarly in both trials. This is under the assumption that diet was not a factor in the BLa levels because subjects adhered to the directions given to them to consume meals similar in composition prior to each test. The BLa levels of 12-13 mmol/L seen in the present study are in agreement with those reported by Gaitanos et al. (1993) (12.6mmol/L) after ten 6-second maximal cycle sprints with 30 seconds of recovery. Hamilton et al. (1991) reported BLa levels of 14.8mM in field athletes and 11.8mM in endurance trained athletes after ten 6-second running sprints on a NMT with 30 seconds of recovery. Based on these results, our subjects with an average BLa of 12.3-13.0mM following the repeat sprint protocol fell in between the two types of athletes.

Therefore, based on our results, we conclude that the repeated sprint protocol on a NMT using a 15% body weight resistance has acceptable reliability and can be used to determine anaerobic performance in American football players. However, we do suggest further familiarization to avoid learning effects and likely improve test-retest reliability even further. Furthermore, the lower CV combined with a higher ICC for total MP compared to performance decrement imply total MP is a more reliable measurement when determining changes in performance.

## **Practical Applications**

Football players can be tested for their anaerobic performance using the football-specific repeated sprint protocol laid out by this study on a NMT. The test is both functionally and metabolically specific to football players because of the modality (i.e. sprint running) and the work-to-rest ratios employed. Therefore, with adequate familiarization, this protocol can be used for differentiating conditioning status between football players, assessing performance after recovery from an injury, and analyzing fatigue accrued throughout the season and the effectiveness of an in season conditioning program among other things. In addition, the test may be beneficial in determining what aspects of performance need to be focused on for individuals. For example, focusing training on improving power production if power outputs are low or improving power maintenance if performance decrements are high.

## REFERENCES

- American College of Sports Medicine. (2010). *ACSM's guidelines for exercise testing and prescription* (8th ed.). (pp. 66-68). Philadelphia: Lippincott Williams & Wilkins.
- Arnold, J. A., Brown, B., Micheli, R. P., & Coker, T. P. (1980). Anatomical and physiologic characteristics to predict football ability Report of study methods and correlations, University of Arkansas, 1976. *The American Journal of Sports Medicine*, 8(2), 119-122.
- Atkinson, G., & Nevill, A. M. (1998). Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine. *Sports Medicine*, 26(4), 217-238.
- Attia, A., Hachana, Y., Chaabène, H., Gaddour, A., Neji, Z., Shephard, R. J., & Chelly, M. S. (2014). Reliability and Validity of a 20-s Alternative to the Wingate Anaerobic Test in Team Sport Male Athletes. *PloS One*, 9(12), e114444.
- Austin, D. J., Gabbett, T. J., & Jenkins, D. G. (2013). Reliability and sensitivity of a repeated high-intensity exercise performance test for rugby league and rugby union. *The Journal of Strength & Conditioning Research*, 27(4), 1128-1135.
- Baumgartner, T. A., & Chung, H. (2001). Confidence limits for intraclass reliability coefficients. *Measurement in Physical Education and Exercise Science*, 5(3), 179-188.
- Berkes, P. (2015, May 15). Baylor has college football's fastest offense, but where does your team rank? Retrieved from <http://www.sbnation.com/college-football/2015/5/15/8586169/hurry-up-offense-fastest-slowest>.
- Billaut, F., & Smith, K. (2010). Prolonged repeated-sprint ability is related to arterial O<sub>2</sub> desaturation in men. *International Journal of Sports Physiology and Performance*, 5(2), 197-209.
- Bishop, D., Spencer, M., Duffield, R., & Lawrence, S. (2001). The validity of a repeated sprint ability test. *Journal of Science and Medicine in Sport* 4 (1), 19-29.
- Boddington, M. K., Lambert, M. I., Gibson, A. S. C., & Noakes, T. D. (2001). Reliability of a 5-m multiple shuttle test. *Journal of Sports Sciences*, 19(3), 223-228.

- Bogdanis, G. C., Nevill, M. E., Boobis, L. H., Lakomy, H. K., & Nevill, A. M. (1995). Recovery of power output and muscle metabolites following 30 s of maximal sprint cycling in man. *The Journal of Physiology*, 482(2), 467-480.
- Brožek, J., Grande, F., Anderson, J. T., & Keys, A. (1963). Densitometric analysis of body composition: revision of some quantitative assumptions. *Annals of the New York Academy of Sciences*, 110(1), 113-140.
- Fitzsimons, M., Dawson, B., Ward, D., & Wilkinson, A. (1993). Cycling and running tests of repeated sprint ability. *Australian Journal of Science and Medicine in Sport*, 25(4), 82-82.
- Fry, A. C., & Kraemer, W. J. (1991). Physical Performance Characteristics of American Collegiate Football Players. *The Journal of Strength & Conditioning Research*, 5(3), 126-138.
- Gaitanos, G. C., Williams, C., Boobis, L. H., & Brooks, S. (1993). Human muscle metabolism during intermittent maximal exercise. *Journal of Applied Physiology*, 75(2), 712-719.
- Glaister, M. (2005). Multiple sprint work. *Sports Medicine*, 35(9), 757-777.
- Glaister, M., Howatson, G., Pattison, J. R., & McInnes, G. (2008). The reliability and validity of fatigue measures during multiple-sprint work: An issue revisited. *The Journal of Strength & Conditioning Research*, 22(5), 1597-1601.
- Gleim, G. W., Witman, P. A., & Nicholas, J. A. (1981). Indirect assessment of "cardiovascular" demands" using telemetry on professional football players. *The American Journal of Sports Medicine*, 9(3), 178-183.
- Glencross, D. J. (1966). The nature of the vertical jump test and the standing broad jump. *Research Quarterly. American Association for Health, Physical Education and Recreation*, 37(3), 353-359.
- Hamilton, A. L., Nevill, M. E., Brooks, S., & Williams, C. (1991). Physiological responses to maximal intermittent exercise: Differences between endurance-trained runners and games players. *Journal of Sports Sciences*, 9(4), 371-382.
- Harris, R. C., Edwards, R. H. T., Hultman, E., Nordesjö, L. O., Ny Lind, B., & Sahlin, K. (1976). The time course of phosphorylcreatine resynthesis during recovery of the quadriceps muscle in man. *Pflügers Archive*, 367(2), 137-142.
- Hetzler, R. K., Vogelpohl, R. E., Stickley, C. D., Kuramoto, A. N., DeLaura, M. R., & Kimura, I. F. (2010). Development of a modified Margaria-Kalamen anaerobic power test for American football athletes. *The Journal of Strength & Conditioning Research*, 24(4), 978-984.

- Hoffman, J. (2008). The applied physiology of American Football. *International Journal of Sport Physiology and Performance*, 3, 387-392.
- Hoffman, J. R., Ratamess, N. A., & Kang, J. (2011). Performance changes during a college playing career in NCAA division III football athletes. *The Journal of Strength & Conditioning Research*, 25(9), 2351-2357.
- Hoffman, J. R., Im, J., Kang, J., Ratamess, N. A., Nioka, S., Rundell, K. W., ... & Chance, B. (2005). The effect of a competitive collegiate football season on power performance and muscle oxygen recovery kinetics. *The Journal of Strength & Conditioning Research*, 19(3), 509-513.
- Holmyard, D. J., Cheetham, M. E., Lakomy, H. K. A., & Williams, C. (1988). Effect of recovery duration on performance during multiple treadmill sprints. *Science and Football*, 134-142.
- Hopkins, W. G. (2000). Measures of reliability in sports medicine and science. *Sports Medicine*, 30(1), 1-15.
- Hopkins, W. G. (2004). How to interpret changes in an athletic performance test. *Sportscience*, 8(1), 1-7.
- Hughes, M. G., Doherty, M., Tong, R. J., Reilly, T., & Cable, N. T. (2006). Reliability of repeated sprint exercise in non-motorised treadmill ergometry. *International Journal of Sports Medicine*, 27(11), 900-904.
- Inbar, O., Bar-Or, O., & Sinner, J.S. The Wingate Anaerobic Test. Champaign, IL: Human Kinetics, 1996.
- Iosia, M. & Bishop, P. (2008). Analysis of exercise-to-rest ratios during division IA televised football competition. *Journal of Strength and Conditioning Research*, 22(2), 332-340.
- Jackson, A. S., & Pollock, M. L. (1978). Generalized equations for predicting body density of men. *British Journal of Nutrition*, 40(03), 497-504.
- Johnston, R. D., & Gabbett, T. J. (2011). Repeated-sprint and effort ability in rugby league players. *The Journal of Strength & Conditioning Research*, 25(10), 2789-2795.
- Krustrup, P., Mohr, M., Amstrup, T., Rysgaard, T., Johansen, J., Steensberg, A., ... & Bangsbo, J. (2003). The yo-yo intermittent recovery test: physiological response, reliability, and validity. *Medicine and Science in Sports and Exercise*, 35(4), 697-705.

- Lockie, R. G., Schultz, A. B., Callaghan, S. J., Jeffriess, M. D., & Berry, S. P. (2013). Reliability and validity of a new test of change-of-direction speed for field-based sports: the change-of-direction and acceleration test (CODAT). *Journal of Sports Science & Medicine*, *12*(1), 88-96.
- Margaria, R., Aghemo, P., & Rovelli, E. (1966). Measurement of muscular power (anaerobic) in man. *Journal of Applied Physiology*, *21*(5), 1662-1664.
- Mayhew, S. R., & Wenger, H. A. (1985). Time-motion analysis of professional soccer. *Journal of Human Movement Studies*, *11*(1), 49-52.
- McGawley, K., & Bishop, D. (2006). Reliability of a 5× 6-s maximal cycling repeated-sprint test in trained female team-sport athletes. *European Journal of Applied Physiology*, *98*(4), 383-393.
- McGawley, K., & Bishop, D. J. (2015). Oxygen uptake during repeated-sprint exercise. *Journal of Science and Medicine in Sport*, *18*(2), 214-218.
- McKenna, M. J., Patrick, J. D., & Chennells, M. H. D. (1988). *Computer-video analysis of activity patterns in Australian Rules football*. London: E & FN Spon, 274-281.
- McLain, T., Wright, G., Camic, C., Kovacs, A., Hegge, J., & Brice, G. (2015). The development of an anaerobic sprint running test utilizing a nonmotorized treadmill. *Journal of Strength and Conditioning Research*, *29*(8), 2197-2204.
- Nummela, A., Hämäläinen, I., & Rusko, H. (2007). Comparison of maximal anaerobic running tests on a treadmill and track. *Journal of Sports Sciences*, *25*(1), 87-96.
- Patton, J., Murphy, M., & Frederick, F. (1985). Maximal power outputs during the Wingate anaerobic test. *International Journal of Sports Medicine*, *6*(1), 82-85.
- Pendleton, M. H. W. (1997). Reliability and validity of the Welsh Rugby Union shuttle run test. *Unpublished BSc dissertation, University of Wales Institute Cardiff*.
- Pincivero, D. M., & Bompa, T. O. (1997). A physiological review of American football. *Sports Medicine*, *23*(4), 247-260.
- Rhea, M., Hunter, R., & Hunter, T. (2006). Competition modeling of American football: Observational data and implications for high school, collegiate, and professional player conditioning. *Journal of Strength and Conditioning Research*, *20*(1), 58-61.
- Seiler, S., Taylor, M., Diana, R., Layes, J., Newton, P., & Brown, B. (1990). Assessing Anaerobic Power in Collegiate Football Players. *The Journal of Strength & Conditioning Research*, *4*(1), 9-15.

- Smith, M. E., & Jackson, C. G. R. (1991). Lactate response of college football players to practices and a game [abstract]. *Journal of Applied Sport Science Research*, 5, 163.
- Tanaka, H., Monahan, K. D., & Seals, D. R. (2001). Age-predicted maximal heart rate revisited. *Journal of the American College of Cardiology*, 37(1), 153-156.
- Wright, G. A., Isaacson, M. I., Malecek, D. J., & Steffen, J. P. (2015). Development and assessment of reliability for a sandbag throw conditioning test for wrestlers. *The Journal of Strength & Conditioning Research*, 29(2), 451-457.
- Zacharogiannis, E., Paradisis, G., & Tziortzis, S. (2004). An evaluation of tests of anaerobic power and capacity. *Medicine & Science in Sports & Exercise*, (36), 116.
- Zagatto, A. M., Beck, W. R., & Gobatto, C. A. (2009). Validity of the running anaerobic sprint test for assessing anaerobic power and predicting short-distance performances. *The Journal of Strength & Conditioning Research*, 23(6), 1820-1827.
- Zapiec, C., & Taylor, A. W. (1979). Muscle fibre composition and energy utilization in CFL football players. *Canadian Journal of Applied Sport Sciences*, 4(2), 140-142.
- Zemková, E. & Hamar, D. (2004). "All-out" tethered running as an alternative to Wingate Anaerobic Test. *Kinesiology*, 36(2), 165-172.

APPENDIX  
LITERATURE REVIEW

## **LITERATURE REVIEW**

### **Section I – Anaerobic Performance**

#### **Energy Systems**

The body, through metabolic processes, is able to use chemical energy from the breakdown of substrates and convert it into mechanical energy. These processes allow movement, such as muscular contractions, to occur. The main energy source used by the body for muscular contractions and cell function is adenosine triphosphate (ATP). ATP is a high-energy phosphate that releases energy when it is broken down; a process called hydrolysis (Brooks, Fahey, White, & Baldwin, 2000). The body is designed to maintain ATP homeostasis in the cells. Therefore, these metabolic processes are responsible for regenerating the ATP used during muscular contractions and other cell functions in order to maintain homeostasis. There are three energy-systems (i.e. metabolic processes) responsible for ATP regeneration: immediate energy system (alactic system), short-term energy system (lactic system), and long-term energy system (aerobic system). Although each will be described independently of the others, all three of the energy systems work together in a coordinated effort to replenish ATP (Brooks et al., 2000).

#### **Immediate (Alactic System)**

There are three types of fuels and reactions utilized by this system; stored ATP within the muscles, phosphocreatine (PCr), and the myokinase (MK) reaction. This system has a very limited total ATP production capacity of about 10-15 seconds (Brooks et al., 2000).

The first immediate fuel utilized by the body is stored muscular ATP. At rest, there is about 20-25mmol/kg dry mass (dm) of ATP within the muscle, stored on the heads of the myosin proteins (Boobis, Williams, & Wootton, 1982; Gaitanos, Williams, Boobis, & Brooks, 1993). This is enough fuel for approximately 1-2 seconds of maximal work (Bogdanis, Nevill, Lakomy, & Boobis, 1998). For the majority of sports, this is an insufficient amount of energy to complete desired actions. Consequently, other fuels are needed and available for use.

PCr is a high-energy phosphorylated compound that is more abundant in resting muscle than ATP. Gaitanos and colleagues (1993) observed that under resting conditions there is roughly 80mmol/kg dm of PCr within the muscle. The enzyme creatine kinase (CK) catalyzes the interaction of PCr and ADP in order to make ATP. More specifically, the inorganic phosphate ( $P_i$ ) from PCr phosphorylates adenosine diphosphate (ADP) to produce ATP and free creatine (Cr). This reaction is fast and highlights the role of PCr as a provider of a reserve of phosphate energy that can quickly regenerate ATP (Brooks et al., 2000). The initial PCr stores are largely depleted within 10 seconds of maximal work (Glaister, 2005; Hirvonen, Rehunen, Rusko, & Harkonen, 1987; Walter, Vandenborne, McCully, & Leigh, 1997). Hirvonen et al. (1987) reported that roughly 56% of resting PCr concentration was depleted in a 60m (~5.5 seconds) maximal sprint. In addition, Gaitanos and colleagues (1993) found that after a maximal 6-second cycle sprint, PCr concentration fell about 57% and the ATP production rate from PCr degradation was roughly 7.4 mmol/kg dm/sec.

At extreme intensities when ATP is being used faster than it can be resynthesized by the CK reaction, there is an accumulation of ADP molecules. An increased ADP

concentration inhibits ATPase activity (the enzyme that hydrolyzes ATP), causing a disruption in muscular contraction, specifically crossbridge cycling (McLester, 1997). The myokinase (also known as adenylate kinase) reaction takes place in order to prevent this accumulation of ADP to maintain crossbridge cycling rate. The myokinase reaction is characterized by the enzyme myokinase phosphorylating two ADP molecules to form one ATP and one adenosine monophosphate (AMP) molecule (Brooks et al., 2000). The reaction produces the needed ATP while also controlling the ADP concentration. A negative effect of this reaction is that the AMP is further deaminated into inosine monophosphate (IMP) and ammonia (which is toxic to the cell) by a corresponding reaction involving the enzyme AMP deaminase (Glaister, 2005).

#### **Short-term (Lactic System)**

The short-term or lactic system is characterized by a fast response to high intensity activity and moderate capacity to produce ATP. It has a limited total ATP production capacity of about 60-180 seconds (Brooks et al., 2000). Consequently, it has a greater capacity to produce ATP than the immediate energy system, but at a slightly slower rate (Alactic: 7.4mmol/kg dm/sec vs. Lactic: 6.6mmol/kg dm/sec) (Gaitanos et al., 1993). Its major fuel source is glucose, which comes directly from both stored muscle glycogen and the blood (Brooks et al., 2000).

Glycolysis and glycogenolysis are the two metabolic pathways involved in this system. Glycolysis involves the breakdown of a glucose-6-phosphate (G-6-P) molecule into pyruvate in order to produce ATP. Muscle glycogenolysis is the breakdown of muscle glycogen into G-6-P molecules, which then undergo glycolysis. Stored muscle glycogen concentrations at rest have been reported around 300mmol/kg dm in untrained

subjects and over 400mmol/kg dm in recreational athletes (Bogdanis, Nevill, Boobis, & Lakomy, 1996; Bogdanis et al., 1998; Gaitanos et al., 1993). Because of this, glycolysis is heavily dependent on the stored muscle glycogen as its immediate means for fuel (Brooks et al., 2000).

The rate of ATP utilization determines if “slow” or “fast” glycolysis is occurring. Fast glycolysis is what we will focus on for the purpose of this review. Fast glycolysis has been reported to reach peak ATP turnover rates of 6-7mmol/kg dm/sec with the rate of glycogen degradation after 6 seconds of maximal exercise being roughly 7mmol/kg dm/sec (Gaitanos et al., 1993; Parolin, Chesley, Matsos, Spriet, Jones, & Heigenhauser, 1999). Fast glycolysis is most commonly associated with its production of lactate and hydrogen ions ( $H^+$ ). The result is a change in the metabolic environment (i.e. lowered pH) causing some key enzymes associated with glycolysis to become inhibited (Brooks et al., 2000; Nakamaru & Schwartz, 1972). The effect of this inhibition on glycolysis from an increased  $H^+$  concentration ( $[H^+]$ ) will be discussed in a later section.

### **Long-term (Aerobic Metabolism)**

The long-term energy system, has a slow response and low ATP production rate compared to the other two energy systems, but has the highest ATP production capacity. Theoretically, all other things held constant, as long as there are energy substrates and a supply of oxygen, there is an unlimited capacity for this system. The major factor differing aerobic metabolism from the other systems is that it requires oxygen to function whereas the others do not (Brooks et al., 2000). For this reason, the alactic and lactic systems are commonly referred to as the anaerobic energy systems. Due to aerobic metabolism's slower response, it is not a major contributor in producing high intensity

exercise until the exercise continues to last over a couple of minutes. In terms of maximal and fatiguing exercises, aerobic metabolism is essential to recovery from the maximal and fatiguing exercise (Brooks et al., 2000).

Due to PCr's ability to quickly assist in maintaining ATP homeostasis, the resynthesis of PCr is an important process to understand. PCr resynthesis is achieved primarily via aerobic ATP resynthesis, leading to the limited ATP production capacity exhibited by the alactic system (Haseler, Hogan, & Richardson, 1999; Turner & Stewart, 2013). In order to resynthesize PCr, ATP phosphorylates creatine from the sarcoplasm to produce a PCr molecule. The ATP used in this resynthesis process is typically made in the mitochondria aerobically. It has been found that PCr resynthesis occurs at a similar rate after a single 10-second maximal sprint and 20-second maximal sprint regardless of an increase in blood lactate (BLa), indicating the glycolytic system may not be involved in PCr resynthesis to a great extent (Bogdanis et al., 1998). Further support of the aerobic system's contribution comes from studies reporting individuals with a higher aerobic capacity have been shown to recover between high intensity work bouts to a greater degree than those with a lower capacity (Bogdanis et al., 1996; Hamilton, Nevill, Brook, & Williams, 1991; Tomlin & Wegner, 2001). Moreover, PCr resynthesis appears to be a biphasic response. It begins with a fast phase, dependent on aerobic processes, followed by a slow phase, dependent on pH recovery (Harris, Edwards, Hultman, Nordesjo, Nylind, & Sahlin, 1976; Sahlin, Harris, & Hultman, 1979). Bogdanis and colleagues (1998) supported this theory when they found that during 2 minutes of recovery, PCr concentrations were resynthesized to the same degree after a 10 second and a 20 second cycle sprint regardless of the  $[H^+]$  and pH level. The initial resynthesis of PCr after the

cessation of activity (i.e. the fast phase) has been given its name because of its reasonably fast restoration rate of about 2-3 mmol/kg dry dm/sec (Harris et al., 1976). It has been shown that around 50% of PCr values are resynthesized after approximately 21-57 seconds of recovery and roughly 80% after 3.8 minutes of recovery (Bogdanis, Nevill, Boobis, Lakomy, & Nevill, 1995; Bogdanis et al., 1996; Harris et al., 1976). However, the slow phase is shown to have a half-life PCr resynthesis of more than 170 seconds, leading to longer time periods for full resynthesis (Harris et al., 1976). While some have shown PCr to be fully restored within 10 minutes of cessation of PCr depleting activity (Hultman, Bergstrom, & McLennan-Anderson, 1967), Bogdanis and colleagues (1995) reported that 6 minutes after a maximal 30-second cycle sprint, PCr had resynthesized to only 85% of initial values and that it was estimated to take over 13 minutes for 95% resynthesis.

### **Single Sprint Metabolism**

The metabolism involved in a single sprint of maximum effort is dependent on the duration and intensity of the sprint. The shorter and more intense a sprint is, the greater the percent contribution from the alactic system. The longer and less intense a sprint is, the greater the percent contribution from the lactic system, and possibly even some aerobic metabolism.

During a single, brief 5-6 second maximum sprint, PCr degradation and fast glycolysis are the predominant providers of ATP resynthesis, with aerobic metabolism only proving a minimal contribution (<10%) (Gaitanos et al., 1993; Parolin et al., 1999). Of the anaerobic sources of ATP production, PCr degradation is the primary provider accounting for nearly 50% of the total anaerobic ATP production, followed by fast

glycolysis (44%) and stored ATP (6%) (Gaitanos et al., 1993). This is demonstrated by PCr depletion being somewhat greater than glycogen depletion (57% vs. 14-15%) during 6 seconds of maximal sprinting when taking into account the amount of ATP produced from a single glucosyl unit (3 ATP) compared to one PCr (1 ATP) (Gaitanos et al., 1993; Parolin et al., 1999).

Slightly lengthening the duration of a sprint to 10 seconds alters the relative contributions of each energy system. The contribution from the lactic system begins to become more prominent than the alactic system and aerobic metabolism begins to increase its contribution as well. Hirvonen et al. (1987) reinforced this notion when they discovered that during a 100m sprint (~11 seconds), roughly 69% of the resting PCr concentration was depleted. Of the total PCr used during that 100m sprint, 88% of it was already depleted after only 5.5 seconds, suggesting the majority of PCr degradation occurs in the beginning of a sprint during the acceleration phase. They also found that the rate of muscle and blood lactate accumulation (an indicator of the lactic system) remained constant throughout the 100m, suggesting that the lactic system is contributing a constant amount to ATP production throughout the entire sprint. Combined with the decreasing contribution from the alactic system throughout the sprint, the lactic system subsequently becomes the main anaerobic energy source by the end of the sprint. In addition, aerobic metabolism has been shown to account for ~13% of the ATP production during a maximal 10-second sprint on a cycle ergometer, with the rest coming from a contribution of the alactic (32-37%) and lactic systems (50-55%) (Bogdanis et al., 1998). Bogdanis and colleagues (1998) found that the PCr concentration decreased 55% and glycogen concentration decreased 11.5% over the 10-second cycle sprint. If the resting

values are taken into account, (PCr = 76.5mmol/kg dm; glycogen = 316.8mmol/kg dm) the absolute degradation of each (43.5mmol/kg dm) is actually the same. As the peak rate of ATP production from PCr degradation is faster than fast glycolysis and three times the ATP is produced from a single glucosyl unit than a single PCr molecule, it appears as though the contribution from the alactic system may be diminishing by the end of the sprint.

The majority of research has focused on the metabolism occurring during a single, maximal 30-second sprint. Smith & Hill (1991) found that during a 30-second Wingate anaerobic test (WAnT) the contribution from the alactic system was 28%, the lactic system was 56%, and aerobic metabolism was 16%. It has been shown that 80% of the resting PCr may be depleted over 30 seconds of maximal sprint cycling (Bogdanis et al., 1995), with the majority of PCr being depleted within the first 10 seconds (Smith & Hill, 1991). The alactic contribution peaked during the first 5 seconds, while the lactic system was active during the entire sprint and peaked around 12.5 seconds. Aerobic contribution was delayed during the first 5 seconds, peaking in the last 5 seconds (Smith & Hill, 1991). Bogdanis and colleagues (1995) determined that when comparing the contributions of the anaerobic sources of ATP production to one another, the lactic system's contribution was just over double that of the alactic system. It can be concluded that the lactic system is the predominant ATP provider during a 30 sec all-out cycling sprint, such as a WAnT, and aerobic metabolism's contribution continues to grow as the duration lengthens.

## **Repeated Sprint Metabolism**

Repeated sprints simply mean performing multiple sprints interspersed with some form of limited recovery. For the purposes of this review, we will be focusing on repeated sprints that involve performing any number of maximal sprints, equal in duration, with recovery periods of fixed duration between sprints. The metabolism and ability to perform each sprint is directly altered by the events taking place prior to each sprint. Specifically, the intensity and duration of the sprints, as well as the type of recovery processes between sprints, will alter successive sprints.

Energy substrates used to resynthesize ATP during and between sprints are depleted to differing degrees during a maximal sprint, dependent on the duration of the sprint and the length of the recovery between sprints. The recovery period between sprints is when energy substrates are replenished in order to help fuel the next sprint. PCr concentrations are only about half restored after 21-57 seconds of recovery (Bogdanis et al., 1995; Harris et al., 1976). Glycogen resynthesis is much slower and may take at least 6-8 hours to fully restore to resting concentrations (Pascoe & Gladden, 1996). Therefore, without the extensive recovery time allowed, an individual begins the next sprint at lower PCr and glycogen concentrations.

Gaitanos and colleagues (1993) conducted a study where subjects completed 10 maximal 6-second cycling sprints with 30 seconds of recovery between sprints. They reported that subjects' resting PCr concentration (i.e. pre-sprint 1) was roughly 76.5 mmol/kg dm and dropped to 32.9 mmol/kg dm after the first sprint. By the beginning of the 10<sup>th</sup> sprint, however, the subjects' pre-sprint PCr concentration dropped to only 37.5 mmol/kg dm and fell to 12.2 mmol/kg dm by the end of the final sprint. These results

suggest that while 10 repeated sprints use a significant amount of PCr, it is likely that most of the PCr is used in the first few sprints. The decreased PCr concentration seen following the early sprints likely inhibits power production that can be produced by the alactic system in subsequent sprints. Strong relationships have been found between the amount of PCr resynthesis during recovery and the recovery of power output (PO) in successive sprints (Bogdanis et al., 1996). However, it still appears as though the power decrement is less than expected based on decreases in the alactic system. For example, in the Gaitanos et al. (1993) study, although PCr concentration prior to the 10<sup>th</sup> sprint was 49% of the resting concentration, the mean power output of the 10<sup>th</sup> sprint only dropped to 73% of that achieved in the first sprint. This likely means that in order to maintain the maximal power achieved in the first sprint, the aerobic energy system contributes more to ATP production in later sprints than earlier sprints. Most studies agree and have found that aerobic metabolism increases its contribution in the later sprints (Bogdanis et al., 1996; Gaitanos et al., 1993). It is important to remember that PCr resynthesis is an aerobic process, so one may postulate that having a higher aerobic capacity would lead to a higher maintenance of PO from an increased resynthesis of PCr due to increased support from aerobic metabolism. There are multiple studies supporting this notion showing that individuals with a higher aerobic capacity recover between repeated sprints to a greater degree than individuals with a lower aerobic capacity (Bogdanis et al., 1996; Brown, Hughes, & Tong, 2007; Hamilton et al., 1991; Tomlin, 1998). However, caution must be used, as some studies have shown little to no benefit in having a higher aerobic capacity in terms of recovering from repeated sprints (Aziz, Chia, & Teh, 2000; Bishop, Lawrence, & Spencer, 2003; Wadley & Le Rossignol, 1998).

The degree of contributions from each of the three energy systems varies with differing metabolic environments during repeated sprint protocols. The 10-sprint protocol observed by Gaitanos et al. (1993) determined that aerobic metabolism contributed a larger amount with each successive sprint due to decreases in the contribution from the anaerobic systems. Within the anaerobic systems' contributions during the last sprint, the relative contribution from the alactic system was greater than the relative contribution of the lactic system (84% vs. 16%). A likely contributor to this phenomenon is the inhibition of the lactic system from a lowered pH and an increased inorganic phosphate ( $P_i$ ) concentration. However, a lowered pH also has an effect on the alactic system by inhibiting PCr resynthesis (Brooks et al., 2000). Therefore, repeated short sprints with brief recovery periods result in overall smaller relative contributions from both the alactic and lactic systems and a greater reliance on aerobic metabolism as the number of repeated sprints increases. With these changes in energy contribution observed, Gaitanos et al. (1993) observed that peak power and mean power on the 10<sup>th</sup> sprint of a 10x6 seconds repeated sprint protocol decreased to only 66.6% and 73.5% of the first sprint's PO, respectively. Furthermore, longer recovery periods, allowing greater resynthesis of PCr between sprints, allow individuals to maintain PO to a greater degree (Holmyard, Cheetham, Lakomy, & Williams, 1988).

## **Section II – Physiological Responses to Repeated Sprints**

### **Lactate**

Lactate and  $H^+$  are by-products of the lactic system. The two by-products are associated with one another because lactate can only be formed with the addition of two  $H^+$ . When pyruvate accumulates in the sarcoplasm, the enzyme lactate dehydrogenase

(LDH) utilizes the  $H^+$  from accrued NADH ( $NADH + H^+$ ; reduced nicotinamide adenine dinucleotide) to reduce pyruvate into lactate (Brooks et al., 2000). During fast glycolysis, pyruvate is formed at a faster rate than it can be taken up into the mitochondria. This coupled with an accumulation of NADH results in an increase in lactate. Lactate and  $H^+$  are produced in the muscle and are then co-transported out of the muscle into the blood via a monocarboxylate transporter (MCT) (Brooks et al., 2000). Therefore, many researchers measure BLa levels as an indicator of the lactate production within the muscle and the contribution of the lactic system.

Blood lactate levels at rest are typically between 1-2mmol/L as lactate is always being produced by the cells (Brooks et al., 2000). After a single, maximal 6-second cycle sprint, Gaitanos and colleagues (1993) discovered BLa levels only increased about 1.3mmol/L from resting values (0.6mmol/L) in healthy, active males. However, after four more sprints were repeated with 30 seconds of recovery, BLa increased another 7.3mmol/L from the end of the first sprint. Thus, after five repeated sprints, BLa levels reached 9.2mmol/L (Gaitanos et al., 1993). Bishop and Spencer (2004) reported similar BLa levels in endurance-trained athletes ( $9.9 \pm 2.1$ mmol/L) after five 6-second maximal cycle sprints with 24 seconds of recovery. Team sport athletes in this same study, however, reported higher BLa levels ( $11.4 \pm 0.8$ mmol/L) suggesting team sport athletes may utilize the lactic system better than endurance trained athletes (Bishop & Spencer, 2004). In the Gaitanos et al. (1993) study, the subjects completed four more maximal sprints for a total of nine 6-second repeated sprints with 30 seconds of recovery. They found that the BLa levels increased another 3.4mmol/L during sprints 6-9, resulting in a peak BLa value of 12.6mmol/L after nine total sprints. The difference in amount of

lactate accumulation over sprints 2-5 compared to the last four sprints (7.3mmol/L vs. 3.4mmol/L) infers that the relative contribution from fast glycolysis is declining in the latter part of the test compared to the beginning. Other studies using cycle ergometers with similar protocols to the 10 maximal 6-second cycle sprints with 30 seconds of recovery used by Gaitanos et al. (1993) have reported lower BLa levels after 10 sprints. Using the same protocol as Gaitanos et al., (1993), Balsom and colleagues (1994) reported BLa of 8.5mmol/L after 10 sprints. Glaister and colleagues (2007) reported BLa levels of roughly 9.5mmol/L after ten 5-second sprints with 30 seconds of recovery. Overall, it appears that BLa levels increase with additional sprints, but the rate of increase slows in later sprints.

The differences in BLa values after similar test protocols highlight the sensitivity of when BLa values are measured post-test. Glaister et al. (2007) measured BLa immediately post-test, Balsom et al. (1994) measured BLa 3-minutes post-test, and Gaitanos et al. (1993) measured BLa 5-minutes post-test. The variance in post-test timings of BLa sampling could account for the differences seen. At the cessation of exercise, there is a delayed response in diffusion of lactate from the muscle to the blood. Therefore, researchers typically take BLa measurements anywhere between 1-7 minutes post-exercise in order to determine the peak BLa reached due to the test (Balsom et al., 1994; Fitzsimmons, Dawson, Ward, & Wilkinson, 1993; Gaitanos et al., 1993; Glaister et al., 2007; Hamilton et al., 1991; Holmyard et al., 1988). An ideal time to measure BLa has not been determined as there are inconsistent results with different protocols. Comparing studies using the same protocol, Hamilton and colleagues (1991) reported 3-

minutes post-test provided the highest BLA levels, whereas Gaitanos and colleagues (1993) reported 5-minutes post-test to have the highest BLA levels.

Since lactate and  $H^+$  are co-transported out of the muscle, it seems logical that decreases in blood pH have been found to be modestly correlated ( $r = .69$ ) with increased BLA levels (Hamilton et al., 1991). Resting blood pH levels have a narrow range around 7.36 to 7.41 (Bishop & Spencer, 2004; Gaitanos et al., 1993; Hamilton et al., 1991), and are only minimally changed (-0.02 units) after a single 6-second maximal effort sprint (Gaitanos et al., 1993). As with BLA, when sprints are repeated, blood pH also continues to decrease; more rapidly during the first five sprints (0.19 units) than in the final five sprints (0.08 units) (Gaitanos et al., 1993). The drop in pH for the first five sprints is similar to the results of Bishop and Spencer (2004) who reported pH decreased 0.21 units in team athletes and 0.13 units in endurance athletes. This is in line with the comparisons of BLA from Gaitanos et al. (1993) and Bishop and Spencer (2004). The total pH change of 0.27 units after 10 sprints found by Gaitanos et al. (1993) is in agreement with reports by Hamilton and colleagues (1991) indicating pH declined 0.31 units and 0.28 units in game players and endurance-trained athletes, respectively.

### **Heart Rate**

In terms of repeated sprints, few researchers have measured and reported trends in heart rate (HR). Of the limited research, there have been two trends that have been found with training status not being a factor. First, there is a progressive increase in HR during each successive sprint throughout the entirety of ten 6-second maximal sprints with 30 seconds of recovery (Balsom et al., 1994; Hamilton et al., 1991). Conversely, the other trend demonstrates that, with the same protocol, peak HR values are reached half way

through the test and are then maintained for the remainder of the sprints (Holmyard et al., 1988). Regardless of the trend seen, peak HR values have been reported between 170-188 bpm, with cycling (Balsom et al., 1994) producing lower HR values than running (Hamilton et al., 1991; Holmyard et al., 1988). The average age of all participants from these three studies was roughly 23 years old. Estimating their maximum HRs using the equation  $208 - (0.7 * \text{age})$  developed by Tanaka and colleagues (2001), that means on average, individuals will likely reach at least 89% of their maximum HR at some point during ten 6-second maximal repeated sprints with only 30 seconds of recovery.

Holmyard and colleagues (1988) also measured HR with a protocol that allowed 60 seconds of recovery between sprints. Although not statistically different, peak heart rates during the 60-second protocol tended to be lower than during the 30-second recovery protocol (180bpm vs. 188bpm, respectively). In addition, Billaut and Smith (2010) found that HR increased rapidly after the first sprint and plateaued between sprints 5 and 8.

Interestingly, HR remained fairly constant for the remainder of the twenty 5-second cycle sprints and maximum HR was never reached (peak HR = 176.4 bpm). More studies on repeated sprints need to be conducted with HR being measured to support or reject the two trends seen and determine why there is a difference in trends when training status is not a determining factor.

### **Ventilation & Breathing Rate**

As with HR, there is limited research on ventilation during repeated sprints and no studies were found reporting breathing rate as a variable. Hamilton and colleagues (1991) conducted ten 6-second maximal running sprints with 30 seconds of recovery with games players and endurance-trained athletes. They found that ventilation increased rapidly at

the onset of the test, with endurance-trained athletes peaking at sprint five (99.5 L/min) and games players at sprint seven (105 L/min). These values were near the individuals' maximum ventilation values measured during a  $VO_{2max}$  test (ET: 107 L/min; GP: 117 L/min). In addition, Balsom and colleagues (1994) had physical education students perform ten 6-second maximal sprints on a cycle ergometer and reported peak ventilation values during the repeated sprint test of ~110 L/min. However, maximal ventilation values (i.e. highest ventilation achieved during a  $VO_{2max}$  test) in this study were not reported.

A possible explanation as to why the endurance athletes had the lowest ventilation of all subjects may be linked to the energy systems utilized. An increased ventilatory response is a product of an increased stimulation of peripheral chemoreceptors (Wasserman, 1976). Chemoreceptors are sensitive to changes in  $[H^+]$  in the blood (Jeyaranjan, Goode, Beamish, & Duffin, 1987). One of the products of the lactic system is  $H^+$ . Therefore, if an endurance athlete utilizes the lactic system to a lesser degree than a team sport athlete in resynthesis of ATP, there is a smaller increase in  $[H^+]$ . In turn, this does not cause an increased stimulation of the chemoreceptors and thus a lessened ventilatory response is produced.

### **Section III – Anaerobic Performance Tests**

#### **The Reasoning Behind These Tests**

Anaerobic performance field tests are utilized as a way of estimating an individual's power and capacity of the anaerobic energy systems in a non-invasive way. In turn, these tests are used as predictors or measures of success in anaerobic activities. These types of tests have work periods that usually last anywhere between 1-30 seconds

to focus on anaerobic metabolism and contributions (Inbar, Bar-Or, & Sinner, 1996; Margaria, Aghemo, & Rovelli, 1966; Hachana, Attia, Nassib, Shepard, & Chelly, 2012).

### **Variables Measured**

Each individual anaerobic performance test has specific variables that can be measured based on the equipment and mode utilized, but three main variables of interest in anaerobic tests include: peak power (PP), mean power (MP), and fatigue index. Based on the test and researchers, different verbiage is used to indicate these variables. For example, Tharp and colleagues (1985) refer to peak and mean power as anaerobic power and anaerobic capacity, whereas Kaczkowski and colleagues (1982) use the verbiage maximal anaerobic power and total “work”. Regardless of the terms used, these variables are measured in similar fashion.

Peak power is recognized as the highest mechanical power produced by the muscles in a short period of time (Inbar et al., 1996). This commonly occurs within the first 5-10 seconds (Inbar et al., 1996; Tharp et al., 1985; Zemková & Hamar, 2004), yet researchers have also calculated it by the highest average power exerted over any 2.5-5-second period throughout the test (Falk et al., 1996; Kaczkowski et al., 1982). In the past it was believed that “anaerobic power” was a reflection solely of the alactic component of anaerobic performance (Tharp, Johnson, & Thorland, 1984), yet this has appeared to be challenged over the years (Inbar et al., 1996). Hultman & Sjöholm (1983) electrically stimulated the quadriceps femoris of healthy men and women and reported increases in muscle lactate within 5 seconds of electrical stimulation, suggesting that the alactic system rarely works alone.

Mean power is defined as the ability of the muscles to sustain mechanical power over a period of time (Inbar et al., 1996). For most anaerobic capacity tests, that time period ranges between 20-30 seconds (Inbar et al., 1996; Falk et al., 1996; McLain, Wright, Camic, Kovacs, Hegge, & Brice, 2015). The MP value is calculated as the average of all power values within that time period (Inbar et al., 1996). Researchers using the verbiage “anaerobic capacity” for this variable believed this related to both the lactic and alactic components combined during anaerobic performance (Tharp et al., 1984). Tharp et al. (1984), along with most other researchers, dismissed any aerobic contribution as being minimal and therefore nonsignificant (Inbar, Dotan, & Bar-Or, 1976). Later studies estimated that for a 30-second all-out effort, 16% of the energy is produced by the aerobic energy system (Smith & Hill, 1991). In performance tests that include multiple sprints, another way to quantify MP of the test as a whole is through the total power value. Total power of a test is the sum of each individual sprint’s MP or PP (Fitzsimmons et al., 1993).

Lastly, fatigue during the test is typically represented as a percentage relative to the highest PO. There is a multitude of ways one can calculate fatigue depending on the nature of the test involved. Fatigue index, simply defined as how much does PO decline from early in the test to late in the test, is typically used for single, continuous sprint effort tests (Esbjörnsson, Sylvén, Holm, & Jansson, 1993; Inbar et al., 1996). The most common way to determine fatigue index for a single sprint test is:

Fatigue index (%) = [(Peak Power Value – Lowest Power Value)/Peak Power Value] \* 100.

Power or performance decrement, defined as the degree to which PO is diminished over the entire test, is typically used in repeated effort tests. Glaister and colleagues (2004; 2008) performed two separate studies analyzing and comparing different fatigue calculations for repeated sprint tests to determine the best and most reliable formula. Both studies revealed the power decrement formula.

Fatigue (power decrement-%) =  $[100 * (\text{Total Power}/\text{Ideal Power})] - 100$

was the most reliable for determining fatigue over a repeated sprint anaerobic performance test. Total power is the same variable as described above (Fitzsimmons et al., 1993) and calculated previously. Ideal power is calculated by taking the highest PP or MP and multiplying it by the number of sprints performed. It should be noted that although performance decrement is reliable, multiple studies have shown total power (or time in the case of field tests) to have better reliability than that shown by performance decrement (Austin, Gabbett, & Jenkins, 2013; Fitzsimmons et al., 1993; Johnston & Gabbett, 2011; Wright, Isaacson, Malecek, & Steffen, 2015).

### **Common Variations of Anaerobic Performance Tests**

#### **Margarita Step Test**

In the 1960's, Margarita and his colleagues (1966) developed the Margarita step test, a very short duration test (less than 2 seconds) to measure anaerobic power and stress the alactic energy system. For this test, subjects are prompted to run up nine steps, usually two to three steps at a time (stepping on the third, sixth and ninth steps), attempting to go up the steps as fast as possible. The time to get from the third step to the ninth step is recorded, starting when the foot was first in contact with the third step, and stopped when the foot contacts the ninth step. To determine maximum power, body

mass, time to nearest 0.01 seconds, and vertical distance between steps three and nine are variables collected [ $\text{Power} = (\text{mass} \times \text{vertical distance}) \times 9.8 / \text{time}$ ]. The test has been modified to typically include a 6-meter run up (Kalamian, 1968). In terms of determining the anaerobic power of the lower body, this test is still commonly used because of its simplicity, low cost, and accessibility. This test is comparable to very brief anaerobic field tests such as vertical jumps and very short sprints.

Recently, Hetzler and colleagues (2010) developed a modified version of the Margaria step test specific to football players because it has been reported that football players complete the original version too quickly that it becomes less accurate. The main adjustment included increasing the distance to 20 steps (~3.12m vertical distance). Due to the greater vertical distance, it took an average 2 seconds to complete, making it significantly longer than the original version. In comparison, football players can complete the original version in as little as 0.4 seconds (Seiler et al., 1990). It should be noted that when compared to the original Margaria step test, power values appeared to be lower (1544 W vs. 2256 W) (Hetzler et al., 2010; Seiler et al., 1990).

### **Wingate Anaerobic Test**

As seen, the Margaria step test only measures one variable of an individual's anaerobic performance. More tests were developed over the years to encompass anaerobic performance as a whole and therefore, were longer in duration. These tests were usually performed on a cycle or treadmill in some fashion as to measure total PO (mean power) or time to exhaustion (Inbar et al., 1996). Of these tests, the Wingate Anaerobic Test (WAnT) has been the most popular and widely utilized anaerobic performance test (Inbar et al., 1996). The WAnT involves an individual on a cycle

ergometer pedaling against a set load (originally suggested as 0.075kp/kg body mass, but has shown variability over the years) in a maximum “all out” effort for 30 seconds (Inbar et al., 1996). In doing so, the WAnT encompasses measures of PP, MP, and fatigue index. Part of what makes the WAnT one of the most widely accepted methods for testing anaerobic performance is that it has been shown to be highly reliable in terms of PP ( $r = 0.91-0.93$ ) and MP ( $r = 0.93$ ) and moderately reliable in terms of fatigue index ( $r = 0.43 - 0.74$ ) (Patton, Murphy, & Frederick, 1985)

There have been a multitude of studies that have attempted to find a shorter alternative to the WAnT to correct the negatives of the test. First, there is a high incidence of individuals experiencing undesirable side effects, such as headaches, dizziness, and vomiting, from the duration and intensity of the WAnT (Hachana et al., 2012). Second, during a 30-second maximum sprint, there is a contribution from aerobic metabolism that some feel do not make the WAnT a truly anaerobic test (Attia et al., 2014). Hachana and colleagues (2012) found that a 15-second version of the WAnT showed reliability and validity of PP (ICC = .989) and MP (ICC = .993,  $R^2 = .925$ ), but not fatigue index (ICC = .854,  $R^2 = .330$ ) when compared to the traditional 30-second version. More recently, Attia and colleagues (2014) also found that a 20-second version of the WAnT showed reliability and the ability to accurately predict PP (ICC = .98,  $R^2 = .71$ ) and MP (ICC = .98,  $R^2 = .98$ ), but not fatigue index (ICC = .53,  $R^2 = .41$ ) values of the traditional 30-second version. Neither of the studies of shorter duration (Attia et al., 2014; Hachana et al., 2012) reported any undesirable incidences as a result of the test.

### **Single Sprint Running Tests**

Although the WAnT is still the most popular method of anaerobic performance testing regardless of the training status or sport played by the individual, there is a major drawback in that it utilizes a cycle ergometer. Most sports do not involve cycling, raising the question of how well this test transfers to actual performance. Tharp and colleagues (1985) found the WAnT to only be a moderate predictor of success in the 50- and 600-yard runs ( $r = -.53$  and  $-.29$ ) for 10-15 year old male track athletes. A more sport-specific test for most field and court athletes would involve running, and therefore that has been the focus of many researchers recently. There is evidence to show that sprint running tests provide higher and more accurate results for runners when compared to the WAnT or cycling tests (Falk et al., 1996; Mangine et al., 2014).

A common method of testing utilized by researchers involves maximum tethered running. Tethered running can be defined as a subject being fastened to a fixed object behind them (such as a wall) by a belt around their waist as they sprint (Zemková & Hamar, 2004). An early attempt at developing a running specific test using this method that could also measure PO was done by Falk and colleagues (1996). They devised a 20-sec maximum effort tethered running test using a specific type of motorized treadmill (Gymrol model BRL 1800, France), developed from a non-motorized treadmill (NMT) model. The subject powers the treadmill belt through running, but there is a constant-torque motor that reduces friction that ultimately does not give true subject controlled power output values. Their subjects included young athletes from a variety of sports. They found that the power outputs from their treadmill test were higher than those of

cycle ergometer test results from other studies. A major disadvantage to this test, though, was the treadmill itself that they used. It is a unique treadmill that has limited availability.

Tethered running is more commonly performed on a NMT. A NMT is a treadmill that does not have a motor driving the belt speed. Therefore, the treadmill belt is powered solely by the force of the individual. Studies have been conducted on a variety of populations, including untrained adults, active adults, and athletes, and have found maximal sprinting tests of varying durations to be reliable on this ergometer (Hughes, Doherty, Tong, Reilly, & Cable, 2006; Lim & Chia, 2007; McLain et al., 2015).

Zemková & Hamar (2004) had participants perform an “all-out” maximal tethered sprint on a treadmill (non-specified) for 30 seconds at 13km/hr to determine maximum power, MP, and fatigue index. Participants also performed an “all-out” 30-second sprint on an isokinetic cycle ergometer at a revolution rate of 100 rpm. When comparing the treadmill sprint protocol to the cycle ergometer version, they did not see any significant differences in PP or MP, but saw significantly higher fatigue indexes (31% vs 27%) and BLa concentrations (12.5 vs 10.6 mmol/L) after the treadmill sprint protocol. This may be a result of a larger muscle mass being utilized when running. Cycling is limited to the power of the leg muscles, whereas running includes total body movement, in turn leading to more muscles working and producing by-products that could potentially be causing the increased fatigue observed.

Most recently McLain and colleagues (2015) developed an anaerobic sprint running test (ASRT) on the Woodway Force 2.0 (Woodway, Waukesha, WI) NMT as a more sport-specific alternative to the traditional WAnT. The ASRT is 25 seconds in duration and involves the subject running all-out against a load equal to 18% of their

body mass by means of a belt harnessed against their waist. The advantage of this test is that this NMT has a motor that acts as a brake to allow for subjects to run against a load, leading to greater possible PO. In addition, the PO comes solely from the individual's ability to power the belt without the help of a motor controlling the speed. The ASRT was demonstrated to be reliable for PP (ICC = 0.96, CV = 7%), MP (ICC = 0.97, CV = 6%), and fatigue index (ICC = 0.83, CV = 6%).

Not all sprint-running tests on NMTs are tethered. Multiple studies have utilized the Woodway Curve 3.0 NMT (TM; Woodway, Inc., Waukesha, WI, USA) to conduct a 30-second maximal sprint test that did not involve being harnessed to the back of the treadmill by a waist belt (Gonzalez et al., 2013; Mangine et al., 2014). It has been shown to be reliable for PP and MP (ICC = 0.887 and 0.940) as well as significantly correlated to WAnT results ( $r^2 = 0.56$  and  $0.71$ ) (Gonzalez et al., 2013). Mangine and colleagues (2014) found that this method of testing could also predict 30-m run times on a flat or track surface. However, the limitation of this type of treadmill is that no additional load can be applied to allow for greater power production, resulting in the power derived from this treadmill during sprint tests to be limited to how fast a subject can run.

### **Repeated Sprint Tests**

As described above, many anaerobic performance tests involve just one maximum effort sprint (of varying durations, but typically around 20-30 seconds) in order to determine PP, MP, and fatigue index. Due to the nature of most field and court sports, tests of repeated effort have become more abundant. Repeated sprint ability (RSA) is the ability to recover and maintain maximal work in subsequent sprints (Turner & Stewart, 2013.). Starting as early as 1969, Margaria and colleagues (1969) utilized test protocols

that consisted of multiple sprints of the same duration (10 seconds) interspersed with a constant recovery time (either 10, 20, or 30 seconds).

Since that time, there have been a wide variety of different protocols used as a way of measuring an individual's RSA. The most commonly seen protocol in laboratory studies consists of ten 6-second maximal sprints, interspersed with 30 seconds of recovery (Balsom et al., 1994; Gaitanos, Nevill, Brooks, & Williams, 1991; Gaitanos et al., 1993; Hamilton et al., 1991; Holmyard et al., 1988). This protocol has been utilized with a cycle ergometer as well as on a NMT. Although this protocol has been used countless times to test the effects of different conditions, such as hypoxia and creatine supplementation (Balsom et al., 1994; Gaitanos et al., 1991), the reliability of the protocol on either ergometer remains unclear. The closest reliability of the protocol found was in a study by Hughes and colleagues (2006). They reported that mean maximum speed and average force values were reliable (CV = 2.75%, CV = 3.86%, respectively) during six 6-second maximal sprints on a NMT with 30 seconds of recovery, while performance decrements of the maximum speed and average force (CV = 31.5%, CV = 30.1%, respectively) were less reliable. Consequently, without known reliability, it may be argued that after 10 sprints, changes seen in performance may be due to the test itself and not any intervening treatment.

There have been studies that have taken the 10 x 6 sec sprint protocol and shortened the number of repetitions and/or shortened the recovery duration. Fitzsimmons and colleagues (1993) found that a test characterized by six 6-second maximal sprints on the cycle ergometer with 24 seconds of recovery proved to be reliable for total work ( $r = 0.97$ ; TEM% = 1.7) and percent decrement ( $r = 0.88$ ; TEM% = 14.0) in amateur male

team sport players. Later, Bishop and colleagues (2001) tested a similar protocol (5 x 6sec cycle sprints, 24sec of recovery) for its validity to field hockey game simulated situations with moderately trained males. Interestingly, they found that this specific RSA test protocol was better for assessing decrement in 15m sprint times ( $r = 0.76$ ), but not decrements in 10m ( $r = 0.54$ ) or 5m ( $r = 0.42$ ) sprint times. It was concluded that when testing RSA, the protocol selected should be closely related to the actual distance or time period typically covered in match situations for the best results. Lastly, Bishop and Spencer (2004) shortened the popular 10 x 6 sec protocol to only five 6-second maximal cycle sprints, maintaining the 30-second recovery. Again, however, reliability was not measured or mentioned.

As laboratory tests are not always accessible and practical to athletes, field tests have also been developed for the purpose of testing field sport athletes specifically. Fitzsimmons and colleagues (1993) tested the reliability of a 6 x 40m sprint running test on a track with 24 seconds of recovery in hopes of finding a more sport-specific modality. A photoelectric cell timing system was utilized to measure the time it took to complete each 40m sprint. They found that it was reliable for total work ( $r = 0.94$ ; TEM% = 0.8) and percent decrement ( $r = 0.75$ ; TEM% = 18.5) in amateur male team sport players.

The Welsh Rugby Union developed a 5m multiple shuttle test as a way to assess their athlete's RSA (Pendleton, 1997). This test is characterized by 30 seconds of work with 35 seconds of recovery between repetitions. There are 6 cones set up in a straight line with 5 meters between them. During the 30 seconds, the subject sprints 5 meters from the first cone to the second cone, touches the ground adjacent to the cone with their

foot, and then sprints back to the first cone. The subject then sprints 10 meters to the third cone, touches it with their foot, and then sprints back to the start. This continues until 30 seconds has lapsed and the total distance covered is recorded. One test session involves completing this process six times. The test was determined to be reliable ( $r = 0.89$ ) for rugby players (Pendleton, 1997). Boddington and colleagues (2001) modified the test for field hockey players by instructing the players to touch the ground adjacent to the cones with their hand instead of their foot. Even with the slight modification, the test was still deemed reliable, with total and peak distances covered ( $r = 0.98$ ,  $r = 0.86$ ) being more reliable than delta distance (i.e. the difference between the longest and shortest distance covered) ( $r = 0.74$ ) and fatigue index ( $r = 0.74$ ).

Possibly one of the most recognized tests of recent years, the running anaerobic sprint test (RAST), was developed to provide a specific modality for field athletes (Zacharogiannis, Paradisis, & Tziortizis, 2004). Researchers at Wolverhampton University developed the RAST, which is characterized by six 35m maximal sprints on a track with 10 seconds of recovery. The reliability of the RAST has been found to be high in all variables (ICC = 0.90-0.97) except fatigue index and peak BLa, where correlations were only moderate (ICC = 0.70, ICC = 0.65, respectively) (Zagatto, Beck, & Gobatto, 2009). The RAST has also been verified against the WAnT multiple times and significant correlations (PP:  $r = 0.46 - 0.82$ ; MP:  $r = 0.53 - 0.75$ ) were found defending the RAST's validity in assessing anaerobic performance (Zacharogiannis et al., 2004; Zagatto et al., 2009). In addition, Zagatto and colleagues (2009) determined the RAST to be a good predictor of actual running performances as it was highly correlated (PP:  $r = 0.46 - 0.99$ ; MP:  $r = 0.64 - 0.86$ ) with 25, 50, 100, 200, and 400m sprint performances.

Finally, when comparing RSA tests to one another, specificity to the sport tested tends to provide better results. Fitzsimmons and colleagues (1993) compared the results of a cycle version (6 x 6sec sprints, 24sec of recovery) and a track version (6 x 40m sprints, 24sec of recovery) of a RSA protocol to see if the two tests were correlated for field sport athletes. They found that the best individual sprint scores (best 6s work vs. 40m time) of each method were not significantly correlated, regardless if they were expressed relative to body weight ( $r = -0.29$ ) or not ( $r = -0.21$ ). In addition, only moderate correlations were seen between the relative RSA scores (percent decrement) ( $r = 0.622$ ) and the best total test scores (total work vs. total time) when expressed relative to body weight ( $r = -0.684$ ). In all, it appears there are significant differences in performance measurements in running and cycling RSA tests with similar protocols, implicating running tests are more appropriate for field sports than cycle tests.

Lastly, Numella and colleagues (2007) developed a track version of their previous treadmill test, termed the maximal anaerobic running test (MART), in order to determine if the treadmill or setting of the test would affect the results. The original version involved 20 second maximal sprints on a treadmill at a set speed and 4° incline with 100 seconds of recovery (Nummela, Alberts, Rijntjes, Luhtanen, & Rusko, 1996). With each sprint the speed increased 1.37km/hr until the subject was no longer able to continue. The sole fact that the MART ends with volitional exhaustion with no set number of sprint repetitions makes it different than the other repeated sprint tests developed. The track version, however, replaced the 20-second sprints with 150m sprints and only 10 sprints were performed. In addition, the velocities used in each stage of the treadmill version were maintained in the first 9 sprints of the track version with the help of a “light rabbit”

that set the pace for the runners to follow. The last sprint was maximal effort. For both tests three countermovement jumps (CMJ) were performed pre and post as a measure of PP and power decrement. The treadmill version was found to be highly reliable for PP ( $r = 0.92$ ) and CMJ ( $r = 0.96$ ), but its validity matched against the WAnT was low to moderate ( $r = 0.43-0.59$ ). Researchers attributed this to the difference in the nature of the tests (i.e. submaximal vs. maximal, interval vs. one effort, 15min vs. 30sec) (Numella et al., 1996). When compared to one another (i.e. track vs. treadmill), there were strong correlations between the two in maximal velocity ( $r = 0.96$ ) and peak CMJ ( $r = 0.98$ ) and only a moderate correlation in decrement in CMJ ( $r = 0.58$ ) (Numella et al., 2007). In addition, maximal velocity in the treadmill and track versions was found to correlate with actual race performance in sprinters and runners making the MART a valid test as well. These results suggest that it does not matter if the test is conducted on a treadmill or a track in order to assess anaerobic performance.

In the end, there are a wide variety of tests because there is a wide variety in the nature of sports. For this reason, it is important to utilize a test of RSA that is applicable and relates to the work-to-rest ratios of the sport of interest.

### **Typical Outcomes Specific to Athletes**

As the WAnT is the most extensively reported anaerobic performance test, it has the most data available. In regards to age, PP and MP (both relative and absolute) from the WAnT are lower at younger ages and appear to increase to a maximum as one ages to around 30 years before declining again. It is thought that this trend is related to differing biochemical characteristics, mainly lower PCr and glycogen concentrations in muscle between children and adults (Inbar et al., 1996). At all ages, women have been shown to

consistently have lower anaerobic performance (both in relative and absolute terms) when compared to their male counterparts, regardless of the test used (Esbjörnsson et al., 1993; Falk et al., 1996; Froese and Houston, 1987; Inbar et al., 1996; Tharp et al., 1984). Consistent with what one would predict, physically active individuals perform better than their untrained counterparts. The WAnT and other tests have also shown their ability to differentiate between specific training practices of athletes (Tharp et al., 1984; Nummela et al., 2007). During a WAnT, anaerobically trained athletes will tend to have higher initial POs (i.e. peak power), but are unable to maintain high PO, indicated by a high fatigue index. In contrast, aerobically trained athletes tend to have a lower PP compared to their anaerobic counterparts, yet they have the ability to maintain the power for longer (i.e. lower fatigue index) (Inbar et al., 1996).

Multiple studies on repeated sprint tests show a similar trend (Bishop & Spencer, 2004; Hamilton et al., 1991). Hamilton and colleagues (1991) found that during a repeated sprint protocol on a NMT, game players (individuals who regularly participated in multiple sprint-type sports) were able to produce a greater PP output, MP output, peak running speed, and mean running speed compared to endurance athletes (individuals who ran more than 20 miles per week). However, a greater drop-off in sprint performance in terms of MP output, peak running speed, and mean running speed was observed in the game players compared to the endurance athletes. Simply, the game players were able to produce greater power and speed (maximum performance) early in the sprint protocol, but the endurance athletes were able to better maintain power and speed throughout the sprints. Furthermore, there is typically a strong relationship ( $r = 0.80-0.89$ ) between initial performance (i.e. peak power in first sprint) and fatigue variables (both fatigue

index and power decrement); the higher the PP, the more likely the fatigue index or power decrement will be greater (Bishop et al., 2003; Hamilton et al., 1991; Mendez-Villanueva, Hamer, & Bishop, 2008).

When comparing tests of different modalities, slight variations will typically be seen in power and metabolite variables measured. For measures of power, treadmill tests (Falk et al., 1996; McLain et al., 2015) have generally shown to produce higher PP and MP outputs overall compared to cycle ergometer tests (Hoffman et al., 2005). However, it appears more common to see higher fatigue values in cycling tests compared to running tests (Fitzsimmons et al., 1993; Gaitanos et al., 1993; Hamilton et al., 1991; Holmyard et al., 1988), although the reverse has been seen as well (Zemková & Hamar, 2004). A possible explanation is that cycling focuses on the power generated solely in the leg muscles. Consequently, any fatigue experienced by the muscles is localized in the legs, making it more difficult to maintain POs. BLa values are commonly higher after a running RSA test versus a cycle RSA test (Bishop & Spencer, 2004; Fitzsimmons et al., 1993; Hamilton et al., 1991; Holmyard et al., 1988). Although BLa values are often associated with higher fatigue, BLa levels are also associated with higher POs (Hamilton et al., 1991). Therefore, the disassociation between BLa and fatigue in cycling versus running RSA tests may be explained by the fiber type and amount of muscle mass involved. Running is a full-body exercise and is able to generate higher POs by recruiting more total fast twitch fibers. Fast twitch fibers produce more lactate than slow twitch fibers (Essén & Häggmark, 1975). Therefore, more by-products (i.e. lactate and  $H^+$ ) are formed. This may be why field sport athletes, who tend to have a larger amount of fast twitch fibers, typically produce higher BLa values by about 2mmol/L compared to their

endurance-trained counterparts, regardless of modality (i.e. cycle versus NMT) (Bishop & Spencer, 2004; Hamilton et al., 1991). While the absolute amount of by-products may be higher in running because of the type and total number of muscles producing it, the relative concentration in the muscles during cycling may be higher leading to greater fatigue induced side effects. Finally, the more sport-specific the test, the better the performance will be for that athlete (Fitzsimmons et al., 1993). Zemková and Hamar (2004) referenced how track sprinters performed significantly better on tethered running on the treadmill compared to the cycle ergometer and vice versa for cyclists.

#### **Section IV – Fatigue**

##### **Definitions**

Fatigue during physical performance is most often defined as the inability to maintain a given intensity, workload, or pace (Edwards, 1981; Brooks et al., 2000). Due to its broad definition, there are a variety of ways to identify fatigue, dependent on the test involved. In terms of anaerobic performance tests, it depends on the style of test (i.e. single effort versus multiple effort). In single effort tests, such as the WAnT, fatigue index is often used. It is simply determining how much power output declines from early in the test to the end of the test, which makes calculating the fatigue index quite simple.

Repeated sprint tests, on the other hand, include a multitude of ways to calculate power decrement over the entire test. Glaister and colleagues (2004) recognized this issue and sought to compare four (and then subsequently eight [Glaister et al., 2008]) commonly used fatigue formulas and determine which formula is the most reliable and valid for measuring fatigue during a short-recovery and long-recovery repeated sprint test. They determined in both studies that the percentage decrement score was the most

reliable and valid formula of the ones tested for both cycling (ICC = 0.81 and 0.83) and running (ICC = 0.55 and 0.41; CV = 31.7% and 37.4%). While some protocols (mainly track versions) use sprint time as the primary measurement because the sprints are determined by a set distance, other tests using varying types of cycle and running ergometers use PO as the primary measurement because the sprints are determined by a set time. Consequently, PO values can replace sprint times in the formula when needed (Glaister et al., 2004).

### **Causes**

The sources of fatigue are still uncertain. It is commonly accepted that a lack of ATP, inhibition of crossbridge cycling, and alterations in the excitation-contraction coupling process directly affect muscle contraction (Brooks et al., 2000; Girard, Mendez-Villanueva, & Bishop, 2011; Glaister, 2005). What, in turn, is causing these problems is where the debate still occurs. There are arguments for metabolic, neurological, and psychological disturbances affecting muscle contraction. The problem lies in determining which of these theories is truly a cause and what is merely a coinciding consequence.

#### **Metabolic**

The most commonly recognized source of fatigue is the inability to resynthesize ATP as fast as it is being utilized (Glaister, 2005). ATP is the energy substrate that allows muscle contraction to occur. An inability to maintain ATP during exercise, therefore, does not allow the muscle to maintain a rate of contraction achieved at the onset of performance. The causes of ATP depletion are where the questions still lie.

The first place to examine is the three energy systems responsible for generating ATP. Depletion in any of the energy substrates for high intensity exercise (i.e. PCr,

glycogen, blood glucose) used in these systems will in turn cause a reduction in the amount of ATP that can be produced by the energy system that uses the depleted substrate. In terms of repeated-sprint exercise, the most accepted and supported theory is that depletion in PCr causes a decrease in power production (Bogdanis et al., 1995). This theory is reinforced by a multitude of different factors. First, the recovery of PO and the resynthesis of PCr follow a similar time-course (Bogdanis et al., 1995; Bogdanis et al., 1996). Bogdanis and colleagues (1995) had subjects perform two 30-second maximal sprints on the cycle ergometer. After 1.5 and 3 minutes of recovery from the first sprint, they discovered high correlations ( $r = 0.71-0.86$ ) between the percentage of PCr resynthesized and the values of PP output, peak pedal speed, and MP output in the first 6-seconds of the second sprint. Secondly, in connection with the similarity in time-course, decreases in PCr concentrations after multiple sprints are present with lower POs (Bogdanis et al., 1996; Gaitanos et al., 1993). In a repeated sprint test with brief recovery, PCr concentrations cannot fully resynthesize to resting levels. Gaitanos and colleagues (1993) found that just before the tenth 6-second maximal cycle sprint with 30 seconds of recovery between sprints, PCr concentration was only 49% of the resting value and dropped to 16% after the tenth sprint. This would suggest that PCr concentrations drop roughly the same extent with each sprint and therefore each sprint begins with a lower PCr concentration than the previous sprint. This leads to less absolute ATP production from the alactic system, and thus a lower PO in the latter sprints. Lastly, in studies utilizing Cr supplementation, which increases PCr stored in the muscle, there have been reports of reduced fatigue in repeated sprint tests after ingestion of Cr (Balsom, Ekholm, Söderlund, Sjödln, & Hultman, 1993; Greenhaff et al., 1993). Balsom and colleagues

(1993) discovered that after Cr supplementation, subjects were able to maintain a significantly higher PO in the last 2 seconds of each 6-second sprint starting after the 6<sup>th</sup> sprint.

Differences between muscle fiber types for PCr utilization and resynthesis rates have been observed, such that fast twitch fibers have a greater utilization of PCr than do slow twitch fibers (Greenhaff, Nevill, Söderlund, Boobis, Williams, & Hultman, 1992; Tesch, Thorsson, & Fujitsuka, 1989). Besides the highly anaerobic nature of fast twitch fibers, part of this may be explained simply by the higher resting levels of PCr in fast twitch fibers compared to slow twitch fibers (Greenhaff et al., 1992; Söderlund & Hultman, 1991; Tesch et al., 1989). Tesch and colleagues (1989) found that after 60 seconds of recovery from 30 consecutive maximal knee extensions, PCr levels in slow twitch fibers were significantly higher than in fast twitch fibers (69% vs. 48% of resting value), suggesting that the PCr resynthesis rate is greater in slow twitch fibers than in fast twitch fibers. Slow twitch fibers are more aerobically based, so this finding would appear to make sense, as PCr resynthesis is an aerobic process (Haseler et al., 1999). These differences between fiber types may help explain why some studies show higher  $VO_{2max}$  as being more beneficial to repeating sprints (Hamilton et al., 1991; Tomlin, 1998) and others show little to no benefit of a higher  $VO_{2max}$  (Aziz et al., 2000; Bishop et al., 2003; Wadley & Le Rossignol, 1998). Fast twitch fibers are utilizing more PCr during a maximal sprint, but the slow twitch fibers are resynthesizing PCr faster than fast twitch fibers, so in effect, if an individual with a high  $VO_{2max}$  has mostly slow twitch fibers, this will not necessarily help to resynthesize the majority of the PCr depleted. However, if the fast twitch fibers are trained in a way that increases their aerobic capacity, an increased

$VO_{2max}$  would then result in a greater ability to resynthesize a majority of the depleted PCr. In conclusion, the conflicting findings in the relationship between  $VO_{2max}$  and RSA may be generated by differences in the metabolic capacities of the subjects' muscle fiber types.

Although the lactic system is a large contributor in repeated sprint exercise, it is doubtful that depletion in glycogen stores would be a cause of fatigue (Glaister, 2005). Resting levels are typically around 300mmol/kg dm in untrained subjects and have been reported to only decrease to about 220mmol/kg dm after ten 6-second sprints (Gaitanos et al., 1993). This small reduction (~15%) is virtually negligible in repeated sprint exercise as there is still more than an adequate amount of glycogen left to be utilized to produce ATP through the lactic system in subsequent sprints.

Other causes of fatigue may be found in the byproducts of the energy systems. For many years, researchers blamed lactate as the cause of muscular fatigue because increased lactate accumulation after high intensity exercise is often found to correlate with increased power decrement (Myers & Ashley, 1997). However, it must be remembered that lactate and  $H^+$  are by-products that occur in parallel. Therefore, researchers shifted their view to  $H^+$  accumulation as being the true cause of fatigue, not lactate (Allen, Westerblad, & Lännergren, 1995; Brooks et al, 2000). Significant correlations ( $r = 0.75$ ) have been reported between change in blood pH and performance decrement during repeated-sprint exercise, supporting this view (Bishop et al., 2003).

Enzymes are pH sensitive and thus only work properly within a narrow pH range (Brooks et al., 2000). Therefore, when muscle pH is decreased during repeated-sprint exercise from an accumulation of  $H^+$ , it can cause inhibition of the enzymes associated

with glycolysis and PCr resynthesis (Brooks et al., 2000; Hermansen, 1981; Sahlin, Harris, & Hultman, 1975). In turn, this causes an impairment of performance by inhibiting ATP production through those energy systems. It has also been suggested that lowered muscle pH may cause disruptions with muscle contractile processes, such as the sensitivity of  $\text{Ca}^{2+}$  binding to troponin (Allen et al., 1995; Brooks et al., 2000; Fabiato & Fabiato, 1978; Nakamaru & Schwartz, 1972). However, most studies conduct testing in lab temperatures of 15°C, which is much colder than physiological temperatures of roughly 37°C. Tests conducted at 30° & 37°C discovered that lowered pH did not have as great of an effect on decreased force production as seen at laboratory temperatures (Adams, Fisher, & Meyers, 1991; Pate, Bhimani, Franks-Skiba, & Cooke, 1995).

In two separate studies, power and work decrement were found to be negatively related ( $r = -0.69$  to  $-0.72$ ) to muscle buffer capacity, suggesting that an increased ability to buffer muscle  $\text{H}^+$  ions may improve RSA by maintaining proper blood and muscle pH levels (Bishop et al. 2003; Bishop, Edge, & Goodman, 2004). Further support of the role of  $\text{H}^+$  accumulation in fatigue comes from studies that utilize sodium bicarbonate ingestion as a way of increasing the buffering of blood  $\text{H}^+$ . Repeated sprint tests that occurred after ingestion of sodium bicarbonate resulted in significantly higher MP outputs ( $p < 0.05$ ) and the differences in those MP outputs increased as the number of sprints increased (Lavender & Bird, 1989).

Recently, however, studies have provided evidence to suggest that increased muscle  $[\text{H}^+]$  does not significantly affect power decrement in repeated-sprint exercise (Westerblad, Allen, & Lannergren, 2002). There has been a lack of association found between muscle pH and power recovery both during and after exercise. Saugen and

colleagues (1997) found that during voluntary and electrically stimulated intermittent exercise, pH levels stabilized while maximum voluntary contraction (MVC) continued to drop as the exercise continued. During recovery, MVC increased towards resting levels while pH continued to drop or remained stable. Those findings suggest an imbalanced relationship between pH and PO in regards to fatigue. Therefore, although pH has been shown multiple times to have an effect on the enzymes of the energy systems and muscle buffer capacity, other factors are likely involved to account for the overall imbalanced relationship that has also been demonstrated. For example, it is often cited that the failure of  $\text{Ca}^{2+}$  release from the sarcoplasmic reticulum (SR) that occurs during fatigue is not caused by a lowered pH, again suggesting other factors are involved (Allen et al., 1995).

Researchers are now citing an accumulation of inorganic phosphate ( $\text{P}_i$ ) as a cause of fatigue in muscles (Allen, Kabbara, & Westerblad, 2002; Stackhouse, Reisman, & Binder-Macleod, 2001; Westerblad et al., 2002). To begin, it is hypothesized that  $\text{P}_i$ , not  $\text{H}^+$ , inhibits  $\text{Ca}^{2+}$  release from the SR (Glaister, 2005; Westerblad et al., 2002). Another hypothesis involves the direct inhibition of crossbridge cycling. In order for the power stroke of crossbridge cycling to continue properly during muscular contraction,  $\text{P}_i$  has to be released from the myosin head. It is believed that when there is an accumulation of  $\text{P}_i$  in the sarcoplasm, there is an inhibition of  $\text{P}_i$  releasing during a crossbridge cycle, causing a decrement in the muscle's ability to produce force (McLester, 1997). It is likely that all of the mentioned causes (i.e. lack of ATP, increased  $\text{H}^+$ , and increased  $\text{P}_i$ ) are connected in causing fatigue.

## Neurological

Another postulated cause of fatigue is deemed “central fatigue”(Brooks et al., 2000; Vollestad, 1997). This focuses on complications in the central nervous system (CNS) affecting muscular contraction. The thought is that there is a problem with the transmission of action potentials to muscles, seen in disruptions in neural drive, recruitment strategies, and/or muscle excitability. Tetanic stimulation, MVC force, twitch interpolation, and electromyography (EMG) data provide the leading evidence to support this theory (Vollestad, 1997).

The body is constantly trying to maintain a homeostasis through feedforward and feedback controls. Therefore, it is postulated that the CNS determines what needs to occur in order to maintain homeostasis of the muscles (Noakes, Gibson, & Lambert, 2005). In two separate studies, Mendez-Villanueva and colleagues (2007, 2008) determined that an inability of the CNS to increase motor unit activity is associated with the decline in PO during repeated sprints. They based this off of their findings that there was a parallel decline in PO and EMG amplitude throughout the sprints. In addition, based on the results of many studies, Girard and colleagues (2011) determined that the EMG evidence suggests this decreased neural activation is only present when considerable fatigue (FI > 10%) occurs. It is still unclear if this is due to lack of motor unit recruitment or rate coding (Mendez-Villanueva et al., 2008).

In connection with intramuscular characteristics of fatigue, a decreased excitability of a muscle may be caused by ionic imbalances (Girard et al., 2011). Increased interstitial  $K^+$  concentrations have been reported and the notion is that this is caused by the  $Na^+/K^+$  pump being unable to pump  $K^+$  back into the cell fast enough

during exercise causing an accumulation of interstitial  $K^+$  (Girard et al., 2011; Juel, Pilegaard, Nielsen, & Bangsbo, 2000). The accumulated interstitial  $K^+$  causes the membrane potential of the cell to become hyperpolarized, making it more difficult to reach threshold to excite the cell. Support for this theory comes from reports of reduced  $Na^+/K^+$ -ATPase activity with dynamic fatiguing exercise (Fraser et al., 2002). This imbalance causes decreased muscle excitability that ultimately results in decreased force development (Girard et al., 2011).

### **Psychological**

Lastly, related to central fatigue, is the assumption that individuals will voluntarily/consciously limit their performance. The reasons for doing this can include trying to save energy for the end of an event, trying to reduce any pain felt during the performance, etc.

In relation to both neurological and metabolic factors of fatigue, it is believed that the CNS can detect the changes in metabolites (such as increased  $[H^+]$ ) through activation of group III and IV nerve afferents and thus cause an increased sense of discomfort, which ultimately causes conscious decreases in PO and muscular contraction in order to maintain homeostasis (Amann & Dempsey, 2008; Noakes et al., 2005; Westerblad et al., 2002). In this way, the body is maintaining its homeostasis and inhibiting a further accumulation in  $H^+$  and other metabolites, such as ammonia produced from the myokinase reaction. This is beneficial as an excessive increase in blood ammonia can cause high levels of ammonia in the brain that can lead to brain damage in severe cases (Baker, McCormick, Robergs, 2010).

In summary, although the cause of fatigue may be unknown, what is clear is that the fatigue that occurs during exercise is most likely not caused solely by one factor, rather by a combination of factors (metabolic, neurological, psychological) all interacting with one another. Thus it is important to recognize many factors when analyzing fatigue.

## **Section V – Field Sports**

### **General**

Field sports (i.e. football, soccer, rugby, etc.) can typically be characterized by multiple, brief high intensity work bouts combined with relatively short, low to moderate intensity recovery bouts (Glaister 2005). It is this nature that has led many coaches and researchers to use RSA as a way of assessing and predicting an athlete's performance. Although all field sports can be generalized this way, there are differences among them that make each unique for RSA purposes. For example, when combining sprinting and striding, soccer has a mean sprint time of 3.7-4.4 seconds and on average 40-56 seconds between bouts, whereas Australian Rules football has a mean sprint time of 2.7 seconds and on average 73 seconds between bouts (Mayhew & Wenger, 1985; McKenna, Patrick, Sandstorm, & Chennells, 1988; Withers, Maricic, Wasilewski, & Kelly, 1982). In addition, soccer, field hockey, and rugby matches have a wide variation in the frequency of sprinting (20-60 bouts per game) and the total distance sprinted (700-1000m) (Spencer, Bishop, Dawson, & Goodman, 2005). For this reason, each sport should have an individual RSA test specifically for testing athletes of said sport.

### **American Football Specific**

For the purpose of this review, American football will be focused on specifically. American football is characterized by brief, high intensity work during the plays and

short rest bouts between plays. Rhea and colleagues (2006) analyzed high school, college, and National Football League (NFL) games and discovered some differences between the three. An average duration of a play (combining both run and pass plays) was longer in high school (5.64s) compared to college (5.55s) and the NFL (5.52s). When breaking it down between run plays and pass plays, however, pass plays were constantly longer than run plays regardless of the level. Iosia & Bishop (2008) suggest that more time is needed for routes to fully develop on pass plays and can therefore account for the longer play duration. Special teams plays had the longest average durations (8.45-10.11s) for all levels. With the average play being between 5-6 seconds, it has been suggested that the alactic system is the predominant source of ATP (~90%) during an American football game (Hoffman, 2008). However, it has also been shown that BLa levels are increased to three to five times resting values during intrasquad and All-Star football games (Smith & Jackson, 1991; Zapiec & Taylor, 1979), providing evidence for greater contributions from the lactic system.

The other important aspect to consider is the average duration of recovery between plays. This aspect of the game has shown some changes throughout the years. Prior to 2008, the play clock from college football was 25-seconds and started on the referee's signal once the ball was placed. During this time, average duration of recovery between plays was anywhere from 33.98 to 38.08 seconds (Iosia & Bishop, 2008; Rhea et al., 2006). After 2008, the play clock was altered to mimic the NFL with a 25/40-second system. Simply, the play clock starts as soon as the play is blown dead and allows 40-seconds until the next play must be run. If the game clock is stopped for any number of reasons, then the play clock will start at 25-seconds once the ball is placed. (Redding,

2015). This change was accompanied by a decline in average recovery time between plays. The average recovery time between plays for 128 DI college football teams in 2014 was between 18-30 seconds (Berkes, 2015). Due to the decrease in recovery duration, football players are now receiving less time to resynthesize PCr and remove H<sup>+</sup> before the next play. A study by Hoffman and colleagues (2002) monitored performance throughout a competitive game and found a significant decrease in force and power in the first quarter that continued into a plateau at halftime. Researchers have stressed the importance of training the aerobic energy system for football players (Gleim, Witman, & Nicholas, 1981; Pincivero & Bompa, 1997). This could suggest an increased utilization of the aerobic energy system in resynthesizing PCr between plays that ultimately can help to lessen performance decrements throughout multiple-play drives and the game itself. Support of this notion comes from McGawley and Bishop (2015) who had professional women soccer players perform five 6-second maximal sprints with 24 seconds of low-intensity, active recovery. They showed that VO<sub>2</sub> is increased substantially from the first sprint (1.08 ± 0.26 L/min) to the fifth sprint (2.86 ± 0.77 L/min) and reached 93 ± 17 % of their VO<sub>2max</sub> in that fifth sprint. The average number of plays per “drive” in college has been observed to be 6.26 ± 2.74 plays (Rhea et al., 2006). Based on laboratory repeated sprint tests, this would suggest performance could decrease by 10-17% by the end of a drive (Holmyard et al., 1988).

Differences in player positions may also have an effect on the recovery type and length achieved during games. Linemen run shorter distances and are many times active for shorter durations of a play than skill players and also probably do not reach maximum speed when doing so. In addition, Rhea and colleagues (2006) observed that linemen

usually walk short distances back to the line of scrimmage (fairly passive recovery), whereas receivers and defensive backs typically jog back longer distances to the line of scrimmage for the next play (active recovery). There are conflicting findings in terms of active versus passive recovery and its role in maintaining performance for subsequent work bouts. Spencer and colleagues (2006) compared active and passive recovery on repeated sprint performance (six 4-sec cycle sprints, 21s recovery) and found that active recovery significantly lowered final PP, increased power decrement, increased muscle lactate and trended towards lowered PCr concentrations post-test, suggesting active recovery may hinder PCr recovery. This is supported by evidence from Buchheit and colleagues (2009) who found that jogging during recovery increased BLA, muscle deoxygenation, and reduced RSA, suggesting that a more passive (i.e. walking or standing) recovery may benefit RSA. This is in disagreement, however, with earlier reports of active recovery being more beneficial. Signorile and colleagues (1993) compared active and passive recovery on repeated sprint performance (eight 6-sec cycle sprints, 30s recovery) that found that passive recovery significantly lowered PP and total work throughout the test compared to active recovery, but did not change fatigue index, suggesting an active recovery is better at maintaining power throughout repeated sprints. Even with conflicting findings, the type of recovery between plays in a game situation is an active process, which may be a factor in maintaining performance.

## **Section VI – Conclusion**

Anaerobic performance tests have been around for many years, yet their specificity to some sports, specifically American football, is still lacking. Research shows that the more sport-specific an anaerobic performance test is, in terms of modality and

duration, the more likely the results of the test will correlate greater with actual sport performance. The main reasoning behind designing a more sport specific test is to assess the metabolism that is utilized during the actual sporting event. This includes how ATP is produced, which by-products are produced and the quantity produced, and recovery kinetics. An anaerobic performance test should stress the energy systems in a similar degree to the way they are maximally stressed during a game to truly test maximum performance. Therefore, it is imperative to develop a reliable anaerobic performance test that is specific to football players both metabolically and functionally.

## REFERENCES

- Adams, G. R., Fisher, M. J., & Meyer, R. A. (1991). Hypercapnic acidosis and increased H<sub>2</sub>PO<sub>4</sub>-concentration do not decrease force in cat skeletal muscle. *American Journal of Physiology-Cell Physiology*, 260(4), 805-812.
- Allen, D. G., Kabbara, A. A., & Westerblad, H. (2002). Muscle fatigue: the role of intracellular calcium stores. *Canadian Journal of Applied Physiology*, 27(1), 83-96.
- Allen, D. G., Westerblad, H., & Lännergren, J. (1995). The role of intracellular acidosis in muscle fatigue. *Advances In Experimental Medicine And Biology*, 384, 57-68.
- Amann, M., & Dempsey, J. A. (2008). Locomotor muscle fatigue modifies central motor drive in healthy humans and imposes a limitation to exercise performance. *The Journal of Physiology*, 586(1), 161-173.
- Attia, A., Hachana, Y., Chaabène, H., Gaddour, A., Neji, Z., Shephard, R. J., & Chelly, M. S. (2014). Reliability and Validity of a 20-s Alternative to the Wingate Anaerobic Test in Team Sport Male Athletes. *PloS One*, 9(12), e114444.
- Austin, D. J., Gabbett, T. J., & Jenkins, D. G. (2013). Reliability and sensitivity of a repeated high-intensity exercise performance test for rugby league and rugby union. *The Journal of Strength & Conditioning Research*, 27(4), 1128-1135.
- Aziz, A. R., Chia, M., & Teh, K. C. (2000). The relationship between maximal oxygen uptake and repeated sprint performance indices in field hockey and soccer players. *Journal of Sports Medicine and Physical Fitness*, 40(3), 195.
- Baker, J. S., McCormick, M. C., & Robergs, R. A. (2010). Interaction among skeletal muscle metabolic energy systems during intense exercise. *Journal of Nutrition and Metabolism*, 2010.
- Balsom, P. D., Ekblom, B., Söderlund, K., Sjödln, B., & Hultman, E. (1993). Creatine supplementation and dynamic high-intensity intermittent exercise. *Scandinavian Journal of Medicine & Science in Sports*, 3(3), 143-149.
- Balsom, P. D., Gaitanos, G. C., Ekblom, B., & Sjödln, B. (1994). Reduced oxygen availability during high intensity intermittent exercise impairs performance. *Acta Physiologica Scandinavica*, 152(3), 279-285.

- Berkes, P. (2015, May 15). Baylor has college football's fastest offense, but where does your team rank? Retrieved from <http://www.sbnation.com/college-football/2015/5/15/8586169/hurry-up-offense-fastest-slowest>.
- Billaut, F., & Smith, K. (2010). Prolonged repeated-sprint ability is related to arterial O<sub>2</sub> desaturation in men. *International Journal of Sports Physiology and Performance*, 5(2), 197-209.
- Bishop, D., & Spencer, M. (2004). Determinants of repeated-sprint ability in well-trained team-sport athletes. *Journal of Sports Medicine and Physical Fitness*, 44, 1.
- Bishop, D., Edge, J., & Goodman, C. (2004). Muscle buffer capacity and aerobic fitness are associated with repeated-sprint ability in women. *European Journal of Applied Physiology*, 92(4-5), 540-547.
- Bishop, D., Lawrence, S., & Spencer, M. (2003). Predictors of repeated-sprint ability in elite female hockey players. *Journal of Science and Medicine in Sport*, 6(2), 199-209.
- Bishop, D., Spencer, M., Duffield, R., & Lawrence, S. (2001). The validity of a repeated sprint ability test. *Journal of Science and Medicine in Sport* 4 (1), 19-29.
- Boddington, M. K., Lambert, M. I., Gibson, A. S. C., & Noakes, T. D. (2001). Reliability of a 5-m multiple shuttle test. *Journal of Sports Sciences*, 19(3), 223-228.
- Bogdanis, G. C., Nevill, M. E., Boobis, L. H., & Lakomy, H. K. (1996). Contribution of phosphocreatine and aerobic metabolism to energy supply during repeated sprint exercise. *Journal of Applied Physiology*, 80(3), 876-884.
- Bogdanis, G. C., Nevill, M. E., Boobis, L. H., Lakomy, H. K., & Nevill, A. M. (1995). Recovery of power output and muscle metabolites following 30 s of maximal sprint cycling in man. *The Journal of Physiology*, 482(2), 467-480.
- Bogdanis, G. C., Nevill, M. E., Lakomy, H. K. A., & Boobis, L. H. (1998). Power output and muscle metabolism during and following recovery from 10 and 20 s of maximal sprint exercise in humans. *Acta Physiologica Scandinavica*, 163(3), 261-272.
- Boobis, L. H., Williams, C., & Wooton, S. A. (1982). Human muscle metabolism during brief maximal exercise in man. *Journal of Physiology - London*, 338(1), 21-22.
- Brooks, G. A., Fahey, T. D., White, T. P., & Baldwin, K. M. (2000). *Exercise physiology: Human bioenergetics and its applications* (3rd ed.) Mountain View, CA: Mayfield Publishing Company.
- Brown, P., Hughes, M., & Tong, R. (2007). Relationship between VO<sub>2</sub>max and repeated sprint ability using non-motorised treadmill ergometry. *Journal of Sports Medicine & Physical Fitness*, 47(2), 186-190.

- Buchheit, M., Cormie, P., Abbiss, C. R., Ahmaidi, S., Nosaka, K. K., & Laursen, P. B. (2009). Muscle deoxygenation during repeated sprint running: Effect of active vs. passive recovery. *International Journal of Sports Medicine*, 30(6), 418-425.
- Edwards, R. H. (1981). Human muscle function and fatigue. *Ciba Foundation Symposium*, 82, 1-18.
- Esbjörnsson, M., Sylvén, C., Holm, I., & Jansson, E. (1993). Fast twitch fibres may predict anaerobic performance in both females and males. *International Journal of Sports Medicine*, 14(5), 257-263.
- Essén, B., & Häggmark, T. (1975). Lactate concentration in type I and II muscle fibres during muscular contraction in man. *Acta Physiologica Scandinavica*, 95(3), 344-346.
- Fabiato, A., & Fabiato, F. (1978). Effects of pH on the myofilaments and the sarcoplasmic reticulum of skinned cells from cardiac and skeletal muscles. *The Journal of Physiology*, 276(1), 233-255.
- Falk, B., Weinstein, Y., Dotan, R., Abramson, D.A., Mann-Segal, D., & Hoffman, J.R. (1996). A treadmill test of sprint running. *Scandinavian Journal of Medicine & Science in Sports*, 6(1), 259-264.
- Fitzsimmons, M., Dawson, B., Ward, D., & Wilkinson, A. (1993). Cycling and running tests of repeated sprint ability. *Australian Journal of Science and Medicine in Sport*, 25(4), 82-82.
- Fraser, S. F., Li, J. L., Carey, M. F., Wang, X. N., Sangkabutra, T., Sostaric, S., ... & McKenna, M. J. (2002). Fatigue depresses maximal in vitro skeletal muscle Na<sup>+</sup>-K<sup>+</sup>-ATPase activity in untrained and trained individuals. *Journal of Applied Physiology*, 93(5), 1650-1659.
- Froese, E.A. & Houston, M.E. (1987). Performance during the Wingate Anaerobic Test and muscle morphology in males and females. *International Journal of Sports Medicine*, 8(1), 35-39.
- Gaitanos, G. C., Nevill, M. E., Brooks, S., & Williams, C. (1991). Repeated bouts of sprint running after induced alkalosis. *Journal of Sports Sciences*, 9(4), 355-370.
- Gaitanos, G. C., Williams, C., Boobis, L. H., & Brooks, S. (1993). Human muscle metabolism during intermittent maximal exercise. *Journal of Applied Physiology*, 75(2), 712-719.
- Girard, O., Mendez-Villanueva, A., & Bishop, D. (2011). Repeated-sprint ability—Part I. *Sports Medicine*, 41(8), 673-694.

- Glaister, M. (2005). Multiple sprint work. *Sports Medicine*, 35(9), 757-777.
- Glaister, M., Howatson, G., Pattison, J. R., & McInnes, G. (2008). The reliability and validity of fatigue measures during multiple-sprint work: An issue revisited. *The Journal of Strength & Conditioning Research*, 22(5), 1597-1601.
- Glaister, M., Stone, M. H., Stewart, A. M., Hughes, M., & Moir, G. L. (2004). The reliability and validity of fatigue measures during short-duration maximal-intensity intermittent cycling. *The Journal of Strength & Conditioning Research*, 18(3), 459-462.
- Glaister, M., Stone, M. H., Stewart, A. M., Hughes, M. G., & Moir, G. L. (2007). The influence of endurance training on multiple sprint cycling performance. *The Journal of Strength & Conditioning Research*, 21(2), 606-612.
- Gleim, G. W., Witman, P. A., & Nicholas, J. A. (1981). Indirect assessment of cardiovascular "demands" using telemetry on professional football players. *The American Journal of Sports Medicine*, 9(3), 178-183.
- Gonzalez, A. M., Wells, A. J., Hoffman, J. R., Stout, J. R., Fragala, M. S., Mangine, G. T., ... & Robinson IV, E. H. (2013). Reliability of the Woodway Curve™ non-motorized treadmill for assessing anaerobic performance. *Journal of Sports Science & Medicine*, 12(1), 104.
- Greenhaff, P. L., Casey, A., Short, A. H., Harris, R., Söderlund, K., & Hultman, E. (1993). Influence of oral creatine supplementation of muscle torque during repeated bouts of maximal voluntary exercise in man. *Clinical Science*, 84, 565-565.
- Greenhaff, P. L., Nevill, M. E., Söderlund, K., Boobis, L., Williams, C., & Hultman, E. (1992). Energy-metabolism in single muscle-fibers during maximal sprint exercise in man. *Journal of Physiology-London*, 446(1), 528.
- Hachana, Y., Attia, A., Nassib, S., Shephard, R. J., & Chelly, M. S. (2012). Test-retest reliability, criterion-related validity, and minimal detectable change of score on an abbreviated Wingate test for field sport participants. *The Journal of Strength & Conditioning Research*, 26(5), 1324-1330.
- Hamilton, A. L., Nevill, M. E., Brooks, S., & Williams, C. (1991). Physiological responses to maximal intermittent exercise: Differences between endurance-trained runners and games players. *Journal of Sports Sciences*, 9(4), 371-382.
- Harris, R. C., Edwards, R. H. T., Hultman, E., Nordesjö, L. O., Ny Lind, B., & Sahlin, K. (1976). The time course of phosphorylcreatine resynthesis during recovery of the quadriceps muscle in man. *Pflügers Archive*, 367(2), 137-142.

- Haseler, L. J., Hogan, M. C., & Richardson, R. S. (1999). Skeletal muscle phosphocreatine recovery in exercise-trained humans is dependent on O<sub>2</sub> availability. *Journal of Applied Physiology*, 86(6), 2013-2018.
- Hermansen, L. (1981). Effect of metabolic changes on force generation in skeletal muscle during maximal exercise. In , *Ciba Foundation Symposium (82)*, 75-88.
- Hetzler, R. K., Vogelpohl, R. E., Stickley, C. D., Kuramoto, A. N., DeLaura, M. R., & Kimura, I. F. (2010). Development of a modified Margaria-Kalamen anaerobic power test for American football athletes. *The Journal of Strength & Conditioning Research*, 24(4), 978-984.
- Hirvonen, J., Rehunen, S., Rusko, H., & Härkönen, M. (1987). Breakdown of high-energy phosphate compounds and lactate accumulation during short supra-maximal exercise. *European Journal of Applied Physiology and Occupational Physiology*, 56(3), 253-259.
- Hoffman, J. (2008). The applied physiology of American Football. *International Journal of Sport Physiology and Performance*, 3, 387-392.
- Hoffman, J. R., Im, J., Kang, J., Ratamess, N. A., Nioka, S., Rundell, K. W., ... & Chance, B. (2005). The effect of a competitive collegiate football season on power performance and muscle oxygen recovery kinetics. *The Journal of Strength & Conditioning Research*, 19(3), 509-513.
- Hoffman, J.R., Maresh, C.M., Newton, R.U., Rubin, M.R., French, D.N., Volek, J.S., ... & Kraemer, W.J. (2002). Performance, biochemical, and endocrine changes during a competitive American football game. *Medicine, Science, & Sports Exercise*, 34(11), 1845-1853.
- Holmyard, D. J., Cheatham, M. E., Lakomy, H. K. A., & Williams, C. (1988). Effect of recovery duration on performance during multiple treadmill sprints. *Science and Football*, 134-142.
- Hughes, M. G., Doherty, M., Tong, R. J., Reilly, T., & Cable, N. T. (2006). Reliability of repeated sprint exercise in non-motorised treadmill ergometry. *International Journal of Sports Medicine*, 27(11), 900-904.
- Hultman, E., & Sjöholm, H. (1983). Energy metabolism and contraction force of human skeletal muscle in situ during electrical stimulation. *The Journal of Physiology*, 345, 525.
- Hultman, E., Bergström, J., & Anderson, N. M. (1967). Breakdown and resynthesis of phosphorylcreatine and adenosine triphosphate in connection with muscular work in man. *Scandinavian Journal of Clinical and Laboratory Investigation*, 19(1), 56-66.

- Inbar, O., Bar-Or, O., & Sinner, J.S. The Wingate Anaerobic Test. Champaign, IL: Human Kinetics, 1996.
- Inbar, O., Dotan, R., & Bar-Or, O. (1976). Aerobic and anaerobic components of a thirty-second supramaximal cycling task. *Medicine & Science in Sports & Exercise*, 8(1), 51.
- Iosia, M. & Bishop, P. (2008). Analysis of exercise-to-rest ratios during division IA televised football competition. *Journal of Strength and Conditioning Research*, 22(2), 332-340.
- Jeyaranjan, R., Goode, R., Beamish, S., & Duffin, J. (1987). The contribution of peripheral chemoreceptors to ventilation during heavy exercise. *Respiration Physiology*, 68(2), 203-213.
- Johnston, R. D., & Gabbett, T. J. (2011). Repeated-sprint and effort ability in rugby league players. *The Journal of Strength & Conditioning Research*, 25(10), 2789-2795.
- Juel, C., Pilegaard, H., Nielsen, J. J., & Bangsbo, J. (2000). Interstitial K<sup>+</sup> in human skeletal muscle during and after dynamic graded exercise determined by microdialysis. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology*, 278(2), 400-406.
- Kaczkowski, W., Montgomery, D.L., Taylor, A.W., & Klissouras, V. (1982). The relationship between muscle fiber composition and maximal anaerobic power and capacity. *Journal of Sports Medicine*, 22(1), 407-413.
- Kalaman, J. (1968). *Measurement of maximum anaerobic power in man* (Unpublished Ph. D. thesis) Ohio State University, Columbus, Ohio.
- Lavender, G., & Bird, S. R. (1989). Effect of sodium bicarbonate ingestion upon repeated sprints. *British Journal of Sports Medicine*, 23(1), 41-45.
- Lim, J. M., & Chia, M. Y. (2007). Reliability of power output derived from the nonmotorized treadmill test. *The Journal of Strength & Conditioning Research*, 21(3), 993-996.
- Mangine, G. T., Hoffman, J. R., Gonzalez, A. M., Wells, A. J., Townsend, J. R., Jajtner, A. R., ... & Stout, J. R. (2014). Speed, force, and power values produced from nonmotorized treadmill test are related to sprinting performance. *The Journal of Strength & Conditioning Research*, 28(7), 1812-1819.
- Margarita, R., Aghemo, P., & Rovelli, E. (1966). Measurement of muscular power (anaerobic) in man. *Journal of Applied Physiology*, 21(5), 1662-1664.

- Margaria, R., Oliva, R. D., Di Prampero, P. E., & Cerretelli, P. (1969). Energy utilization in intermittent exercise of supramaximal intensity. *Journal of Applied Physiology*, 26(6).
- Mayhew, S. R., & Wenger, H. A. (1985). Time-motion analysis of professional soccer. *Journal of Human Movement Studies*, 11(1), 49-52.
- McGawley, K., & Bishop, D. J. (2015). Oxygen uptake during repeated-sprint exercise. *Journal of Science and Medicine in Sport*, 18(2), 214-218.
- McKenna, M. J., Patrick, J. D., & Chennells, M. H. D. (1988). *Computer-video analysis of activity patterns in Australian Rules football*. London: E & FN Spon, 274-281.
- McLain, T., Wright, G., Camie, C., Kovacs, A., Hegge, J., & Brice, G. (2015). The development of an anaerobic sprint running test utilizing a nonmotorized treadmill. *Journal of Strength and Conditioning Research*, 29(8), 2197-2204.
- McLester Jr, J. R. (1997). Muscle contraction and fatigue: the role of adenosine 5'-diphosphate and inorganic phosphate. *Sports Medicine*, 23(5), 287-305.
- Mendez-Villanueva, A., Hamer, P., & Bishop, D. (2007). Fatigue responses during repeated sprints matched for initial mechanical output. *Medicine and Science in Sports and Exercise*, 39(12), 2219-2225.
- Mendez-Villanueva, A., Hamer, P., & Bishop, D. (2008). Fatigue in repeated-sprint exercise is related to muscle power factors and reduced neuromuscular activity. *European Journal of Applied Physiology*, 103(4), 411-419.
- Myers, J., & Ashley, E. (1997). Dangerous curves: a perspective on exercise, lactate, and the anaerobic threshold. *Chest Journal*, 111(3), 787-795.
- Nakamaru, Y., & Schwartz, A. (1972). The influence of hydrogen ion concentration on calcium binding and release by skeletal muscle sarcoplasmic reticulum. *The Journal of General Physiology*, 59(1), 22-32.
- Noakes, T., Gibson, A., & Lambert, E. (2005). From catastrophe to complexity: A novel model of integrative central neural regulation of effort and fatigue during exercise in humans: Summary and conclusions. *British Journal of Sports Medicine*, 39(2), 120-124.
- Nummela, A., Alberts, M., Rijntjes, R. P., Luhtanen, P., & Rusko, H. (1996). Reliability and validity of the maximal anaerobic running test. *International Journal of Sports Medicine*, 17(2), 97-102.
- Nummela, A., Hämmäläinen, I., & Rusko, H. (2007). Comparison of maximal anaerobic running tests on a treadmill and track. *Journal of Sports Sciences*, 25(1), 87-96.

- Parolin, M. L., Chesley, A., Matsos, M. P., Spriet, L. L., Jones, N. L., & Heigenhauser, G. J. (1999). Regulation of skeletal muscle glycogen phosphorylase and PDH during maximal intermittent exercise. *American Journal of Physiology, Endocrinology, & Metabolism*, 277, 890-900.
- Pascoe, D. D., & Gladden, L. B. (1996). Muscle glycogen resynthesis after short term, high intensity exercise and resistance exercise. *Sports Medicine*, 21(2), 98-118.
- Pate, E., Bhimani, M., Franks-Skiba, K., & Cooke, R. (1995). Reduced effect of pH on skinned rabbit psoas muscle mechanics at high temperatures: implications for fatigue. *The Journal of Physiology*, 486(3), 689-694.
- Patton, J., Murphy, M., & Frederick, F. (1985). Maximal power outputs during the Wingate anaerobic test. *International Journal of Sports Medicine*, 6(1), 82-85.
- Pendleton, M. H. W. (1997). Reliability and validity of the Welsh Rugby Union shuttle run test. *Unpublished BSc dissertation, University of Wales Institute Cardip*.
- Pincivero, D. M., & Bompa, T. O. (1997). A physiological review of American football. *Sports Medicine*, 23(4), 247-260.
- Redding, R. (2015). *2015 NCAA football rules and interpretations*. Retrieved from <http://www.ncaapublications.com/p-4387-2015-ncaa-football-rules-and-interpretations.aspx>
- Rhea, M., Hunter, R., & Hunter, T. (2006). Competition modeling of American football: Observational data and implications for high school, collegiate, and professional player conditioning. *Journal of Strength and Conditioning Research*, 20(1), 58-61.
- Sahlin, K., Harris, R. C., & Hultman, E. (1975). Creatine kinase equilibrium and lactate content compared with muscle pH in tissue samples obtained after isometric exercise. *Biochemical Journal*, 152(2), 173-180.
- Sahlin, K., Harris, R. C., & Hultman, E. (1979). Resynthesis of creatine phosphate in human muscle after exercise in relation to intramuscular pH and availability of oxygen. *Scandinavian Journal of Clinical & Laboratory Investigation*, 39(6), 551-557.
- Saugen, E., Vollestad, N. K., Gibson, H., Martin, P. A., & Edwards, R. H. (1997). Dissociation between metabolic and contractile responses during intermittent isometric exercise in man. *Experimental Physiology*, 82(1), 213-226.
- Seiler, S., Taylor, M., Diana, R., Layes, J., Newton, P., & Brown, B. (1990). Assessing anaerobic power in collegiate football players. *The Journal of Strength & Conditioning Research*, 4(1), 9-15.

- Signorile, J. F., Tremblay, L. M., & Ingalls, C. (1993). The effects of active and passive recovery on short-term, high intensity power output. *Canadian Journal of Applied Physiology*, 18(1), 31-42.
- Smith, J. C., & Hill, D. W. (1991). Contribution of energy systems during a Wingate power test. *British Journal of Sports Medicine*, 25(4), 196-199.
- Smith, M. E., & Jackson, C. G. R. (1991). Lactate response of college football players to practices and a game [abstract]. *Journal of Applied Sport Science Research*, 5, 163.
- Söderlund, K., & Hultman, E. (1991). ATP and phosphocreatine changes in single human muscle fibers after intense electrical stimulation. *American Journal of Physiology-Endocrinology And Metabolism*, 261(6), 737-741.
- Spencer, M., Bishop, D., Dawson, B., & Goodman, C. (2005). Physiological and metabolic responses of repeated-sprint activities. *Sports Medicine*, 35(12), 1025-1044.
- Spencer, M., Bishop, D., Dawson, B., Goodman, C., & Duffield, R. (2006). Metabolism and performance in repeated cycle sprints: active versus passive recovery. *Medicine and Science in Sports and Exercise*, 38(8), 1492-1499.
- Stackhouse, S. K., Reisman, D. S., & Binder-Macleod, S. A. (2001). Challenging the role of pH in skeletal muscle fatigue. *Physical Therapy*, 81(12), 1897-1903.
- Tanaka, H., Monahan, K. D., & Seals, D. R. (2001). Age-predicted maximal heart rate revisited. *Journal of the American College of Cardiology*, 37(1), 153-156.
- Tesch, P. A., Thorsson, A., & Fujitsuka, N. (1989). Creatine phosphate in fiber types of skeletal muscle before and after exhaustive exercise. *Journal of Applied Physiology*, 66(4), 1756-1759.
- Tharp, G. D., Johnson, G. O., & Thorland, W. G. (1984). Measurement of anaerobic power and capacity in elite young track athletes using the Wingate test. *Journal of Sports Medicine and Physical Fitness*, 24(2), 100-106.
- Tharp, G.D., Newhouse, R.K., Uffelman, L., Thorland, W.G., & Johnson, G.O. (1985). Comparison of sprint and run times with performance on the Wingate Anaerobic Test. *Research Quarterly for Exercise and Sport*, 56(1), 73-76.
- Tomlin, D. L. (1998). The aerobic response to intense intermittent exercise [thesis]. *Victoria (BC): University of Victoria*.
- Tomlin, D. L., & Wenger, H. A. (2001). The relationship between aerobic fitness and recovery from high intensity intermittent exercise. *Sports Medicine*, 31(1), 1-11.

- Turner, A. N., & Stewart, P. F. (2013). Repeat sprint ability. *Strength & Conditioning Journal*, 35(1), 37-41.
- Vøllestad, N. K. (1997). Measurement of human muscle fatigue. *Journal of Neuroscience Methods*, 74(2), 219-227.
- Wadley, G., & Le Rossignol, P. (1998). The relationship between repeated sprint ability and the aerobic and anaerobic energy systems. *Journal of Science and Medicine in Sport*, 1(2), 100-110.
- Walter, G., Vandenborne, K., McCully, K., & Leigh, J. (1997). Noninvasive measurement of phosphocreatine recovery kinetics in single human muscles. *American Journal of Physiology*, 272(2), 525-534.
- Wasserman, K. (1976). Testing regulation of ventilation with exercise. *CHEST Journal*, 70(1 Supplement), 173-178.
- Westerblad, H., Allen, D. G., & Lännergren, J. (2002). Muscle fatigue: lactic acid or inorganic phosphate the major cause? *Physiology*, 17(1), 17-21.
- Withers, R. T., Maricic, Z., Wasilewski, S., & Kelly, L. (1982). Match analysis of Australian professional soccer players. *Journal of Human Movement Studies*, 8(1), 159-176.
- Wright, G. A., Isaacson, M. I., Malecek, D. J., & Steffen, J. P. (2015). Development and assessment of reliability for a sandbag throw conditioning test for wrestlers. *The Journal of Strength & Conditioning Research*, 29(2), 451-457.
- Zacharogiannis, E., Paradisis, G., & Tziortzis, S. (2004). An evaluation of tests of anaerobic power and capacity. *Medicine & Science in Sports & Exercise*, (36), 116.
- Zagatto, A. M., Beck, W. R., & Gobatto, C. A. (2009). Validity of the running anaerobic sprint test for assessing anaerobic power and predicting short-distance performances. *The Journal of Strength & Conditioning Research*, 23(6), 1820-1827.
- Zapiec, C., & Taylor, A. W. (1979). Muscle fibre composition and energy utilization in CFL football players. *Canadian Journal of Applied Sport Sciences*, 4(2), 140-142.
- Zemková, E. & Hamar, D. (2004). "All-out" tethered running as an alternative to Wingate Anaerobic Test. *Kinesiology*, 36(2), 165-172.