2013

The Effect of Muscle Imbalance on Running Performance in Collegiate Level Athletes

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THE EFFECT OF MUSCLE IMBALANCE ON RUNNING PERFORMANCE IN COLLEGIATE LEVEL ATHLETES

by

Mark Oxford

A Thesis
Submitted to the Faculty of Graduate Studies through Human Kinetics in Partial Fulfillment of the Requirements for the Degree of Master of Human Kinetics at the University of Windsor

Windsor, Ontario, Canada

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The Effect of Muscle Imbalance on Running Performance in Collegiate Level Athletes

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DECLARATION OF ORIGINALITY

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ABSTRACT

The existence of a lower body muscle imbalance has previously been correlated with increased injury risk, and has the potential to alter running mechanics and influence running performance. The purpose of this investigation was to identify lower body functional asymmetry in a wide range of collegiate level athletes and to determine how these imbalances, if they exist, correlated with anaerobic performance. Participants underwent a standing long jump test consisting of one-leg and two-leg jumps, followed by a running-based sprint test. Significant anthropometric and performance differences between males and females were observed, however, no differences were found in lower limb power asymmetries between sexes. Significant differences were found in maximum jumping distance between the dominant and nondominant leg (p<0.05). Fatigue index and maximum power were correlated with increased performance, measured as a percentage of the Canadian record, however, lower limb power asymmetry was not correlated with either of these performance variables.
ACKNOWLEDGEMENTS

I would first and foremost like to thank Dr. Kevin Milne, my advisor, for allowing this investigation to occur. His willingness to offer guidance, answer questions and edit documents was more than I could hope for. I am very appreciative of Dr. Milne’s interest in sponsoring an unfunded project, and treating it no differently than a fully funded project. I could not have asked for a better thesis and overall graduate experience. I could not have completed this project without my undergraduate volunteers with all their help in the lab and with testing; Jeffery Little, Brittany Annan, Shane Freeman & Gabrielle Malette.

I would also like to thank the Department of Kinesiology, including all faculty and staff, for all of their assistance in allowing me to complete my Master’s degree. My work at the University of Windsor would have been much more difficult if I had not been for a Graduate Assistantship, for which I am truly grateful. I cannot leave out my fellow graduate students, past and presence, for their continued support, friendship, and good times.
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CHAPTER I
LITERATURE REVIEW

In the world of elite athletic competition, small margins separate medal finishers from also-rans. In one of the most classic examples, Greg Lemond won the 1989 Tour De France, a race spanning a total of approximately 3497 kilometres, by only 8 seconds over Laurent Fignon. In shorter races, such as the 100-meter sprint, these margins are reduced to hundredths of seconds and the limits of reliable timing. For example, at the 2012 Olympic Games in London, 0.35 seconds (about the time it takes to say the word “Bolt”) separated first place from seventh place in the men’s 100-meter final.

The factors that contribute to running performance are numerous and include physiological factors such as warm-up type (Chaouachi, Castagna, Chtara, Brughello, Turki, Oliver & Behm, 2010), pre exercise meal and metabolism (Bennett, Chilibeck, Barss, Vatanparast, Vandenberg & Zello, 2012), anaerobic (Losnegard, Myklebust, & Hallen, 2012) and aerobic capacity (Mendez-Villanueva, Hamer, & Bishop, 2008), muscle fibre type (Esbjornsson-Liljedahl, Sundberg, Norman, & Jansson, 1999), biomechanical factors such as running mechanics and efficiency (Cavagna & Kaneko, 1977) and psychological factors such as confidence or self-efficacy (Gernigon & Delloye, 2003). Today, genetics determines the limits of potential performance, while environmental factors, such as proper athletic training, allow individuals to approach their full potential (Hagberg, 2011; Tiainen, Pajala, Sipila, Kaprio, Koskenvuo, Alen, … Rantanen, 2007). However, it is intuitive that optimization of training programs is improved by knowledge of an individual’s physiology and adequate performance metrics.
In extreme examples, an Australian rugby team has employed genetic testing to shape the training of their team members (Dennis 2005) and investigations are ongoing to determine the success of genotyping-related predictions of endurance versus power athletes (Buxens, Ruiz, Arteta, Artieda, Santiago, Gonzalez-Freire, … Lucia, 2011). Nonetheless, most coaches do not have access to these resources, and quick, reliable assessment of athletic potential and performance remain important parts of a training regimen. While there are several tests to determine the physiological, biomechanical and psychological characteristics noted previously (Carpes, Diefenthaeler, Bini, Stepahyshym, Faria, & Mota, 2011), assessment of bilateral asymmetry in power development is not regularly employed even though this is an important part of running performance (Izquierdo, Hakkinen, Gonzalez-Badillo, Ibanez, & Gorostiaga, 2002).

RUNNING KINEMATICS

Running requires the coordinated contraction of muscles at a progressively increasing speed, accelerating the body forward at an increasing velocity (Cavagna, Komarek & Mazzoleni, 1971). There are several crucial factors involved in optimizing running performance and efficiency including, stride/step length, stride/step rate, ground contact time, and joint angles (Paulson & Braun, 2011). The latter tend to exhibit a more significant difference between males and females as a result of different anatomical joint angles (Ferber, Davis & Williams, 2003).

One aspect of running, sprinting, can be subdivided into four phases: the starting phase, the acceleration phase, the maximal speed phase, and finally the deceleration
phase (Debaere, Jonkers & Delecluse, 2012). The acceleration phase can further be subdivided into an initial acceleration phase and transition phase (Debaere et al., 2012). During the initial acceleration phase, a sprinter aims to achieve maximal horizontal velocity to maximize overall acceleration (Hunter, Marchall & McNair, 2005). Until maximal speed is reached, the runner attempts to be in a state of acceleration and speed development relying heavily on the powerful extension of the joints of the lower leg (Debaere et al., 2012), and the swing back velocity of the support leg at touchdown (Hunter et al., 2005). The transition phase is defined by the raising of the trunk into a fully upright position (Debaere et al., 2012). Whether step length or step rate (i.e. the two main determining factors in sprint speed) is more influential to sprint speed remains unclear, although both require unilateral (i.e. single leg) power output and bilateral (i.e. two-leg) coordination. Furthermore, any actions requiring energy expenditure that do not result in direct forward motion of the body decrease the efficiency at which an individual can perform. An example of an action that would have this effect would be a side-to-side swaying motion. As a result, a key component to success in running is an individual’s ability to maintain stability, and it has been shown that running with specific step widths to counter any side-to-side instability improves running efficiency (Arellano & Kram, 2011). Consequently, if one leg is able to output more power than the other, this could potentially result in altered running mechanics and possibly reduced performance.

The hamstrings (composed of the semitendinosus, semimembranosus and biceps femoris muscles) and quadriceps (composed of the rectus femoris, vastus lateralis, vastus medialis and vastus intermedius muscles), are the two most powerful muscle groups
involved in the mechanics of sprinting. The hamstring muscles work to function as a brake, contracting eccentrically to oppose the powerful concentric contraction of the quadriceps muscle group (Yeung, Suen & Yeung, 2009). If these muscle groups are not balanced, functional performance is limited and injury risk is high (Wang & Cochrane, 2001). However, while muscle imbalance within a leg is important, this review focuses on asymmetries in power between limbs on opposite sides of the body (described below).

**BILATERAL DEFICIT**

Bilateral (two-side simultaneously) lower body resistance training is used to enhance athletic performance by inducing improvements in muscular strength and power (Dunn, Klein, Kroll, McLaughlin, O’Shea & Wathen, 1984; Smilios, Sotiropoulos, Douda, Spaia & Tokmakidis, 2012). However, most sport specific actions require the function of one limb at a time even though that action may require the coordinated actions of several muscle groups in several parts of the body. For example, a layup in basketball is typically initiated by a take-off from one leg, a long jumper jumps off of one leg, and a sprinter relies on the power output of each leg independently at alternating intervals during a sprint. Consequently, it is not surprising that the utilization and understanding of unilateral (i.e. single limb) training and its potential benefits to sport performance has received investigation (Janzen, Chiliback & Davison, 2006; McCurdy, Langford, Doscher, Wiley & Mallard, 2005; Santana, 2001) and traditional bilateral (i.e. two limb simultaneous) exercises for sport training have been challenged (Jones, Ambegaonkar, Nindl, Smith & Headley, 2012).
A phenomenon known as the bilateral deficit has previously been defined as the ability to lift a relatively larger load unilaterally when compared to a load lifted bilaterally (Bobbert, Graad, Jonk & Casius, 2006; Howard & Enoka, 1991). This larger unilateral load (versus a strict division of total bilateral load) is “under-trained” in typical bilateral training and contralateral (opposing limb) strength or power balance is unaccounted for. As noted above, running performance relies on the individual power output of each leg independently at alternating intervals throughout an event. Although this bilateral deficit favours the performance of a sprinter in this way (i.e. greater power developed by one leg at a time than would be suggested by dividing simply half of the bilateral power), the possibility of lower limb power asymmetry between legs may not be as favourable to their ability to maximize sprinting performance.

**LOWER LIMB FUNCTIONAL ASYMMETRY**

The development of muscle imbalances and functional limb asymmetries do not occur overnight. They can result from improper training, previous injury or other environmental factors causing deviations from bilateral symmetry and an imbalance between opposing sides of the body (Trivers, Manning, Thornhill, Singh & McGuire, 1999). Moreover, functional asymmetries could have a genetic component that results from bilateral asymmetries such as different limb lengths. For example, leg length asymmetry affects approximately 90% of the population, and has been associated with injury, muscular strength imbalance and other physiological changes (Knutson, 2005). In previous research examining leg and hand dominance, contralateral neural differences have been proposed as a possible mechanism for the differences observed between the
dominant and non-dominant side (Tucker & Williamson, 1984). Neural influences have also been seen with motor control and associated tasks, where one hemisphere of the brain is dominant, specifically the left with respect to motor control of the hands (Kimura & Archibald, 1974; Brown & Wolpert, 1990) and feet (Gabbard & Hart, 1996), however, these are beyond the scope of this document. Other researchers have also concluded that the body is not symmetrical in many other respects, including physiological or anatomical conditions and that motor tasks and these differences are typically dominated by one side of the body (Blaszczyk, Prince, Raiche & Hebert, 2000).

Functional asymmetries may include differences existing between the right and left sides of the body or between agonist (causing movement) and antagonist (opposing movement) muscle groups (Knapik, Bauman, Jones, Harris & Vaughan, 1991). For example, the hamstrings (antagonist) and quadriceps (agonist) muscles work in an opposing manner and an imbalance in these two muscle groups could result in overpowering or injury (Yeung et al., 2009). The method in which the hamstrings and quadriceps function during a sprint induces high intrinsic forces within the hamstring muscle, and an imbalance in hamstring strength compared to quadriceps strength is an increased risk factor for injury (Croisier, Ganteaume, Binet, Genty & Ferret, 2008; Yeung et al., 2009). For example, in Australian professional football players, it has been observed that when a hamstring injury has occurred, the uninjured hamstring had a significantly higher peak torque than that of the injured hamstring (Orchard, Marsden, Lord & Garlick, 1997). Further, the ratio of concentric peak torque between hamstring and quadriceps (referred to as the Hcon:Qcon ratio) has been used to assess injury risk,
with a ratio of at least 0.60 being advocated to minimize chance of injury (Orchard et al., 1997; Yeung et al., 2009).

Running (predominantly sprinting) performance is highly dependent on the ability to generate maximum speed in a short period of time through highly explosive force generating movements. During this force generation, the eccentric contraction of the hamstring generates high intrinsic forces within the muscle, resulting in a significant injury risk for the hamstring muscles compared to the quadriceps muscles. Consequently, susceptibility to injury is increased by as much as four to five times greater compared to individuals without a muscle imbalance (Croisier et al., 2008; Yeung et al., 2009). Muscle imbalances may not result in injury or decreased performance immediately, however, with training, an imbalance could grow larger. Testing for muscle imbalance should be an aspect of a regular training regimen to maximize performance and reduce injury.

Since functional asymmetries of the lower extremities may potentially decrease athletic performance, individuals who are more symmetrical (i.e. can produce the same power between legs), may exhibit improved performance (Tomkinson, Popovic & Martin, 2003), especially when the margin of difference between competitors is small, such as in a sprinting event. Determining a functional asymmetry is also an important variable in predicting an athlete’s risk of injury during an event or training (Impellizzeri, Rampinini, Maddiuletti & Marcora, 2007). The resulting increase in injury risk and decreased performance due to asymmetries between legs may be a reflection of
favouring the dominant leg (i.e. the stronger leg = the dominant leg), a result of leg length discrepancies or influenced by previous injury (Newton, Gerber, Nimphius, Shim, Doan, Robertson, … Kraemer, 2006). Using concentric and eccentric isokinetic knee assessments, Croisier et al. (2008) observed that of all the players tested, those who sustained a hamstring injury had the greatest strength asymmetries.

FATIGUE

During dynamic exercise at a high intensity, there is a rapid loss of muscle power (James, Sacco & Jones, 1995). A variation in the muscles’ functional capability to develop force, a change in neural input resulting in an alteration in coordination, or a combination of both may be the cause of a noted decline in performance (Rodacki, Fowler & Bennett, 2002). It has been observed in measurements of power output that after the first few seconds, or once peak force is reached, power decreases at a rate of approximately 50-60 percent every 30 seconds after peak force is reached (Sargeant, Hoinville & Young, 1981). This phenomenon is known as the force-fatigability relationship and states that the greater the force exerted by a muscle, the more the muscle will fatigue (Hunter & Enoka, 2001). Measuring changes in fatigue can also be done using measurement of amount of force produced, time to complete a task, or ratings of perceived exertion. The ability of an athlete to resist or prolong fatigue while exerting maximal muscle force, is a very strong indicator of performance.

Fatigue is multifaceted and includes central fatigue, which is the inability to maintain motor drive during the execution of complex tasks (James et al., 1995).
Variations in neuromuscular factors (Kaplan, 2010) and metabolic-induced disturbances (Gaitanos, Williams, Bobbis & Brooks, 1993; Nordland, Thorstensson & Cresswell, 2004), among other influences, affect fatigue as a result from microdamage occurring to the muscle architecture. Further, an individual with better sprinting performance is more heavily suited to anaerobic metabolism to support muscle function compared to those with poorer sprinting performance (Hirvonen, Rehunen, Rusko & Harkonen, 1987; Gaitanos et al., 1993).

Injuries during training or athletic events have been associated with fatigue (Pappas, Sheikhzadeh, Hagins & Nordin, 2007), and conversely, fatigue may be responsible for some injuries because of a loss of balance or muscle function (Johnston et al., 1998). This loss of balance may be a result of changes in performance mechanics that are induced by fatigue. For example, Augustsson, Thomee, Linden, Folkesson Tranberg & Karlsson (2006) observed that during the single leg hop, fatigued conditions resulted in a more upright body position causing a decreased ability to produce horizontal forces, decreased knee and ankle joint power, reduced ground reaction forces, and smaller hip and knee flexion angles (Augustsson et al., 2006). With a muscle imbalance, muscular fatigue could increase the risk of injury due to a greater demand being placed on the stronger side as it compensates for the weaker side. Oda & Moritani (1995) showed that a difference exists contralaterally in the fatigability of left versus right sides of the body. This fatigue imbalance with one side fatiguing faster than the other creates an even greater running dysfunction and injury risk in longer duration running, as not only will
fatigue decrease maximal performance, but the imbalance will compound resulting in a greater performance reduction (Oda & Moritain, 1995).

While it may be reasonable to assume that a runner naturally trains both legs equally, it is important to note that hand and leg dominance are commonly found in the general population and among athletes (Crosby & Wehbe, 1994). In fact, for right handed individuals, there is a general 10% dominant hand rule that therapists follow in rehabilitation (Petersen, Petrick, Connor & Conklin, 1989). This rule states that a person’s dominant hand possesses 10% greater strength than the nondominant hand (Bechtol, 1954). This difference in strength between dominant and nondominant sides of the body has not only been seen in grip strength and rehabilitation, but has also been observed between dominant and nondominant legs in different sports, such as powerlifting and field jumping (Luk, Winter, O’Neill & Thompson, 2013). Luk et al. (2013) suggested that sports requiring different physical demands could explain the varying muscle imbalances we see between sports. These imbalances have the potential to influence performance, with a larger imbalance resulting in decreased performance (Tomkinson et al., 2003).

Given that bilateral asymmetries could present a significant problem to athletic performance, testing for these imbalances should be a standard component of a training regimen. Following the testing for the existence of a muscle imbalance, training protocols could then be tailored around varying degrees of imbalance to minimizing the effect of the imbalance or even correcting it. Unilateral exercises and training regimens have
previously been investigated for their differences from bilateral exercises and regimens in strength and power development (McCurdy et al., 2005), but with respect to functional asymmetries they could be utilized to eliminate the effect of the dominant side on the nondominant side when training, therefore decreasing an imbalance.
CHAPTER II
INTRODUCTION

Athletic performance is complex and dependent on many variables, including the anatomical and physiological components of physical ability (Noakes, 2000), such as fatigue index and maximum power output, and psychological characteristics such as motivation. Although intuitive, lower body bilateral power imbalance or asymmetry is a variable that has received little scientific examination as a major contributor to athletic performance, specifically to those events that are largely dependent on running performance.

Functional asymmetries have been defined as a deviation away from bilateral equality resulting in a difference between opposite sides of the body (Trivers et al., 1999). The existence of a functional asymmetry could be the result of multiple factors including genetic differences in limb length (Newton et al., 2006; Knutson, 2005), neurological differences in motor function (Tucker & Williamson, 1984), individuals favouring their dominant side (Blaszczyk et al., 2000), improper training techniques (McCurdy et al., 2005), and the influence of previous lower body injury (Nadler, Malanga, Feinberg, Rubanni, Moley & Foye, 2002). With respect to anatomical differences, the term bilateral symmetry is used in the literature to denote the sameness of two sides of the body. In fact, the health, quality, and/or developmental stability (i.e. the ability of the genotype to express itself in the phenotype) of an organism can be represented by fluctuating asymmetry (i.e. small deviations from perfect symmetry occurring in an organism (Palmer, 1996)). Bilateral symmetry has been measured in
animals and humans not only at the limbs, but also at such features as the nostrils and ears, and compared to performance (Manning & Pickup, 1998; Manning & Ockenden, 1994; Swaddle, 1997; Tomkinson et al., 2003). Not surprisingly, in both humans and other animals, a lesser degree of bilateral symmetry (smaller imbalance) is associated with improved human and equine running physical performance (Manning & Pickup, 1998; Manning & Ockenden, 1994) and flying efficiency in birds (Swaddle, 1997).

Given that small bilateral anatomical asymmetries are not only dependent on genetics, but also environmental pressures, these differences may manifest themselves even more in functional ability such as power development. During fatiguing physical activity, there is a progressive decline in muscular power contributing to decreased performance (Wilkins, Valovich, Perrin & Gansneders, 2004). This loss of muscular power associated with fatigue (James et al., 1995) has the potential to emphasize an existing muscle imbalance by creating a situation in which one side of the body fatigues more quickly than the other (i.e. bilateral fatigability) (Oda & Moritani, 1995). Moreover, in addition to the functional limitations of muscle power asymmetries, lower limb bilateral asymmetry has also been associated with an increased risk of injury (Newton et al., 2006; Orchard et al., 1997). Consequently, the importance of examining muscle power asymmetries cannot be understated.

Nonetheless, traditional strength and conditioning protocols for athletes involve primarily bilateral movements such as the barbell back squat (lower body) (Appendix C) and bench press (upper body) (Appendix C) or variations of these exercises (Kawamori
This type of training potentially facilitates the development and growth of a muscle imbalance as the stronger side of the body will naturally take on a greater percentage of the overall load or, conversely, the movement can only be performed as great as the weaker side. This contrasts with the performance requirements of most types of physical activity where movement primarily occurs through the force development of one side of the body (i.e. the alternating leg movements that occur during running).

Relatively little information on lower limb functional asymmetries among athletes may have to do with the difficulty in assessing such imbalances. Traditionally, a lower body muscle imbalance is measured using complex equipment such as in-ground force plates and isokinetic dynamometry (Newton et al., 2006). These types of tests are not accessible to many athletes and not easily transported or incorporated into competing venues (i.e. the track, court, field, etc.). However, lower limb functional asymmetry may represent an important trainable variable in athletic performance and injury prevention. Given the scarcity of data in this regard, the intent of the current investigation was to characterize functional asymmetry in a wide group of athletes using a simple field ready jumping protocol.
OBJECTIVES

Given that the extent of lower limb functional asymmetry has not been fully examined in competitive athletes, the objectives of this investigation were:

1. to determine bilateral lower body power asymmetries in a wide range of collegiate level athletes using a field ready jumping test
2. to determine how bilateral lower body power asymmetries in the lower extremities correlated with running performance

HYPOTHESES

Give that bilateral asymmetries are observed in a large percentage of the population (Knutson, 2005), we hypothesized that bilateral power asymmetry as assessed by a field ready jump testing would exist. Secondly, because asymmetries would cause inefficiencies in running we also hypothesized that greater muscle power asymmetries between opposite legs would be correlated with lower running performance as indicated by comparison with national records, fatigue index and power production.
DESIGN AND METHODOLOGY

DESIGN

This study was approved by the University of Windsor Research Ethics Board (REB 12-201-Appendix D). Participants were recruited from the University of Windsor varsity teams with a running based component to competition. Participants underwent physiological testing at the peak of their competitive seasons (immediately prior to CIS championships, or immediately after being eliminated from the playoffs). Muscle (power) imbalances between participants’ right and left legs were determined using a single leg standing long jump test and compared with sprint performance and fatigue index in a repeated 35m sprint test. Further, lower leg asymmetry, anthropometrics, standing long jump and sprint test performance were correlated with event performance for those participants who were track and field athletes with posted personal best competition results during the season. Secondary outcomes included differences and correlations between indices of the existence of a muscle imbalance and performance variables, within different sports and sexes.

PARTICIPANTS

Participants were recruited from the University of Windsor varsity athletic teams and consisted of highly active males and females. Further, the University of Windsor track and field team, and men’s and women’s basketball teams have been nationally ranked programs over the past few years. Testing occurred in the Physical Activity and
Cardiovascular Research Laboratory in the Human Kinetics building as well as in the Field House at the St. Denis Center at the University of Windsor. Upon arriving at the lab, participants were seated and the experiment and risks were explained. Participants were then instructed to read and sign informed consent, complete a Pre-test Participant Information Questionnaire (Appendix A) and ACSM Health Pre-participation Screening Questionnaire (Appendix B).

ANTHROPOMETRIC MEASURES

Participants were then asked to remove their shoes, as well as any heavy clothing (ie. sweat pants, hooded sweat shirts). Each participant’s weight was then measured using a Detecto Weight Beam scale (Missouri, USA) and height was measured in centimetres on a standard wall scale. Participants were then asked to lie down supine on a medical bed or floor mat, and lower limb length was measured in centimetres by a method adopted from Pillay (1971). Briefly, with the participant lying in the “Stand-at Ease” position, the measurement was taken from the Anterior-Superior Iliac Spine to the Medial Malleolus of the same extremity. A visual representation of this protocol can be seen in Figure 1.
Figure 1. Limb length measurement protocol. The measurement was taken on both legs from the anterior-superior iliac spine to the medial malleolus of the corresponding side. This procedure was completed for a total of three measurements per leg.
STANDING LONG JUMP TEST

Participants were then given fifteen minutes to perform their normal pre-competition warm-up which included jogging, static and dynamic stretching and submaximal sprints. Participants were not allowed to wear spiked running shoes for the performance tests. A verbal explanation and demonstration was then given to the participants outlining the jumping procedure and any other relevant information. Participants began by clasping their hands behind their back, and on the leg of their choosing, jump as far as they can on that one leg, landing on the same leg. A visual representation of this process can be seen in Figure 2A. The landing position was then taped off on the jumping surface with the measurement being toe to toe. The participant then walked back to the starting position and repeated the jump procedure on the opposite leg. Participants were then given a 45 second break before repeating this process. The taping procedure provided a visual goal for participants to try and better. After the participant had completed three jumps per leg, they received another 45 second break. They then completed three two-legged standing long jumps (Figure 2B), with their hands still clasped behind their back, with a 45 second break between each jump. These jumps were also taped off, and exact measurements were recorded from toe to toe, of the foot closest to the starting point, once all jump testing was completed. Taping of jumps allowed participants to try and better each previous jump. All jumps were measured in centimetres using a Stanley FatMax Tape.

The standing single leg jump test was chosen because it has been observed to have a high test-retest reliability (Ageberg et al., 2007), and has been used in previous research (Noyes et al., 1991). This test was chosen over the equally popular vertical jump
test due to its similar movement pattern and muscle recruitment pattern to the action of running (Augustsson et al., 2006). During the jump test, participants were not allowed to swing their arms for momentum to assist in the jump. Instead, they were required to clasp their hands behind their backs during the jump. This modification was made to ensure that the jump test produced a more accurate indicator of leg power output. Previous literature has determined that when allowed to use arms freely during a standing long jump, the average jump distance increased by 21.2 percent (Ashby & Heegaard, 2002).
Figure 2. A) Single-leg standing long jump test protocol. Participants, with their hands clasped behind their backs, and toe behind the starting line were required to jump off one foot at a time for a maximal horizontal distance. B) Two-leg standing long jump test protocol. Participants, with their hands clasped behind their backs, and toes behind the starting line were required to jump off both feet at the same time for a maximal horizontal distance.
RUNNING-BASED ANAEROBIC SPRINT TEST (RAST)

After the jump test, participants were given a 5 minute resting period, at which time they were given an explanation of the proper protocol of the running-based anaerobic sprint test (RAST). The RAST consists of six consecutive timed 35-meter all out sprints with a 10 second active recovery between each sprint (time taken to walk back to the starting line). Athletes started in a standardized 2-point crouch position and were instructed to give maximal effort through each of the six sprints. Upon completion of the sprint test, participants were instructed to undergo a cool down period consisting of active recovery and static stretching. The RAST test is a standard anaerobic sprint test that has been used in previous research for measuring power output and fatigue index (Gwacham & Wagner, 2012; Balciunas et al., 2006). The RAST has also been compared to other tests that provide performance variables such as power, including the Wingate test, and 35, 50, 100, 200 and 400 meter performance scores, and has been shown to be a valid and reliable measure of anaerobic power and fatigue index (Zagatto, et al., 2009). The reason the RAST was chosen over other tests for this investigation was due to its applicable nature to the athletes we tested. Most of the athletes we tested participate in events that use running as the primary form of locomotion and the RAST allows for the execution of those movements that are more specific to these sporting events.

Using the time to complete each 35m distance, power (watts) during each of the six sprints was calculated according to the following equation:

EQ1:  \[ \text{Power} = \text{Body Weight (kg)} \times \left( \frac{\text{Running Distance (m)}}{\text{Time (sec)}} \right)^2 \]
Peak power (PP) and minimum power (MP) were taken from the fastest and slowest running times, respectively. The difference in power (or power decay from the peak to the minimum) gives a measure of the ability to sustain that power output and could be used to calculate fatigue index (FI) using the equation:

\[
FI = \frac{PP - MP}{\text{Sum of 6 Sprint Times}}
\]

At the completion of the six 35-meter sprints, participants were instructed to rehydrate, and perform their typical cool down procedures after an event or practice. Participants were visually monitored to ensure safety and full recovery.

**STATISTICAL ANALYSIS**

Participant data was recorded in Microsoft Excel and was then transferred to IBM SPSS statistics version 20. Descriptive statistics (means, SD) and participant differences were analyzed by a 2 x 3 (sex: male, female x sport: track, basketball, volleyball) analysis of variance (ANOVA). To determine mean differences between sports, a Tukey’s post hoc analysis was used. Significance was set at \( p < 0.05 \) and effect size (partial \( \eta^2 \) or \( \eta_p^2 \)) were reported.

To test whether a significant differences existed between legs, a repeated measures 2 x 3 (leg:dominant, non-dominant x jump number: 1,2,3) ANOVA was used to determine significant differences between the dominant and nondominant leg in each of
the three single leg jumps. A tukey’s post hoc analysis was used to determine which jumps differed from the others. In order to account for individuals in whom the maximum jump was not the last, a t-test was performed comparing the maximum recorded dominant leg jump to the maximum recorded non-dominant leg jump for all individuals as well.

In order to assess performance, we first examined only in those individuals competing in track and field events, the percent of the Canadian record in each respective athlete’s main event was determined based on each athlete’s seasonal best performances in that event. It was theorized that this would give the best relative measure of performance since more accomplished athletes would have achieved closer performances to these national records. Subsequently, a bivariate Pearson’s correlation was used to determine significant relationships between the participants’ percentage of Canadian record with variables obtained from the testing protocol (i.e. fatigue index, maximum power, average and maximal difference in single leg jumping distance, and 2-leg standing long jump distance). Significant correlations were determined at an alpha p < 0.05, and correlations (r) and p-value were reported.

Because performance times could not be computed for non-track and field athletes, two measures of performance, fatigue index and maximum power (determined in the running based anaerobic test), were used to examine performance and limb asymmetry relationships within all participants. Significant correlations were set at an alpha p < 0.05, and correlations (r) and p-value were reported.
Bivariate correlations using the Spearman’s rho statistic were performed for the ordinal data of diet, motivation, last week of training and fatigue rating versus jump performance and RAST test variables. Bivariate Pearson’s correlations were determined for the hours since last meal or training and the performance variables. Significant correlations were set at an alpha of $p<0.05$. The rho statistic, $r$ and p-value were reported appropriate to each test.

The participants were then grouped based on injury occurrence within the last two weeks and one year (two separate analyses), and the mean limb asymmetry differences between those who self-reported an injury and those who had not were compared using an independent samples t-test. Significant differences were determined at $p<0.05$.

**ANALYSIS OF RESULTS**

**Participant characteristics**

Twenty-one males and seventeen females completed the study. Athletes were tested at the peak of their competitive season (immediately prior to CIS championships or after being eliminated from the playoffs). However, all athletes were still currently training. Participant characteristics, including anthropometry and pre-test variables, as well as statistical comparisons are listed in Table 1 and 2. Males were significantly taller, heavier and had larger BMIs and also exhibited greater performance measures for standing long jump (2 legs), maximum power and fatigue index. Differences between sports are noted in the tables, however, there were no significant interactions between sex
and sport. For sport, the group sizes were unequal, however, this was observed not to be significant, so harmonic means of group sizes were used, resulting in type I error levels not being guaranteed.
<table>
<thead>
<tr>
<th>Sex</th>
<th>Sport</th>
<th>Age (yrs)</th>
<th>Weight (kg)**</th>
<th>Height (m)*</th>
<th>BMI**</th>
<th>Left Leg Length (cm)*</th>
<th>Right Leg Length (cm)*c</th>
<th>Jump Max Diff (cm)</th>
<th>Max Standing (cm)</th>
<th>Long Jump (cm)*</th>
<th>Max Power (W)*c</th>
<th>Fatigue Index**c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male</td>
<td>Track (n=8)</td>
<td>20.5 (2.2)</td>
<td>70.9 (7.3)</td>
<td>1.78 (0.09)</td>
<td>22.3 (1.2)</td>
<td>95.88 (4.88)</td>
<td>95.69 (5.20)</td>
<td>9.38 (5.71)</td>
<td>249.50 (28.57)</td>
<td>784.13 (167.03)</td>
<td>9.40 (4.13)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Basketball (n=6)</td>
<td>19.7 (1.0)</td>
<td>90.3 (13.5)</td>
<td>1.94 (0.09)</td>
<td>24.0 (2.6)</td>
<td>108.00 (4.12)</td>
<td>108.08 (4.42)</td>
<td>12.33 (13.23)</td>
<td>245.67 (13.40)</td>
<td>1082.83 (272.91)</td>
<td>15.79 (6.48)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Volleyball (n=7)</td>
<td>20.4 (1.4)</td>
<td>83.2 (13.8)</td>
<td>1.82 (0.07)</td>
<td>25.0 (3.5)</td>
<td>100.07 (5.69)</td>
<td>99.43 (5.75)</td>
<td>9.00 (5.07)</td>
<td>250.57 (10.89)</td>
<td>841.29 (97.13)</td>
<td>10.16 (1.80)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total Mean</td>
<td>20.2 (1.5)</td>
<td>81.5 (11.5)</td>
<td>1.85 (0.08)</td>
<td>23.8 (2.4)</td>
<td>101.32 (4.90)</td>
<td>101.07 (5.12)</td>
<td>10.24 (8.00)</td>
<td>248.58 (17.62)</td>
<td>902.75 (179.02)</td>
<td>11.78 (4.14)</td>
<td></td>
</tr>
<tr>
<td>Female</td>
<td>Track (n=5)</td>
<td>21.8 (2.8)</td>
<td>53.9 (4.7)</td>
<td>1.64 (0.07)</td>
<td>20.1 (1.0)</td>
<td>87.00 (4.26)</td>
<td>86.30 (4.63)</td>
<td>10.40 (3.36)</td>
<td>191.00 (22.54)</td>
<td>374.40 (71.58)</td>
<td>2.70 (1.54)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Basketball (n=3)</td>
<td>20.3 (1.2)</td>
<td>64.8 (6.3)</td>
<td>1.70 (0.08)</td>
<td>22.5 (0.2)</td>
<td>93.33 (3.06)</td>
<td>98.83 (4.25)</td>
<td>11.67 (2.89)</td>
<td>219.33 (9.71)</td>
<td>625.67 (66.79)</td>
<td>8.73 (2.07)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Volleyball (n=9)</td>
<td>19.2 (1.6)</td>
<td>68.7 (5.1)</td>
<td>1.73 (0.03)</td>
<td>22.9 (1.6)</td>
<td>94.89 (3.82)</td>
<td>94.44 (3.36)</td>
<td>6.00 (3.32)</td>
<td>202.00 (16.64)</td>
<td>473.33 (70.13)</td>
<td>4.64 (1.68)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total Mean</td>
<td>20.5 (1.9)</td>
<td>62.5 (5.4)</td>
<td>1.69 (0.06)</td>
<td>21.9 (0.9)</td>
<td>91.74 (3.71)</td>
<td>91.52 (4.08)</td>
<td>9.36 (3.19)</td>
<td>204.11 (16.30)</td>
<td>491.13 (69.50)</td>
<td>5.36 (1.76)</td>
<td></td>
</tr>
</tbody>
</table>

* Significant difference between males and females (p<0.05)
**Track significantly different than Basketball
***Track significantly different than Volleyball
++++Volleyball significantly different than Basketball
| Sex  | Sport  | Diet Rating $^{abc}$ | Hours since last meal | Hours since last training | Illness Current | Illness last 2 weeks | Illness last 12 months | Injury Current | Injury last 2 weeks | Injury last 12 months | Meds/Supplements Current | Meds/Supplements last 2 weeks | Motivation for training $^{ab}$ | Motivation for testing $^{ab}$ | Motivation last week $^{a}$ | Fatigue rating $^{d}$ | Fatigue rating hours since last training $^{ab}$ |
|------|--------|-----------------------|-----------------------|--------------------------|----------------|---------------------|----------------------|---------------|-------------------|----------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|----------------|--------------------------------------------------|
| Male | Track  | 3.0 (0.5) 1.6 (0.6)   | 0 1 0 3 0 4           | 3.3 (0.7) 3.4 (0.7)     | 2.6 (0.9)     | 1.5 (0.8)           | 13.6 (5.5)          | Basketball 2.7 (0.5) 1.3 (0.6) 0 0 2 3 1 2 2.7 (1.0) 2.3 (0.8) 1.8 (0.8) 2.0 (0.9) 37.9 (46.8) | Volleyball 2.7 (0.8) 2.5 (1.6) 1 0 1 1 1 2 3.3 (0.5) 3.3 (0.5) 3.0 (0.8) 2.1 (1.1) 28.5 (27.5) | **Total Mean** 2.8 (0.6) 1.8 (0.9) 1 1 3 7 2 8 3.1 (0.7) 3.0 (0.7) 2.5 (0.8) 1.9 (0.9) 26.7 (26.6) |
|      | Basketball | 2.7 (0.5) 1.3 (0.6)   | 0 0 2 3 1 2           | 2.7 (1.0) 2.3 (0.8)     | 1.8 (0.8)     | 2.0 (0.9)           | 37.9 (46.8)          | Basketball 2.7 (0.5) 1.3 (0.6) 0 0 2 3 1 2 2.7 (1.0) 2.3 (0.8) 1.8 (0.8) 2.0 (0.9) 37.9 (46.8) | Volleyball 2.7 (0.8) 2.5 (1.6) 1 0 1 1 1 2 3.3 (0.5) 3.3 (0.5) 3.0 (0.8) 2.1 (1.1) 28.5 (27.5) | **Total Mean** 2.8 (0.6) 1.8 (0.9) 1 1 3 7 2 8 3.1 (0.7) 3.0 (0.7) 2.5 (0.8) 1.9 (0.9) 26.7 (26.6) |
| Female | Track  | 3.6 (0.6) 2.2 (0.6)   | 0 0 1 1 0 2           | 3.4 (0.6) 3.4 (0.6)     | 3.2 (1.3)     | 2.8 (0.8)           | 16.0 (20.2)          | Basketball 1.3 (0.6) 2.3 (1.8) 0 0 0 2 1 1 2.0 (1.0) 2.3 (0.6) 2.3 (0.6) 3.0 (1.7) 62.0 (52.4) | Volleyball 2.8 (0.4) 1.8 (0.8) 1 3 1 4 3 6 3.1 (0.6) 3.0 (0.5) 2.6 (0.5) 1.9 (0.8) 20.3 (10.1) | **Total Mean** 2.6 (0.5) 2.1 (1.0) 1 3 2 7 4 9 2.8 (0.7) 2.9 (0.5) 2.7 (0.8) 2.6 (1.1) 32.8 (27.6) |
|      | Basketball | 1.3 (0.6) 2.3 (1.8)   | 0 0 0 2 1 1           | 2.0 (1.0) 2.3 (0.6)     | 2.3 (0.6)     | 3.0 (1.7)           | 62.0 (52.4)          | Basketball 1.3 (0.6) 2.3 (1.8) 0 0 0 2 1 1 2.0 (1.0) 2.3 (0.6) 2.3 (0.6) 3.0 (1.7) 62.0 (52.4) | Volleyball 2.8 (0.4) 1.8 (0.8) 1 3 1 4 3 6 3.1 (0.6) 3.0 (0.5) 2.6 (0.5) 1.9 (0.8) 20.3 (10.1) | **Total Mean** 2.6 (0.5) 2.1 (1.0) 1 3 2 7 4 9 2.8 (0.7) 2.9 (0.5) 2.7 (0.8) 2.6 (1.1) 32.8 (27.6) |

Diet Rating was self-reported on a scale from 1 (poor)- 4 (excellent)
Illness (both current and last 2 weeks) was self-reported by stating 'yes' or 'no'
Injury (both current and last 12 months) was self-reported by stating 'yes' or 'no'
Medication and supplement use (both current and last 2 weeks) was self-reported by stating 'yes' or 'no'
Motivation for training and testing was self-reported on a scale from 1 (poor)- 4 (excellent)
Last weeks training was self-reported on a scale from 1 (easy)- 4 (very hard)
Current fatigue rating was self-reported on a scale from 0-5

$^a$Significant difference between track&field and basketball
$^b$Significant difference between volleyball and basketball
$^c$Significant difference between track&field and volleyball
$^d$Significant difference between males and females
A significant main effect for sex (males greater than females) was observed for height, weight, BMI and limb lengths (p<0.05). A significant main effect for sport was observed in diet rating, motivation for testing and training, hours since last trained and last week’s training rating (p<0.05). Post-hoc analysis revealed that track and field athletes rated their diet, motivation for training, and motivation for testing significantly higher than volleyball and basketball athletes. Track and field athletes also had significantly less hours since they had last trained over volleyball and basketball, and rated their training in the last week harder than basketball athletes (Table 2).

Maximum single leg jumps and leg dominance

When dominant and non-dominant leg maximum jumps were compared across all three jumps, a significant main effect was found between each of the three jumps (F=87.716, p<0.05, \( \eta^2_p = 0.703 \)). A significant main effect was also found between dominant and nondominant legs (F=71.510, p<0.05, \( \eta^2_p = 0.659 \)). No significant interaction was found between jump number and leg dominance. In post-hoc analysis, it was observed that each jump significantly improved compared to the previous jump in both the dominant and non-dominant legs (Figure 3).
Figure 3. Effect of jump order, leg dominance and sex on single leg jump distance. Males (M, black and white bars) jumped significantly greater distances than females (F, gray bars) irrespective of jump order or dominant leg (†, p<0.05). Participants jumped significantly greater distance on the dominant (Dom; black bars for males, dark gray bars for females) leg versus the non-dominant (N Dom; white bars for males, light gray bars for females) leg irrespective of sex and jump order (*, p<0.05). Each jump was significantly greater than the previous jump indicated by a significant main effect for jump order (β, p<0.05).
Performance correlates - Track and Field Athletes

Eleven of the participants that competed in track and field events had posted performance times that were obtained via Canadian Interuniversity Sport (CIS) and Ontario University Athletics (OUA) websites. These performance times were then converted to a percentage of the current Canadian Records to best compare multiple events. Significant correlations were observed for maximum power ($r=-0.695$, $p=0.018$), and fatigue index ($r=-0.810$, $p=0.002$) with performance as determined by percentage of Canadian records ($p<0.05$) (Table 3). A graphical representation of the power outputs for these eleven track and field athletes, along with their respective events, can be seen in Appendix E.
TABLE 3. Correlation Matrix for Predictors of Percent of Canadian Records in track and field athletes

<table>
<thead>
<tr>
<th></th>
<th>r</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMI</td>
<td>-0.390</td>
<td>0.236</td>
</tr>
<tr>
<td>Leg Length Difference</td>
<td>-0.211</td>
<td>0.534</td>
</tr>
<tr>
<td>Maximum Jump Difference</td>
<td>-0.094</td>
<td>0.784</td>
</tr>
<tr>
<td>Minimum Jump Difference</td>
<td>-0.580</td>
<td>0.062</td>
</tr>
<tr>
<td>Average Jump Difference</td>
<td>-0.598</td>
<td>0.052</td>
</tr>
<tr>
<td>Maximum Two-Leg Jump</td>
<td>-0.378</td>
<td>0.252</td>
</tr>
<tr>
<td>Maximum Power</td>
<td>-0.695*</td>
<td>0.018</td>
</tr>
<tr>
<td>Fatigue Index</td>
<td>-0.810*</td>
<td>0.002</td>
</tr>
</tbody>
</table>

Pearson’s correlations (r) were determined for select variables and Significance was determined at an alpha p<0.05*.
Figure 4. Scatter plot of maximum power (A) and fatigue index (B) versus best track and field performance as determined by % of the Canadian record. Gray dotted line represents line of best fit ($r = -0.695$ and $-0.810$ for maximum power and fatigue index, respectively, versus % of Canadian record).
Performance correlates - All Athletes

Because participants on team sports could not be adequately compared to a Canadian record and because male and female participants differed with respect to anthropometrics and some performance measurements, participants were then grouped based on sex and event type and correlations were used to determine significant relationships between maximal single-leg jumping difference (dominant – non-dominant) and those predictors of increased performance (i.e. maximum power, average power, and fatigue index). No significant correlations were observed between maximum single leg jump difference and any of the performance variables in any sport and in either males or females (Table 4-9). In male volleyball players, BMI was observed to have a significant correlation with fatigue index (r=-0.843, p=0.017) and in female basketball players minimum jump difference was correlated with fatigue index (r=-1.00, p=0.006).
TABLE 4. Correlation Matrix for Performance Variables in Female Track and Field Athletes

<table>
<thead>
<tr>
<th></th>
<th>Maximum Power</th>
<th>Fatigue Index</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$r$</td>
<td>$p$</td>
</tr>
<tr>
<td>BMI</td>
<td>-0.865</td>
<td>0.058</td>
</tr>
<tr>
<td>Leg Length Difference</td>
<td>-0.218</td>
<td>0.725</td>
</tr>
<tr>
<td>Maximum Jump Difference</td>
<td>-0.435</td>
<td>0.464</td>
</tr>
<tr>
<td>Minimum Jump Difference</td>
<td>0.165</td>
<td>0.791</td>
</tr>
<tr>
<td>Average Jump Difference</td>
<td>-0.174</td>
<td>0.780</td>
</tr>
<tr>
<td>Maximum Two-Leg Jump</td>
<td>0.834</td>
<td>0.079</td>
</tr>
</tbody>
</table>

Pearson’s correlations ($r$) were determined for select variables and Significance was determined at an alpha $p<0.05^*$.  

TABLE 5. Correlation Matrix for Performance Variables in Male Track and Field Athletes

<table>
<thead>
<tr>
<th></th>
<th>Maximum Power</th>
<th>Fatigue Index</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$r$</td>
<td>$p$</td>
</tr>
<tr>
<td>BMI</td>
<td>0.161</td>
<td>0.703</td>
</tr>
<tr>
<td>Leg Length Difference</td>
<td>-0.081</td>
<td>0.848</td>
</tr>
<tr>
<td>Maximum Jump Difference</td>
<td>-0.153</td>
<td>0.718</td>
</tr>
<tr>
<td>Minimum Jump Difference</td>
<td>0.561</td>
<td>0.148</td>
</tr>
<tr>
<td>Average Jump Difference</td>
<td>0.392</td>
<td>0.337</td>
</tr>
<tr>
<td>Maximum Two-Leg Jump</td>
<td>0.744*</td>
<td>0.034</td>
</tr>
</tbody>
</table>

Pearson’s correlations ($r$) were determined for select variables and Significance was determined at an alpha $p<0.05^*$.  

35
TABLE 6. Correlation Matrix for Performance Variables in Female Volleyball Athletes

<table>
<thead>
<tr>
<th></th>
<th>Maximum Power</th>
<th>Fatigue Index</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>r</td>
<td>p</td>
</tr>
<tr>
<td>BMI</td>
<td>0.594</td>
<td>0.092</td>
</tr>
<tr>
<td>Leg Length Difference</td>
<td>-0.654</td>
<td>0.056</td>
</tr>
<tr>
<td>Maximum Jump Difference</td>
<td>0.082</td>
<td>0.835</td>
</tr>
<tr>
<td>Minimum Jump Difference</td>
<td>-0.231</td>
<td>0.550</td>
</tr>
<tr>
<td>Average Jump Difference</td>
<td>-0.044</td>
<td>0.910</td>
</tr>
<tr>
<td>Maximum Two-Leg Jump</td>
<td>0.265</td>
<td>0.491</td>
</tr>
</tbody>
</table>

Pearson’s correlations (r) were determined for select variables and Significance was determined at an alpha p<0.05*.

TABLE 7. Correlation Matrix for Performance Variables in Male Volleyball Athletes

<table>
<thead>
<tr>
<th></th>
<th>Maximum Power</th>
<th>Fatigue Index</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>r</td>
<td>p</td>
</tr>
<tr>
<td>BMI</td>
<td>0.218</td>
<td>0.638</td>
</tr>
<tr>
<td>Leg Length Difference</td>
<td>-0.088</td>
<td>0.851</td>
</tr>
<tr>
<td>Maximum Jump Difference</td>
<td>-0.132</td>
<td>0.778</td>
</tr>
<tr>
<td>Minimum Jump Difference</td>
<td>0.713</td>
<td>0.072</td>
</tr>
<tr>
<td>Average Jump Difference</td>
<td>0.326</td>
<td>0.475</td>
</tr>
<tr>
<td>Maximum Two-Leg Jump</td>
<td>0.526</td>
<td>0.225</td>
</tr>
</tbody>
</table>

Pearson’s correlations (r) were determined for select variables and Significance was determined at an alpha p<0.05*.
TABLE 8. Correlation Matrix for Performance Variables in Female Basketball Athletes

<table>
<thead>
<tr>
<th></th>
<th>Maximum Power</th>
<th>Fatigue Index</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>r</td>
<td>p</td>
</tr>
<tr>
<td>BMI</td>
<td>-0.512</td>
<td>0.658</td>
</tr>
<tr>
<td>Leg Length Difference</td>
<td>-0.618</td>
<td>0.576</td>
</tr>
<tr>
<td>Maximum Jump Difference</td>
<td>0.990</td>
<td>0.091</td>
</tr>
<tr>
<td>Minimum Jump Difference</td>
<td>-0.992</td>
<td>0.079</td>
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<tr>
<td>Average Jump Difference</td>
<td>0.945</td>
<td>0.212</td>
</tr>
<tr>
<td>Maximum Two-Leg Jump</td>
<td>-0.831</td>
<td>0.376</td>
</tr>
</tbody>
</table>

Pearson’s correlations (r) were determined for select variables and Significance was determined at an alpha p<0.05*.

TABLE 9. Correlation Matrix for Performance Variables in Male Basketball Athletes

<table>
<thead>
<tr>
<th></th>
<th>Maximum Power</th>
<th>Fatigue Index</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>r</td>
<td>p</td>
</tr>
<tr>
<td>BMI</td>
<td>0.533</td>
<td>0.277</td>
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<tr>
<td>Leg Length Difference</td>
<td>0.052</td>
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<tr>
<td>Maximum Jump Difference</td>
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<td>0.459</td>
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<tr>
<td>Minimum Jump Difference</td>
<td>-0.450</td>
<td>0.370</td>
</tr>
<tr>
<td>Average Jump Difference</td>
<td>-0.582</td>
<td>0.225</td>
</tr>
<tr>
<td>Maximum Two-Leg Jump</td>
<td>-0.031</td>
<td>0.954</td>
</tr>
</tbody>
</table>

Pearson’s correlations (r) were determined for select variables and Significance was determined at an alpha p<0.05*.
Diet, motivation, training and fatigue ratings versus performance

Spearman’s correlations were determined for the rank ordinal data obtained on the pre-test questionnaire and the performance of the jump and RAST tests, while Pearson’s correlations were determined for hours since last meal or training and these same performance variables for all participants. Rho, r and p-values are reported in Table 10. A significant negative relationship was observed between diet rating and fatigue index (rho = -0.335, p = 0.040) and significant positive relationships were found between hours since last training session and both maximum power and fatigue index (r = 0.363, p = 0.030 and r = 0.460, p = 0.005, respectively).
Table 10. Correlation Matrix for all Participants Pre-Test self-reports and Performance Variables

<table>
<thead>
<tr>
<th></th>
<th>Hours since Last Meal</th>
<th>Diet Rating</th>
<th>Motivation for Training</th>
<th>Motivation for Testing</th>
<th>Last Week Training Rating</th>
<th>Fatigue Rating</th>
<th>Hours since last training</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Jump Difference</td>
<td>-0.023</td>
<td>0.892</td>
<td>0.108</td>
<td>0.520</td>
<td>-0.121</td>
<td>0.468</td>
<td>-0.481</td>
</tr>
<tr>
<td>Maximum Two-Leg Jump</td>
<td>-0.267</td>
<td>0.105</td>
<td>-0.159</td>
<td>0.341</td>
<td>-0.033</td>
<td>0.844</td>
<td>-0.009</td>
</tr>
<tr>
<td>Maximum Power</td>
<td>-0.181</td>
<td>0.276</td>
<td>-0.248</td>
<td>0.133</td>
<td>-0.216</td>
<td>0.194</td>
<td>-0.228</td>
</tr>
<tr>
<td>Fatigue Index</td>
<td>-0.186</td>
<td>0.265</td>
<td>-0.335*</td>
<td>0.040</td>
<td>-0.356*</td>
<td>0.028</td>
<td>-0.336*</td>
</tr>
</tbody>
</table>

Spearman’s correlations (rho) were determined for rank ordinal data while Pearson’s (r) were performed for hours since last meal and last training session and the performance variables. * represents significant correlations at an alpha p<0.05.
Injury and limb asymmetry

To determine if previous injury had any effect on muscle imbalance, two separate independent T-tests were used to determine if mean maximum jump differences were different between participants with and without injury in the last 2 weeks or 12 months (Figure 5A and B, respectively). For those participants with injuries within the last 2 weeks, a significant difference in maximum jumping distance difference was observed (t=3.703; p<0.05), however, there was no significant difference in maximum jumping distance difference when those individuals with injuries over the past year were compared with those without injury (t=1.132; p>0.05).
Figure 5. Difference between maximum single-leg jump of each leg among individuals with and without injury in the 2 weeks prior to testing (A) and within the prior 12 months (B). Data are presented as individual data points and mean difference for each group (solid black bar). Mean maximum jump difference was significantly greater in the group that reported injury (n=5) within the last 2 weeks compared to the uninjured group (n=33) (*, p<0.05). A significant difference was not observed when participants reporting injury within the last 12 months (n=14) was compared with the uninjured group (n=24). Note that some data points overlap in the non-injured group.
DISCUSSION

The intent of this research was to explore the effect of lower body functional asymmetry on running performance in collegiate level athletes. Lower body functional asymmetries were assessed using a single-leg standing long jump protocol, and differences were recorded between distances jumped on each leg. In support of our first hypothesis, a lower body bilateral functional asymmetry was observed. This is similar to the findings of Hewett et al. (1996) who observed an imbalance in jumping performance prior to attempting to correct this imbalance with specific plyometric training. However, a performance related significance of this finding was not observed given that maximum single leg jumping difference was not correlated with performance as measured by either percent of Canadian record in track and field athletes or by fatigue index and power output in all athletes.

There were 11 participants that competed in track and field events who had CIS (Canadian Interuniversity Sport) or OUA (Ontario University Athletics) results posted on the respective website. These results were correlated with variables obtained from the testing sessions to determine predictors of performance. To allow for an accurate comparison of these 11 participants, their individual results were converted into a percentage of the current Canadian record for each event. These percentages were then correlated with variables obtained from the testing sessions to determine if there was a relationship between any of these variables and performance. Maximum jump distance difference was not found to be correlated with performance, however, maximum power output, average power output, and fatigue index were found to be significant predictors of
performance, as measured by the percent of Canadian record. Moreover, these predictors were quite strong (r values greater than 0.5 in all cases, Table 3). While this could be expected, the direction (negative) of the relationship for power and performance is indicative of a difficulty in comparing athletes who require a range of physical characteristics (see below and limitations).

Power, both average and maximum, as measured by the RAST test was significantly negatively correlated with performance in the track and field athletes. This finding is likely due to the range of athletes within the track and field group, with varying competition distances (i.e. 100m, 800m, 3000m). For example, a distance runner (>1500m) would not necessarily benefit from high maximum power as it would not result in improved performance, however, the maintenance of a moderate power output over an extended period of time would better predict improved performance in this type of athlete. Conversely, a short distance sprinter would rely on high maximum power maintained for a much shorter period of time to achieve maximal success. Of the track and field participants we tested, the individuals with the highest percent of the Canadian record, or the best performers (nationally and internationally ranked), were middle distance runners. Therefore the correlation between power and performance was likely influenced by their achievement. Nonetheless, all of the athletes tested would benefit from a low fatigue index (or high maintenance of power output), and this was, again, significantly correlated with performance as dictated by percent of the Canadian record. In fact, fatigue index was the strongest predictor of performance in this regard (r = -0.810). From a practical standpoint, this is notable. The RAST test takes less than 5
minutes to perform and quickly gives a coach or athlete information that could be used in either talent identification or training markers.

The difference between maximum jumping distance of the dominant and non-dominant leg was chosen as the primary marker of lower limb power asymmetry because it was found that jumping distance improved with successive jumps and this could be indicative of a familiarization effect. Also, maximum jump distance is indicative of maximal leg power whereas average or minimal power output could physiologically be compensated for simply by recruiting more muscle fibres to output a higher degree of power in the weaker leg. Consequently, mainly because of this familiarization effect, the difference between legs would be minimized (and hence be more conservative) as opposed to using either the average jumping difference or difference between shortest jumps. However, it is important to note that in the correlations with performance (i.e. % of Canadian record for track and field athletes), differences between the shortest jumps of each leg and the average jumping difference neared significance (p=0.062 and p=0.052, respectively; Table 3). Because familiarization is dependent on a neuromuscular component more than strength, these findings may be indicative of a neuromuscular imbalance between legs that could include differences in central drive, motor unit recruitment (number and synchronicity), alpha motor neuron discharge, autogenic inhibition and/or agonist-antagoinst muscle co-activation. As noted previously, minor differences in ability can have profound implications and even a single non-optimal step (at the start of a race for example) could
impact overall performance. Testing this component of running was not a major objective of the present study, but these findings suggest future studies are required.

Given that fatigue index and maximal power exhibited such strong relationships with Track and Field athletic performance, correlates with these measures were determined in athletes from other sports (i.e. basketball and volleyball). Interestingly, there was no distinct pattern as to the measured variables and performance in either of these 2 measures (i.e. maximum power and fatigue index). It was clear, however, that maximum jumping difference did not correlate with any of these variables. This is suggestive of the complex nature of performance, testing significant in any of the variables provided by this test (muscle imbalance, maximum power, fatigue index, etc.) does not directly result in success in each respective sport. To be successful in sport, more is required than simple physical ability, which our measured variables indicate. The highest jump is not necessarily the best volleyball player, nor is the fastest skater the best hockey player. In this sense, we also employed a self-report of diet, motivation, illness and fatigue and correlated this with performance on the physiological tests employed. Motivation for training and testing and diet rating were significantly higher and fatigue rating was significantly lower (indicating less fatigue) in the track and field athletes than either volleyball or basketball players (Table 2). Moreover, track and field athletes reported less time since their last training bout than basketball players. Consequently, it is possible that the track athletes performed closer to their true maximum efforts in the tests we used, confounding analysis within the entire group of participants when including basketball and volleyball athletes.
Injuries can decrease performance (Verrall et al., 2006). As a result of this, our pre-test questionnaire required participants to self-report injury within the last two weeks and the previous one year. Significant differences in lower limb power asymmetry were observed between participants who reported an injury within the last 2 weeks, but not last year, and those participants who had not. These findings suggest that previous injury not only influenced the performance on the jumping and RAST tests, but also that injury could potential contribute to a higher degree of lower limb imbalance. Further, although injury occurrence was not tracked subsequent to testing, these results indicate that a simple jumping test could potentially be used by a coach or therapist to expose previously unreported/unknown injury in an athlete. This is especially true if this assessment tool is tracked over the span of a training season.

In conclusion, while a significant difference between dominant and non-dominant legs in lower limb power, as determined by jumping distance, was observed, the difference between the maximum jumps off of each leg did not significantly correlate with any measure of performance. However, it was found that those athletes who reported injury within the last 2 weeks showed significantly greater limb asymmetry than those without, implicating this simple field ready jumping test as a potential predictor of injury in athletes. Moreover, the field ready running based anaerobic test (RAST) could be used as a measure of talent identification and performance metric given the strong correlation between fatigue index and performance. These quick field-ready assessment tools that do not require expensive equipment would benefit coaches and athletes at all
levels. More research needs to be performed regarding the practical implications of the observed lower limb functional asymmetry.

**LIMITATIONS**

A possible limitation of this study was that the running based anaerobic sprint test only has the participant running increments of 35 meters. With such a short distance, differences and results may have been reduced due to the short period of time to complete each 35 meter sprint. However, this is a standard anaerobic sprint test that correlates well with running performance and has been used in previous research and has been determined to be a reliable and valid test (Zagatto, et al., 2009).

In this investigation, the variability exists not only within each participant, but within each leg of each participant. This variability can be observed when looking at the variance in the three jumping distances on the same leg. This variability acts as a limitation in our investigation to the extent of, without significant training or familiarization with the jumping protocol, the single leg jumps may not be the most accurate representation of single leg muscle power. Moreover, when the data were analyzed, the stronger leg, determined by jumping distance, was labelled as the dominant leg. By doing this, a difference between the dominant and nondominant leg was almost guaranteed. This method however, has been previously used in research (Stephens II et al., 2007) and has been accepted as common practice to remove any variability in participant self-report of their dominant leg. For example, an individual may kick with their right leg, but jump prefer to jump off of the left leg. Nonetheless, participants
consistently showed a dominant leg (i.e. jumped farther off of one leg than the other in all 3 jump trials).

Different sporting events require different skill sets to be successful. For example, a basketball player’s ability to jump is going to be a more purposeful skill than a hockey player’s ability to jump. Therefore, by doing a vertical jump test with these two types of athletes, it is very difficult to compare the results, especially when attempting to extrapolate them into a playing environment in their respective sports. Likewise, in the current investigation, participants consisted of athletes from different sport disciplines. Basketball and volleyball players utilize jumping in their sports much more frequently than runners, and the jumping patterns may predispose them to a higher degree of muscle imbalance. For this reason, when analyzing the data, it was appropriate to group participants into their respective sports. Dividing the sample into so many groups significantly reduced the sample size for each group.

Lastly, although the study sample included a range of athletic abilities, the athletes were varsity level and consequently; it is possible that any differences would be small as a result of similar training volumes and styles. Nonetheless, as noted in the introduction, small measured differences can account for large performance differences in competition and the implications of this study are most applicable to this sample cohort. Consequently, a sample of untrained individuals would provide little information and relevance, whereas a larger sample that included both less and more trained collegiate athletes would undoubtedly strengthen and confirm the present findings.
IMPLICATIONS AND FUTURE DIRECTIONS

Implications of the findings of this investigation include the application of the simple testing protocols used in the study by coaches and athletes alike so determine the existence of a lower limb functional asymmetry, and also to measure an athlete’s potential performance through the variable used in this investigation (maximum power, average power, and fatigue index). It could also potentially change the type of training an athlete does, focusing more on unilateral movements to attempt to correct for an existing muscle imbalance, to potentially improve performance.

While the hypothesis that lower limb functional asymmetry would be significantly correlated with performance was not supported by the current investigation, the findings do support additional investigation into the predictive ability of lower limb functional asymmetry on both performance and injury. Most importantly, studies could be conducted to determine the relevance of a significant correlation between single leg minimum jump difference and performance. Given that this was predominantly observed during the first jump of the series on each leg, it may be indicative of a neuromuscular component of performance. Further, these data need to be confirmed in a larger sample size with a larger number of representative sports and a more varied performance metric. From a practical standpoint, this is difficult due to the logistics of testing many collegiate level athletes in the same event/sport. Further, investigation of a specific training regimen to reduce lower limb asymmetries, whether the training results in strength or neuromuscular changes, could be investigated to determine performance improvements.
Again, in a collegiate level athlete, there is only a small window in which this may be accomplished so as to not interfere with normal periodization of training and competition tapering schedules.
REFERENCES


APPENDICES

APPENDIX A

Pre-Test Questionnaire

Name:_____________________________________ Date:________________________

Events :____________________________________________________________________

Date of Birth:_____/_____/_____ Gender:_____ Height(cm):______ Weight(kg):______

Testing Location :_____________________________ Testing Surface :____________

Ambient Temp :______________ Humidity :____________ Testing Time :__________

E-mail:________________________________________

Emergency Contact Name:_____________________________________________________

Emergency Contact Phone Number:____________________________________________

Diet

How would you rate your diet over the last 2 days?

__ Poor   __ OK   __ Good   __ Excellent

How many hours ago did you eat your last meal? _____________________

Record foods eaten over the last 24 h:

Breakfast:

Lunch:
Illness

Are you currently suffering from any type of illness?  __ Yes  __ No
If yes, provide details: ______________________________________________________

Have you had any type of illness or health problem over the last 2 weeks? __ Yes  __ No
If yes, provide details: ______________________________________________________

Injury

Do you currently have any injuries?  __ Yes  __ No
If yes, provide details: ______________________________________________________

Have you had any injuries in the last 12 months? __ Yes  __ No
If yes, provide details: ______________________________________________________

Medications and Supplements

Are you currently taking any medication?  __ Yes  __ No
If yes, provide details: ______________________________________________________

Have you taken any medication over the last 2 weeks?  __ Yes  __ No
If yes, provide details: ______________________________________________________

Have you taken any supplements over the last 2 weeks?  __ Yes  __ No
If yes, provide details: ______________________________________________________

Motivation

Evaluate your motivation for training today
__ Poor  __ OK  __ Good  __ Excellent

Evaluate your motivation for testing today
__ Poor  __ OK  __ Good  __ Excellent

Training

Evaluate your last week of physical training
__ Easy  __ Moderate  __ Hard  __ Very Hard

How fatigued are you today? (0=not at all; 5=extremely)
__ 0  __ 1  __ 2  __ 3  __ 4  __ 5

How many hours ago did you last exercise? _______

Describe your last three training sessions (include distances, time & difficulty):

Today:

Yesterday:

2 Days Ago:

Miscellaneous

Please provide any additional information that you believe may influence your testing results:

________________________________________________________________________
________________________________________________________________________
________________________________________________________________________
________________________________________________________________________
APPENDIX B

ACSM Health Pre-Participation Screening Questionnaire

Name:______________________________________  Sex: __M   __F

D.O.B.:____________________________________  Date:____________________________________

Sport:____________________________________  E-mail:____________________________________

Assess your health needs by marking all true statements.

History

You have had:

___ A heart attack

___ Heart surgery

___ Cardiac catheterization

___ Coronary angioplasty (PTCA)

___ Pacemaker/implantable cardiac defibrillator/rhythm disturbance

___ Heart valve disease

___ Heart failure

___ Heart transplant

___ Congenital heart disease

Symptoms

___ You experience chest discomfort with exertion

___ You experience unreasonable breathlessness

___ You experience dizziness, fainting, or blackouts

___ You take heart medications

Other Health Issues
___ You have diabetes
___ You have asthma or other lung disease
___ You have burning or cramping sensations in your lower legs when walking distances
___ You have musculoskeletal problems that limit your physical activity
___ You have concerns about the safety of exercise
___ You take prescription medications
___ You are pregnant

If you marked any of these statements in this section, consult your physician or other appropriate health care provider before engaging in exercise. You may need to use a facility with a medically qualified staff.

Cardiovascular Risk Factors
___ You are a man older than 45 years
___ You are a woman older than 55 years, have had a hysterectomy, or are postmenopausal
___ You smoke, or quit smoking within the previous 6 months
___ Your blood pressure is >140/90 mmHg
___ You do not know your blood pressure
___ You take blood pressure medication
___ Your blood cholesterol level is >200 mg*dl-1
___ You do not know your cholesterol level
___ You have a close blood relative who had a heart attack or heart surgery before age 55 (father or brother) or age 65 (mother or sister)
___ You are physically inactive (ie. you get < 30 minutes of physical activity on at least 3 days per week)

___ You are > 20 pounds overweight

If you marked two or more of the statements in this section you should consult your physician or other appropriate health care provider before engaging in exercise. You might benefit from using a facility with a professionally qualified exercise staff to guide your exercise program.

___ None of the above

You should be able to exercise safely without consulting your physician or other appropriate health care provider in a self-guided program or almost any facility that meets your exercise program needs.

Source: American Heart Association/ACSM Health/Fitness Facility Preparticipation Screening Questionnaire (ACSM 2010). From Australian Institute of Sport, 2013, Physiological tests for elite athletes, 2nd ed. (Champaign, IL: Human Kinetics).
APPENDIX C

Barbell Bench Press and Barbell Back Squat
APPENDIX D
Research Ethics Board Approval

Today's Date: December 12, 2012
Principal Investigator: Mr. Mark Oxford
REB Number: 30462
Research Project Title: REB# 12-201: The Effects of Muscle Imbalance on Running Performance in Collegiate Level Athletes
Clearance Date: December 7, 2012
Project End Date: August 31, 2013
Milestones:
Renewal Due-2013/08/31(Pending)

This is to inform you that the University of Windsor Research Ethics Board (REB), which is organized and operated according to the Tri-Council Policy Statement and the University of Windsor Guidelines for Research Involving Human Subjects, has granted approval to your research project on the date noted above. This approval is valid only until the Project End Date.

A Progress Report or Final Report is due by the date noted above. The REB may ask for monitoring information at some time during the project’s approval period.

During the course of the research, no deviations from, or changes to, the protocol or consent form may be initiated without prior written approval from the REB. Minor change(s) in ongoing studies will be considered when submitted on the Request to Revise form.

Investigators must also report promptly to the REB:
a) changes increasing the risk to the participant(s) and/or affecting significantly the conduct of the study;
b) all adverse and unexpected experiences or events that are both serious and unexpected;
c) new information that may adversely affect the safety of the subjects or the conduct of the study.

Forms for submissions, notifications, or changes are available on the REB website: www.uwindsor.ca/reb. If your data is going to be used for another project, it is necessary to submit another application to the REB.

We wish you every success in your research.

Pierre Boulos, Ph.D.
Chair, Research Ethics Board
301 Assumption University
The information contained in this e-mail message is confidential and protected by law. The information is intended only for the person or organization addressed in this e-mail. If you share or copy the information you may be breaking the law. If you have received this e-mail by mistake, please notify the sender of the e-mail by the telephone number listed on this e-mail. Please destroy the original; do not e-mail back the information or keep the original.
Power output values for 11 track and field athletes, competing in differing events, for each of the six sprints completed. This gives a visual representation of athletes’ peak power output as well as a visual representation of each athlete's fatigue index.
VITA AUCTORIS

Mark Oxford was born in 1989 in Windsor, Ontario. He graduated from Belle River District High School in 2007. From there he went on to the University of Windsor where he obtained a Bachelor of Human Kinetics in 2011. He is currently a candidate for the Masters degree in Human Kinetics at the University of Windsor and hopes to graduate in Fall 2013.