Ability of a Functional Motion Analysis to Predict Running Economy at 10k Race Pace in Trained Male Runners: A Pilot Investigation

By

Justin Maresh

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Chairperson Phil Gallagher, PhD

Phillip Vardiman, PhD, ATC

Joseph Weir, PhD

Date Defended: June 15, 2015
The Thesis Committee for Justin Maresh
certifies that this is the approved version of the following thesis:

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Chairperson Philip Gallagher, PhD

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ABSTRACT

Introduction: Runners have long searched for ways to increase performance and for the ability to quantify these increases in performance. VO_{2max} has long been associated with running performance. Running economy is another performance measure associated with performance, which of late has received increased attention in its influence on race performance. The purpose of this study was to explore the ability of a FMA to predict running economy at 10k race pace in trained male runners by identifying strength imbalances between the legs. Methods: 12 healthy, young, non-injured, trained male runners were recruited for participation. Subjects first completed a FMA at Dynamic Athletics and then within one week completed both an 8 min Running Economy test at 10k race pace and VO_{2max} test. During the RE test, motion capture technology was utilized to measure aspects of gait. Results: No strong relationships were identified between strength imbalances identified in the FMA and running economy at 10k race pace. Few strong relationships were discovered between aspects of the FMA, metabolic and gait measures from the RE and VO_{2max} testing. No strong relationships were identified between strength imbalances in legs from a FMA and stride imbalances at 10k race pace, nor were any strong relationships identified between stride imbalances and running economy at 10k race pace. Conclusion: Based on this investigation, strength imbalances between the legs identified by a FMA do not have any strong relationships with stride imbalances or running economy at 10k race pace, nor is there a strong relationship between stride imbalances and running economy at 10k race pace.
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CHAPTER ONE

Introduction

Runners have long searched for ways to increase performance and for the ability to quantify these increases in performance. VO$_{2\text{max}}$, an athlete’s maximal oxygen uptake, has long been associated with performance in distance running (Saunders et al, 2004). As of late, a variety of other aspects have been explored, both physiological and performance in nature, that affect endurance competition, including race distance, percentage of VO$_{2\text{max}}$ an athlete can maintain without accumulating lactic acid, the athlete’s ability to spare carbohydrate at high velocities, and being able to minimize energy expenditure while maintaining high performance (Saunders et al, 2004). This last is known as running economy, defined as the energy demand for a given velocity of running, and is determined by measuring the steady-state consumption of oxygen and the respiratory exchange ratio (Saunders et al, 2004).

Running economy has become a popular subject in the running community lately and is widely recognized as one of the three important factors in aerobic capacity, the other two being VO$_{2\text{max}}$ and lactate threshold (Turner, 2011). Studies have been performed to show that eight weeks of training can improve running economy in previously untrained individuals (Beneke & Hütler, 2005), while adding strength training to endurance training for experienced male and female runners with no strength training experience did not increase running economy (Ferrauti et al, 2010).

Running economy itself is dependent on many physiological and biomechanical factors, which have been the focus of research by many, but have perhaps best been identified by two groups, Williams and Cavanagh (1987) and Saunders et al (2004). These factors include heart rate, core temperature, ventilation, lactic acid, percentage of slow twitch fibers, stride length, stride rate, and kinetic patterns in running mechanics. This being said, relatively few studies have been performed on parameters that may be used to predict running economy. The ability to predict running economy based on functional movements utilized in a Functional Motion Analysis would allow athletes and their coaches to be better
able to increase running economy by identifying and addressing weaknesses and imbalances of the athlete.

A Functional Motion Analysis consists of a series of movements that assess the participant’s ability to perform movements which are essential to participate in athletic activities with a decreased risk of injury while maximizing abilities (Cook et al, 2006). Although therapists have been utilizing a variety of tests for assessing the capacity of an individual to perform specific movements to determine the abilities of a specific joint, muscle group, or ligament for a number of years, only recently has interest grown in the ability to assess the functional capabilities of the entire individual. The most popular and well known of these tests is the Functional Movement Screen (FMS), which has been designed to assess the quality of fundamental movement patterns for identifying an individual’s physical limitations or asymmetries (O’connor et al, 2011). This screen, comprised of seven movement patterns that are based on fundamental proprioceptive and kinesthetic awareness principles, provides a standardized scoring system to evaluate individuals (Cook et al, 2006).

The ability of a functional motion analysis, and more specifically, the Functional Motion Screen, to predict injury risk has been documented in the military (O’connor et al, 2011), professional football players (Kiesel et al, 2007), and women’s collegiate soccer, volleyball, and basketball players (Chorba et al, 2010), but has not been shown to predict performance in athletic performance tests (Parchmann & McBride, 2011). The ability for a functional analysis, including the FMS, to predict running economy, an important predictor of performance in distance running, has yet to be investigated. With the advent of new technologies making more objective data for a functional motion analysis possible, more questions have been raised about how these types of screens may be applied to athletic performance.

Purpose of the Study

1. Examine the relationship between the results of a functional motion analysis and running economy at 10k race pace in trained male runners.
2. Examine the relationship between strength imbalances in legs identified in a functional motion analysis and stride imbalances in trained male runners at 10k race pace.

3. Examine the relationship between stride imbalances and running economy in trained male runners at 10k race pace.

**Hypotheses**

1. There will be a negative relationship between strength imbalances in legs from a functional motion analysis and running economy in trained runners at 10k race pace.

2. There will be a positive relationship between strength imbalances in legs from a functional motion analysis and gait imbalances in trained runners at 10k race pace.

3. There will be a negative relationship between gait imbalances and running economy in trained runners at 10k race pace.

**Significance of the Study**

Performance testing has long been a steadfast in predicting an athlete’s level of performance in many sports. In relationship to distance running, VO$_{2\text{max}}$ and fractional utilization of VO$_{2\text{max}}$ have been the focus of much research into running performance, while running economy has not received the same amount of attention (Foster & Lucia, 2007). In particular, very little research has gone into being able to predict how economical a runner is. In the few studies that have been performed on the subject, the focus has been on the sit-and-reach flexibility test and its relationship with running economy; while most of this research supports an inverse relationship between flexibility and running economy, there is research that contradicts this (Trehearn & Buresh, 2009). Furthermore, while the results of a functional analysis, such as the FMS, have been shown to be a predictor of injury in a multitude of populations, they have yet to be shown to have a relationship to athletic performance (Parchmann & McBride, 2011). As of recently, no research has been performed to study the relationship of the results of a functional analysis and running economy in trained male runners.
Delimitations

This study was delimited to the following aspects:

1. 12 subjects completed this study.

2. All participants completed a medical history evaluation and a familiarization session to determine if they were qualified subjects for the study.

3. Only participants who qualified as trained runners according to the standards of this study and medically capable participated in this study.

4. Weight was measured using an electronic scale.

5. Height was measured using a standard measuring tape.

6. The functional analysis was performed on the same surface for each individual.

7. Each functional analysis was recorded by the same marker-less 3D motion capture system, and ran by the same technician.

8. During the functional analysis, the same instructions were given to each participant by the same technician.

9. The marker-less 3D motion capture system was calibrated each day of testing.

10. Maximal oxygen consumption was determined via a staged maximal treadmill running test.

11. The same metabolic equipment was utilized for all VO$_{2\text{max}}$ tests and was performed by the same technician.

12. The metabolic equipment was calibrated each day of testing.

13. Running economy tests were captured utilizing marker-based 3D motion capture equipment, and the same equipment was used for each test.

14. The marker-based motion capture system was calibrated each day of testing.

15. The markers for the motion capture system were placed on the same anatomical landmarks for each test by the same technician.

16. All participants were instructed to refrain from exercise twenty-four hours prior to the testing session and from vigorous exercise forty-eight hours prior to testing.
17. Participants were instructed to wear similar clothing and the same footwear to each testing session.

Limitations

The study was limited by the following aspects:

1. Nutritional intake was not taken into consideration.
2. Daily activities other than exercise were not controlled prior to the testing sessions.
3. Subjects were allowed to continue their regular exercise program during the course of this study.

Assumptions

The following assumptions were made:

1. Participants did not exercise twenty-four hours prior to each testing session and did not perform vigorous exercise forty-eight hours prior to testing, as requested.
2. Subjects performed maximally on the VO$_{2\text{max}}$ test and the functional analysis testing.
3. The tests were reliable and valid measures of VO$_{2\text{max}}$, running economy, functional abilities of the individual, and gait parameters.

Definition of Terms

To maintain consistency throughout this study, the following terms are defined as follows:

*Maximal Oxygen Uptake (VO$_{2\text{max}}$).* The highest rate at which oxygen can be taken up and utilized by the body during severe exercise (Bassett & Howley, 2000).

*Ventilatory Threshold (VT).* The point at which pulmonary ventilation increases disproportionately with oxygen consumption during graded exercise (McArdle, Katch, & Katch, 2007).

*Running Economy (RE).* The steady-state rate of oxygen consumption under a specific set of submaximal conditions (McCann & Higginson, 2008; Saunders et al, 2004).
*Functional Motion Screening (FMS)*. A series of movements designed to assess the quality of fundamental movement patterns and presumably identify an individual’s functional limitations or asymmetries (O’Connor et al., 2011; Teyhen, et al., 2012).

*Trained Runners*. For this study, trained runners are defined as males who run more than 20 miles per week and/or regularly competes in races ranging in distance from 5 kilometers to 26.2 miles, and have been doing so for at least one year.

*Functional Motion Analysis (FMA)*. A 16 movement screening performed in a motion capture system, from which the data collected is then processed and reported on using Dynamic Athletics’ Software.

*DARI*. Dynamic Athletics Research Institute.

*Stride Length*. Distance traveled between successive contact periods of the same foot (Weyand et al., 2000).

*Step Length*. The distance between contacts of two successive foot strikes (e.g., right to left or left to right) (Williams and Cavanagh, 1987).

*Cadence*. Number of steps per unit time (Dugan & Bhat, 2005).

*Contact Time*. Time of foot-ground contact (Williams & Cavanagh, 1987).
The functional motion analysis, or functional movement screening, is the product of the evolution of sports rehab away from isolated assessment and strengthening toward an integrated, functional approach that includes principles of proprioceptive neuromuscular fascilitation, muscle synergy, and motor learning (Cook et al, 2006). A functional movement screening has been suggested as a possible predictor of sport-specific performance (Parchmann & McBride, 2011), as well as a predictor of injury in professional football players (Kiesel et al, 2007), Marine Officer candidates during Officer Candidate School (O’Connor et al, 2011), and female collegiate athletes (Chorba et al, 2010). The Functional Movement Screening (FMS), developed by Cook and Burton, is the first standardized assessment designed to evaluate an individual’s ability to perform movements in a specific pattern. The FMS is comprised of seven movements that provide observable performance of basic locomotor, manipulative, and stabilizing movements, while requiring a balance of mobility and stability (Cook et al, 2006). The movements utilized in the FMS place individuals in extreme positions where imbalances and weaknesses are noticeable if the appropriate stability and mobility are not utilized, revealing compensatory movement patterns. If compensatory movements continue for a long enough period of time, they can lead to poor biomechanics, ultimately placing that individual at greater risk for injury, thus making identification and correction of these movements an important aspect of training (Cook et al, 2006).

The FMS utilizes seven movements, the squat, hurdle step, lunge, shoulder mobility, active straight leg raise, push-up, and rotary stability, which are scored on a 0-3 scale (O’Connor et al, 2011). The certified individual scores the participant based on their ability to perform the movement, with a 3 indicating the movement was performed as instructed with no pain or compensation, a score of 2 indicating completion of the movement with no pain but some compensation, a score of 1 indicating the subject could not complete the movement, and a score of 0 being assigned if pain is experienced by the subject during part of the movement (O’Connor et al, 2011). For unilateral movements, the lower score
of the two sides is recorded and counted in the final total (Cook et al, 2006). Once all movements have been performed and scored, the scores for all the movements are added together, with an overall score out of 21 assigned (Frost et al, 2012).

The advent of new technologies has allowed movement screening to evolve. The Functional Motion Analysis from Dynamic Athletics utilizes sixteen unique movements to assess an individual’s abilities. Performed and captured within a marker-less motion capture system, the Dynamic Athletics FMA precisely measures the individual’s performance for each motion and provides a report supplying not only kinematic data, but kinetic data as well. By objectifying traditionally subjective data, interpretation of the results is best seen fit by the coach or clinician.

Reliability of the FMS

One of the biggest questions arising when one is considering using the FMS is the reliability in its usage. Many researchers have focused on this, looking at both the inter- and intra-rater reliability of the screening method. One of the first groups to explore the topic was Minick et al (2010), who looked specifically at the interrater reliability of the screening. A unique aspect incorporated into their exploration was the utilization of two FMS experts (instructors of FMS training courses who had over 10 years of experience with the tool) and two novices (individuals who had <1 year experience with the FMS). Although the experts varied more between themselves in scoring compared to the novices, when the two groups were compared, there was excellent agreement between the two on 14 of the 17 tests, with the remaining 3 having substantial agreement. This study demonstrates that as long as an individual has been properly trained in conducting FMS, the testing and scoring should be reliable, regardless of the amount of experience.

Other studies have analyzed both the inter- and intrarater reliability of the FMS. Groups led by Smith, Teyhen, and Onate, respectively, have investigated these questions in different ways. Smith et al (2012) addressed the question by focusing not only on the real time interrater and intrarater reliability, but also that intrarater reliability during real time administration would be increased with FMS certification. As expected, their results supported the first hypothesis that the FMS would have good interrater and
intrarater reliability; however, their results did not support the second hypothesis. Out of the four Raters utilized, instead of the certified FMS Rater having the highest intrarater reliability, that individual had the lowest, even though the other three Raters utilized in the study had not gone through the entire certification process. Similarly, Onate et al (2012) also looked at the real time intersession and interrater reliability of the FMS, but only utilized two Raters with one holding the credentials of an ATC, CSCS, and FMS Certified Specialist, while the other was a CSCS who had read the FMS manual once before scoring. In agreement with other groups, the FMS certification process did not seem to make a difference in the interrater reliability scores, as they were found to be highly reliable. Similarly, based on the findings, it was concluded that the FMS can be utilized with good reliability when looking at both intersession and interrater reliability.

Looking at the same question in a different way, Teyhen et al (2012) utilized eight physical therapy students, all of which were either in their second or third semesters of a doctor of physical therapy program. All underwent 20 hours of FMS training, after which four were randomly assigned to the participants to assess intrarater test-retest reliability. The other four students where then assigned randomly to simultaneously view the participants’ movements with the first group of raters, so that one rater from the first group was observing and rating the participant at the same time as one from the second. Sixty-four participants were utilized, such that each rater measured between fourteen and eighteen participants. As was expected based on previous research, interrater reliability was found to be good, while intrarater reliability was found to be moderate.

**Ability of the FMS to Predict Injury**

One of the factors in the creation of the FMS was to create a screening tool that offers a different approach to injury prevention, forcing individuals to use compensatory movement patterns if they did not utilize the appropriate motility or stability (Cook et al, 2006). The use of inefficient, compensatory movements reinforced over time leads to poor biomechanics, putting an individual at greater risk for injury. The importance of the FMS to successfully predict injury in a multitude of populations is critical.
to its role in injury prevention. If the FMS is unable to successfully predict injury, then its role in injury prevention would be null and void.

The largest study looking at the ability of the FMS to predict injury was performed by O’Conner et al (2011), and investigated the ability of the FMS to predict injury in a cohort of 847 Marine officer candidates while in either long-(10 wk) or short-(6 wk) cycle training. Along with the FMS, participants also performed the Marine physical fitness test, and were assigned a score for that as well. This investigation found that those with FMS scores ≤14 had a risk of incurring injury 2.0 times greater than that of individuals with a score >14. When it was broken down into scores ≤14, 15-17, and ≥18, although the ≤14 group continued to have the highest rate of injury in both LC and SC, with 52.8% and 40.4% of candidates reporting injury during the training, respectively, the ≥18 had a higher rate of injury in both cycles (44.4% and 28.9%) compared to the 15-17 group (29.3% and 22.2%). It is also important to note that this sample represents a highly fit group of young men who have already been screened by the Marines. It is believed that in-part due to this, out of the total sample investigated, only 10.6% of candidates had scores ≤14.

In another article analyzing the same data, Lisman et al (2013) looked at not only the results of the FMS, but also the results of the Marine Corps Physical Fitness Test (PFT), and self-reported exercise and previous injury history. In their analysis, it was found that that the 3 mile run-time was the only component of the PFT that was predictive of injury, with candidates performing the test in ≥20.5 min being 1.7 times more likely to incur an injury compared to their counterparts who performed the test in <20.5 min. When slow running time was combined with FMS ≤14, it was found candidates who performed poorly on both tests were 4.2 times more likely to suffer an injury.

The FMS has also been used along with an intervention program in firefighters. Although the focus was on a core strengthening intervention program to decrease injuries, Peate et al (2007) used the FMS at the beginning of the intervention to categorize the subjects into two groups based on their score in the screening: Pass (≥17) or Fail (<17). In this study, 69.3% of participants scored in the “Pass”
category, while 30.7% scored in the “Fail”. During the year following the testing and intervention, there was a greater incidence of injury for those who scored less than 17 (32%) compared to those who scored 17 or better (25%).

Additionally, the FMS has been utilized to determine injury risk in athletes. In their study, Keisel, Plisky, & Voight (2007) utilized data on the active roster of a professional football team, with the players going through the screening during training camp, and injury data applied retrospectively. Due to player and team confidentiality, common descriptive data was not provided on the subjects, and the definition of an injury was time spent on the injured reserve and a time loss of 3 weeks. It was revealed that a significant difference existed between the mean scores of injured players (14.3) and that of the players who were not injured (17.4). It was also found that players who score 14 or less on the FMS have an eleven-fold increased risk of injury than those who score greater than 14 at the beginning of training camp.

A study performed on an athletic population by Chorba et al (2010) screened 38 female NCAA D-2 athletes who competed in either soccer, volleyball, or basketball prior to the start of their respective sport season. In this study, an injury was defined as an injury that occurred as a result of participation in an organized intercollegiate practice or competition and required medical attention or the athlete sought advice from a certified athletic trainer, athletic training student, or physician. The authors utilized the cut-off score determined by Kiesel et al (2007) of 14 to determine relationships between a low FMS score and injury. Chorba’s group found that those who scored ≤14 on the FMS were significantly more likely to sustain an injury, with 68.75% of individuals who scored ≤14 sustaining an injury throughout their competitive season.

In the context of the FMA from Dynamic Athletics, research has yet to be published relating to its ability to predict injury. By providing objective data on joint kinematics through a series of movements,
it is hoped that, over time, compensatory movements and stress levels can be identified with the technology to allow for injury prediction, and subsequent injury prevention protocols.

**Ability of the FMS to Predict Athletic Performance**

Another use for the FMS that researchers have looked at has been the ability of the screening to predict performance. Multiple researchers have looked at this possibility from different viewpoints, trying to evaluate training (Frost et al, 2012; Kiesel et al, 2009; Cowen, 2009), seeing if it is related to measures of performance in golf (Parchmann and McBride, 2011), and its relation to standard measures of fitness and performance (Okada et al, 2011).

While these groups all looked at the ability of the FMS to predict performance, each took a unique approach. Frost et al evaluated how firefighters in two intervention (training) groups and a control group chose to perform the movements that make up the FMS, with no significant difference in total score for any group. It is important to note that the scores of 85% of the subjects in the control group did change, thus not allowing the influence of the interventions to be evaluated (Frost et al, 2012). Kiesel’s group applied a more focused approach to professional American football players, having them undergo FMS testing, then applying a seven-week intervention based on the results of the baseline testing. Post-intervention testing resulted in increases in the mean FMS scores for both the lineman and non-lineman groups of 3.0 points, with an increase in the number of players exhibiting a score above the injury threshold (Kiesel et al, 2009). Additionally, Virginia Cowen, PhD, utilized the FMS to explore the benefits of yoga on functional fitness, flexibility, and perceived stress in firefighters over a six-week period. During her study, she found that total FMS scores were significantly increased after just ten yoga sessions (Cowen, 2009).

Parchmann and McBride (2011) took another approach, comparing the results of the FMS to that of the 1 RM (rep max) to determine which was better related to athletic performance. Athletic performance was measured in terms of sprint times, vertical jump height, agility T-test times, and club head velocity for twenty-five NCAA Division I golfers. Compared to data for the 1 RM back squat
(normalized to body mass), the total FMS score did not show significant correlation to any of the athletic performance tests, while the 1 RM did (Parchmann and McBride, 2011). Research has also analyzed the relationship between core stability and functional movement, along with functional movement and performance, and suggests that core stability and FMS are not strong predictors of performance (Okada et al, 2011).

**Runners and the FMS**

One study has been performed to determine the mean values of the FMS screening in a group of long distance runners, which also investigated whether differences existed between the sexes as well as between younger versus older runners, with younger defined as <40 years old and older being >40 years old. Overall, the mean FMS score in this group of runners was 15.4, with 13 of the 43 runners (30%) scoring <14. No significant difference in total score was discovered between males and females, but a significant difference was found between the younger and older group, as the younger group scored a mean of 16.4 and the older group scoring a mean of 13.9 (Loudon et al, 2014).

**Running and Maximal Oxygen Uptake – VO_{2max}**

Runners of all ability levels express interest in VO_{2max} and applying knowledge concerning VO_{2max} to training. VO_{2max}, or maximal oxygen uptake, is the maximum rate that oxygen can be taken up from the ambient air and transported to and used by cells for cellular respiration during physical activity (Midgley et al, 2006). VO_{2max} is one of the three factors that contribute to running performance, with the other two being lactate threshold and running economy (Billat et al, 2001), which have been shown to account for greater than 70% of individual variability in performance speed (di Prampero et al, 1986). VO_{2max} is important as it is often considered the ceiling for a runner’s performance, as it is the ultimate limiter in physiological performance. VO_{2max} is affected by many physiological variables, including, but not limited to, mitochondria size/volume, skeletal muscle capillarity, myoglobin, left ventricular wall thickness, left ventricular chamber size, erythrocyte mass, plasma volume, efficiency of blood redistribution, total peripheral resistance, myocardial contractivity, and maximal minute ventilation.
Training that targets positive changes in any of these physiological variables should help increase the VO$_{2\text{max}}$ of a runner (Midgley et al, 2006). Lactate threshold, another limiter in running performance, occurs below VO$_{2\text{max}}$, and the intensity at which lactate threshold occurs has often been the focus of research (Midgley et al, 2007).

It is thought that there is a trainable limit for an individual’s VO$_{2\text{max}}$. This is best witnessed by comparing the results of training protocols of untrained individuals to those of highly trained, elite runners. Numerous studies have demonstrated the ability to increase VO$_{2\text{max}}$ in both untrained and recreationally trained (Midgley et al, 2006; Burke et al, 1994), while research on elite runners showed little to no change in VO$_{2\text{max}}$ over longer periods of time (Jones, 1998; Midgley et al, 2006).

**Running Economy**

Running economy, more often than not, is the forgotten factor in running performance. While not garnering the attention that VO$_{2\text{max}}$ and lactate threshold do, running economy plays a crucial role in running performance, and can be the deciding factor at the elite level. Running economy (RE), simply defined as the ability to move efficiently, is commonly expressed as the VO$_2$ occurring at a submaximal running velocity (Foster & Lucia, 2007; McLaughlin et al, 2010). When breaking down RE, there are two main areas to explore – physiological and biomechanical. Physiological influences on running economy have been explored by a number of groups. Kyrolainen et al (2003) studied muscle fiber distribution and composition, discovering an inverse relationship between energy expenditure and MCH II, along with Type II fibers, at speeds of 7 m/s. Muscular endurance has been found to play a role in RE, as RE was found to deteriorate after a bout of high speed running in the middle of a running protocol compared to a control protocol (Hayes et al, 2011). Tendon properties also appear to influence running economy in trained distance runners, as more compliant tendon structures for both knee extensors and plantar flexors were associated with enhanced RE in preparation for a road running season compared to a track season (Kubo et al, 2010).

Biomechanics, specifically relating to gait, also influence running economy. Understanding of the biomechanics of running gait along the entire kinetic chain is essential, and improper alignment
starting from the lumbar spine down through the lower limbs can alter mechanics, leading to compensatory movements and potentially causing injury (Dugan & Bhat, 2005). Moore et al observed self-optimizing of gait in ten female beginner runners, with seven kinematic and kinetic variables undergoing significant change during the course of a ten week running program, with gait analysis identifying changes in TO knee extension, TO plantarflexion, TD plantarflexion velocity, TD eversion velocity, peak eversion velocity, timing of peak dorsiflexion, and peak propulsive force (Moore et al, 2012). As biomechanical variables, such as stride length and stride rate, vary with running speeds and individual variances in build, it may be more meaningful to examine various parameters on a case-by-case basis (Williams, 2007).
CHAPTER THREE
Methodology

Participants

Twelve male participants volunteered to participate in the study. All participants were trained runners, defined as having run at least 20 miles per week and/or regularly competed in races ranging in distance from 5k to 26.2 miles, and have been doing so for at least one year. Participants were between the ages of 18-35, and screened based on health and running training history. Prior to testing, all participants read and signed an informed consent form that was approved by the University of Kansas IRB. Additionally, participants completed a medical evaluation form to determine if they were fit to take part in the study.

Participants were instructed to maintain their normal dietary intake during the course of the study, except to fast for three hours prior to each testing session. Additionally, participants were instructed to refrain from exercise for twenty-four hours prior to each testing session, while refraining from vigorous exercise forty-eight hours prior to each testing session. Participants wore the same footwear during all tests, and similar clothing for all the treadmill running tests.

Participant Timeline

- Informed Consent/Familiarization/FMA Testing (Dynamic Athletics Research Institute)
  - Informed Consent
  - Medical History Questionnaire
  - Height/Weight Measurement
  - Familiarization
  - FMA Testing
- VO2max Testing and Gait Analysis (Applied Physiology Lab, Robinson Center, ≤7 days of initial testing session)
  - 10 min warm-up outdoors
  - 10 min RE Test/Gait Analysis
  - VO2max Testing
Procedures

*Informed Consent, Familiarization, FMA Testing*

The initial testing session occurred at Dynamic Athletics Research Institute (9537 Alden St. Lenexa, Kansas 66215) and consisted of obtaining consent, medical history, anthropometric measurements of each participant, as well as having each subject undergo the FMA testing. Once consent and medical history were obtained, each subject was familiarized with the testing protocols, weighed on an electric scale, and had height measured using a standard tape measure.

Prior to the functional analysis testing, each subject was allowed to perform a brief (<5 min) warm-up. The subjects then performed all 16 movements that comprise the Dynamic Athletics Functional Motion Analysis inside a marker-less 3D Motion Capture System (Organic Motion, New York, NY). During this analysis each subject was instructed to perform each of the movements to the best of their abilities by a trained technician, with the technician demonstrating each movement. The subjects were allowed to practice the movement once before data collection occurred. The analysis involved the 16 movements described in Table 1, with data processing and reporting performed by Dynamic Athletics’ software.

Table 1
Dynamic Athletics Functional Motion Analysis

<table>
<thead>
<tr>
<th>Movement</th>
<th>Subject Instructions</th>
</tr>
</thead>
<tbody>
<tr>
<td>T Pose</td>
<td>Standing straight up facing forward, the subject will raise his arms up the side of their body in the frontal plane with elbows straight, until a 90 degree angle is formed with his arms and trunk.</td>
</tr>
<tr>
<td>Shoulder Abduction</td>
<td>Starting from a T Pose and keeping the elbows straight, the subject raises each arm in the frontal plane as high as possible until either the hands touch or he is unable to raise them further, then lower the arms in the frontal plane until he either hits the sides of his body or are unable to lower them anymore, then return the arms to the starting position</td>
</tr>
<tr>
<td>Shoulder Rotation</td>
<td>Starting from a T Pose and keeping the elbows straight, the subject moves each arm in the horizontal plane towards the centerline of the front of the body until either the hands touch or he is unable to move the arms forward any further, then moves the arms towards the centerline of the back of the body as far as he is able to without bending over, then return the arms to the starting position</td>
</tr>
</tbody>
</table>
Trunk Rotation
Starting from a T Pose and keeping the elbows straight and pelvis stationary and pointed forward, the subject rotates the trunk of the body to the right as far as possible, then to the left as far as possible, then back to the starting position.

L&R
Starting from a T Pose, the subject touches the left elbow to the right knee

R&L
Starting from a T pose, the subject touches the right elbow to the left knee

Squat
Starting from a T Pose, feet positioned approximately shoulder width apart in a normal squatting position. He then performs a normal squat, going as low as he can while attempting to keep the back as straight up and down as possible. Once he has gone as low as he can, he immediately returns to the starting position.

Vertical Jump
Starting from a T Pose, the subject does whatever he needs to be able to jump as high as possible without taking multiple steps. He may swing his arms to help build momentum and step back with one leg to “step into the jump”.

Broad Jump
Starting from a T Pose, the subject performs a two legged jump as far forward as possible. The subject may swing his arms for momentum and bend his legs as much or as little as needed, and land on both feet.

Single Leg Squat-Right
Starting from a T Pose, the subject raises his left leg up and holds it behind him. Then he performs a single-leg squat with his right leg, going as low as he can. The subject may move his arms to help maintain balance.

Single Leg Squat-Left
Starting from a T Pose, the subject raises his right leg up and holds it behind him. Then he performs a single-leg squat with his left leg, going as low as he can. The subject may move his arms to help maintain balance.

Vertical Jump-Right Leg
Starting from a T Pose, the subject raises his left leg up and holds it behind him. He then performs a single-leg vertical jump with his right leg, landing on only his right leg. The subject may swing his arms to create momentum, as well as use them to help balance.

Vertical Jump-Left Leg
Starting from a T Pose, the subject raises his right leg up and holds it behind him. He then performs a single-leg vertical jump with his left leg, landing on only his left leg. The subject may swing his arms to create momentum, as well as use them to help balance.

Lunge Right Leg
Starting from a T Pose, the subject steps forward with his right leg as far as possible in a lunging motion. He goes low enough with the lunge so that his left knee barely touches the floor, then return back up to a standing position. The subject may use his arms to help maintain balance.

Lunge Left Leg
Starting from a T Pose, the subject steps forward with his left leg as far as possible in a lunging motion. He goes low enough with the lunge so that his right knee barely touches the floor, then return back up to a standing position. The subject may use his arms to help maintain balance.

Concentric Jump
Starting from a T pose, the subject positions his feet approximately shoulder width apart in a normal squatting position. He then goes into a squat, going as low as he feels necessary to perform a good vertical jump. Once he is in this lowest position, he will hold it until the tester says "Go", which at that time the subject will perform a vertical jump. When the tester says go and the subject performs the jumping motion, he may swing his arms for momentum, but may not drop any lower into a squat with his legs.
This is similar to a plyometric box jump. Starting from a T Pose at the edge of the box, the subject will drop down from the box to the ground and immediately explode back up, jumping as high as possible. This is a very explosive movement, and he should immediately try to jump as soon as he hits the ground. The subject may swing his arms for momentum.

Running Economy Test/Gait Analysis at 10k Race Pace and VO2max Testing

Within 7 days of the Functional Motion Analysis, participants underwent a Running Economy/Gait Analysis test and VO2max test at the Applied Physiology Lab at the University of Kansas (1301 Sunnyside Avenue Lawrence, Kansas 66045-7567). Along with metabolic data, motion capture data relating to aspects of gait was collected. The testing occurred on a Trackmaster TMX425CP treadmill (Full Vision; Newton, KS) using Parvo Medics MMS-2400 Metabolic Cart (Parvo Medics; Murray, UT) and a Garmin HRM Heart Rate (HR) monitor (Garmin; Olathe, KS). Motion capture data for analysis of gait parameters utilized the Optitrack marker-based 3D Motion Capture System (NaturalPoint, Inc; Corvallis, OR). Both the motion capture system and metabolic cart were calibrated each day.

Prior to testing, subjects performed a 10 minute warm up outdoors, not exceeding 80% perceived effort. Following the warm up, subjects were fitted with a headpiece, mouthpiece, and HR monitor, along with markers to track aspects of gait. On the left foot, markers were placed approximately above the calcaneus, head of the first metatarsal, and lateral maleolus, while on the right foot an additional marker was placed above the head of the fifth metatarsal. In addition to the markers placed on the feet, a marker cluster was placed above the sacrum to track center of mass. With the marker set-up outlined above, the following aspects of gait were tracked: Step distance, Stride Distance, Contact Time, and Cadence.
Following placement of the markers, the subject was fitted with a headpiece and mouthpiece, and then began the Running Economy test at self-reported 10k race pace and 1% incline.

The Running Economy test involved subjects running on the treadmill for 8 min at self-reported 10k race pace. During this time, five – ten second captures were taken at random times using the motion capture system. Subjects were not made aware of when data captures were taking place. Once the test was completed and equipment removed, subjects were instructed to rest for 20 minutes before the VO\textsubscript{2max} test.

Following the 20 minute rest period, subjects were re-fitted with a headpiece and mouthpiece, and familiarized with the testing protocol. The VO\textsubscript{2max} test began with 2 min at 7.0 mph (8:34 min/mile pace) and a 1% incline, with the 1% incline remaining constant during the entire test. Immediately after the first stage, the speed increased to 7.5 mph (8 min/mile pace), and continued to increase by the equivalent of 30 sec/mile in pace every 2 minutes until the subject reached exhaustion and signaled the technician to stop the test. Once finished, the headset was removed and subjects were given the opportunity to cool down on the treadmill. For at a minimum of five minutes following the test, subjects were monitored for light headedness, nausea, and dizziness, as well as for HR response.

**Statistical Analysis**

Descriptive statistics, including height, weight, and age, were determined for the subject group demographics. Also analyzed were VO\textsubscript{2max} and treadmill speeds for the metabolic tests. Subsequently, scatter-plots, along with Pearson-product moment correlations were used to exam the relationships between the variables measured during the FMA, RE, and VO\textsubscript{2max} testing. To test Hypothesis One, the following measures of strength imbalances from the FMA will be correlated to RE VO\textsubscript{2submax} % of VO\textsubscript{2max}: Squat % Body Weight Difference, Vertical Jump Loading Takeoff Force Difference, Single Leg Vertical Jump Net Force Impulse Difference, Single Leg Vertical Jump Height Difference, Lunge
Distance Difference. To test Hypothesis Two, the same measures of strength imbalance utilized for Hypothesis One will be correlated to the following measures of gait imbalances: Step Length Differences (both absolute and in relation to height), Differences in Contact Time, Differences in Vertical Displacement. Finally, to test Hypothesis Three, the aforementioned measures of gait imbalances will be correlated to RE VO2submax % of VO2max. All differences were determined by subtracting the value of the left measure from that of the right, such that Difference = Right – Left.
CHAPTER FOUR

Results

Twelve healthy men (N=12) participated in this study. Physiological descriptions of the subjects may be found in Table 2.

Table 2
Mean (SD) of Subject Demographics

<table>
<thead>
<tr>
<th>Measure</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (y)</td>
<td>25.33</td>
<td>± 1.28</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.82</td>
<td>± 0.06</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>75.56</td>
<td>± 1.85</td>
</tr>
<tr>
<td>VO$_{2\text{max}}$ (ml/kg/min)</td>
<td>58.93</td>
<td>± 3.87</td>
</tr>
</tbody>
</table>

The subjects’ performance in the metabolic testing is summarized in Table 3.

Table 3
Mean (SD) of Subject Metabolic Testing Performance

<table>
<thead>
<tr>
<th>Measure</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>RE Treadmill Speed (mph)</td>
<td>8.58</td>
<td>± 0.732</td>
</tr>
<tr>
<td>RE VO2 (ml/kg/min)</td>
<td>51.27</td>
<td>± 1.53</td>
</tr>
<tr>
<td>VO2max Treadmill Speed (mph)</td>
<td>11.03</td>
<td>± 0.678</td>
</tr>
<tr>
<td>RE Speed % of VO2max Speed (%)</td>
<td>77.87</td>
<td>± 5.02</td>
</tr>
<tr>
<td>RE % of VO2max (%)</td>
<td>88.53</td>
<td>± 6.63</td>
</tr>
</tbody>
</table>

The subjects’ performance in the measures of Running Economy, Strength Imbalance from the FMA, and Gait Imbalances are summarized in Table 4.
Strength Imbalances from a FMA and Running Economy scatter plots, in addition to a Pearson-product moment correlation, were used to examine the relationship between strength imbalances identified by the FMA and running economy. A summary of these results may be found in Table 4. Scatter-plots representing the relationships between strength imbalances identified by the FMA and running economy may be found in Figures 1.A-1.E. Out of the 5 relationships examined, two positive relationships were found to exist between strength imbalances identified by the FMA and RE (Squat % BW Difference, VJ Loading Takeoff Force Difference). The three negative relationships included SLVJ Net Force Impulse Difference, SLVJ Height Difference, and Lunge Distance Difference. Lunge Distance Difference and Squat % BW Difference were the only two relationships whose absolute r value was greater than 0.10.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>RE VO\textsubscript{2}\textsubscript{submax} % VO\textsubscript{2}\textsubscript{max} (%)</td>
<td>88.53</td>
<td>± 6.63</td>
</tr>
<tr>
<td>Squat % Body Weight Difference (R-L) (%)</td>
<td>-1.14</td>
<td>± 7.31</td>
</tr>
<tr>
<td>Vertical Jump Loading Takeoff Force Difference (R-L) (N)</td>
<td>-327.84</td>
<td>± 340.99</td>
</tr>
<tr>
<td>Single Leg Vertical Jump Net Force Impulse Difference (R-L) (N*s)</td>
<td>9.56</td>
<td>± 38.63</td>
</tr>
<tr>
<td>Single Leg Vertical Jump Height Difference (R-L) (in)</td>
<td>0.97</td>
<td>± 2.05</td>
</tr>
<tr>
<td>Lunge Distance Difference (R-L) (in)</td>
<td>-0.30</td>
<td>± 2.58</td>
</tr>
<tr>
<td>Step Length Difference (R-L) (cm)</td>
<td>1.85</td>
<td>± 4.8</td>
</tr>
<tr>
<td>Step Length % Height Difference (R-L) (%)</td>
<td>1.01</td>
<td>± 2.62</td>
</tr>
<tr>
<td>Contact Time Difference (R-L) (s)</td>
<td>-0.01</td>
<td>± 0.02</td>
</tr>
<tr>
<td>Vertical Displacement Difference (R-L) (m)</td>
<td>-0.004</td>
<td>± 0.010</td>
</tr>
</tbody>
</table>

Table 4
Mean (SD) of Running Economy, Strength Imbalances from FMA, and Gait Imbalances

Strength Imbalances from a FMA and Running Economy
Strength Imbalances from a FMA and Gait Imbalances

Scatter-plots, in addition to a Pearson-product moment correlation, were used to examine the relationship between strength imbalances identified by the FMA and gait imbalances from a 10k race pace treadmill run. The summary of these results may be found in Table 4. Scatter-plots representing the relationships between strength imbalances identified by the FMA and gait imbalances may be found in Figures 2.A-2.T. Out of the twenty relationships investigated, fifteen of these relationships exhibited positive correlations, with five of these relationships being negative. Twelve of the relationships
exhibited weak correlation ($r < 0.20$), with only two relationships exhibiting correlations above an $r$ of 0.4. The two correlations with $r$ values above 0.4 both involved SLVJ Height Difference, correlating it to Step Length Difference and Step Length Difference % Height.

Figure 2: Strength Imbalances from a FMA and Gait Imbalances
Gait Imbalances and Running Economy

Scatter-plots, in addition to a Pearson-product moment correlation, were used to examine the relationship between gait imbalances and running economy. A summary of these results may be found in Table 4. Scatter-plots representing the relationships between gait imbalances and running economy may be found in Figures 3.A-3.D. Out of the four relationships investigated, two of them (Step Length Difference, Step Length Difference % of Height) exhibited negative correlations of absolute $r < 0.15$, while Contact Time Difference and Vertical Displacement Difference both exhibited positive correlations with $r$ values above 0.30.
Raw data may be found in Appendix E. A complete Pearson-product moment correlation table containing all variables explored may be found in Appendix F.
CHAPTER FIVE

Discussion

Strength Imbalances and Running Economy

There have been a multitude of studies looking at various aspects of running economy; this study is unique in that it is the first study looking at the ability of a FMA to predict aspects associated with running economy in trained male runners. The results of this investigation suggest that there were no strong relationships between strength imbalances identified by the FMA and RE at self-reported 10k race pace.

As can be seen in Figures 1.A-1.D, the strongest relationship between strength imbalances identified by the FMA and RE occurred between Lunge Distance Difference between the legs and RE VO$_{2\text{submax}}$ % of VO$_{2\text{max}}$ (Figure 1.E), producing an $r$ of 0.4519. The only other relationship that produced an $r$ value above 0.10 was between Squat % Body Weight Difference and RE VO$_{2\text{submax}}$ % of VO$_{2\text{max}}$ (Figure 1.A), with an $r$ value of 0.4355. The relationship between VJ Loading Takeoff Force Difference and RE VO$_{2\text{submax}}$ % of VO$_{2\text{max}}$ (Figure 1.B) was also positive in nature, but displayed a very weak relationship, with an $r$ value of 0.0825. The two strength imbalances displaying a negative relationship to RE VO$_{2\text{submax}}$ % of VO$_{2\text{max}}$, SLVJ Net Force Impulse Difference (Figure 1.C, $r = 0.0742$) and SLVJ Height Difference (Figure 1.D, $r = 0.0849$), were weak correlations. With three out of the five relationships between strength imbalances identified in the FMA and RE being positive in nature, along with the two negative relationships showing very weak correlations, the results of this investigation indicate that as the difference between the right and left legs in the FMA measure increased, so did VO$_{2\text{submax}}$ in respect to VO$_{2\text{max}}$. Although the correlations identified in this study were not significant, the investigator believes there is enough evidence to warrant further research into the relationships between strength imbalances identified in a FMA and RE.

Strength Imbalances and Gait Imbalances

There have been a multitude of studies looking at various aspects of running economy; this study is unique in that it is the first study looking at the ability of a FMA to predict aspects associated with
running economy in trained male runners. The results of this investigation suggest that there were no strong relationships between strength imbalances identified by the FMA and gait imbalances at self-reported 10k race pace.

A single relationship, between SLVJ Height Difference and Step Length Difference as a percentage of Height (Figure 2.J), was found to exist above the critical r level for this investigation of 0.576, producing an r value of 0.5815. Another relationship between SLVJ Height Difference and Step Length Difference (Figure 2.E) was very close to critical r, with an r value of 0.5757. Of the twenty relationships investigated, fifteen of these relationships exhibited positive correlations, with five of these relationships being negative. Additionally, twelve of the relationships exhibited weak correlation (r < 0.20), with only two relationships exhibiting correlations above an r of 0.4.

Although a majority of the relationships between strength imbalances identified by the FMA and gait imbalances were positive in nature, negative relationships were found to exist, and many of the relationships showed weak correlation. The inconclusive results found may support the self-optimization of gait (Williams and Cavanagh, 1987; Cavanagh and Williams, 1982; Williams, 2007), where an individual develops a gait pattern over time that is most efficient for their specific build and physiological traits. These results, although showing a positive trend, are too inconclusive to support a positive relationship between strength imbalances identified by the FMA and gait imbalances, but may encourage more investigation into this question.

_Gait and Running Economy_

The results of this research relating to measures of gait and how they correlate to RE produced few significant relationships, as can be seen in Figures 3.A-3.D. The strongest of these relationships, Vertical Displacement Difference and RE VO\textsubscript{2\textsubmax} % of VO\textsubscript{2\max}, produced a r value of .3140, far off from the .8 threshold indicating a strong relationship. It is interesting to note that measures of vertical displacement, as can be seen in Appendix F, seem to have an impact on metabolic measures based on the results of this study, with three of these measures showing a good relationship to metabolic measures from the testing (0.60 < r < 0.80). These good relationships may support the research by Halvorsen et al
(2012), which found a positive relationship between vertical displacement and VO$_2$ of participants. This study induced changes in vertical displacement, along with step frequency, in 16 male runners while running on a level treadmill at 16 km/hr. These agree with conventional thought that the increase in vertical movement will cause an increase in energy utilization, expressed through an increase in oxygen consumption. Although not a part of this study, new technologies that measure vertical displacement in the field, such as the Garmin HRM, may allow for better understanding between vertical displacement and running economy.

Just as telling is the lack of significant relationships between differences in step length and metabolic measures. This lack of identification of significant relationships may support previous research, (Williams and Cavanagh, 1987; Cavanagh and Williams, 1982; Williams, 2007), that these measures need to be investigated on a case by case basis due to self-optimization. Williams and Cavanagh (1987) discussed this in depth regarding their study looking at distance running mechanics economy, and performance. When subjects of their study were placed into three significantly different groups based on VO$_2$$_{submax}$, many trends were identified in the biomechanical factors explored. Still, numerous individual exceptions existed for these, even for those factors that demonstrated the strongest relationship with VO$_2$$_{submax}$. This study expanded on the research of Cavanagh and Williams (1982), looking specifically at the impact of stride length (as a percentage of leg length) on oxygen uptake. First, they examined the freely chosen stride length of 10 recreational runners on a treadmill at a 7:00 min/mile pace, then varied stride length ± 20% of leg length. In their study, it was observed that subjects exhibited a freely chosen stride length that minimized O$_2$ uptake, but at the same time varied widely between subjects. This led to their conclusion that the relatively efficient running patterns used by subjects during unrestricted running indicates either an adaptation to the chosen stride length through training or a successful process of energy optimization. In his review *Biomechanical Factors Contributing to Marathon Race Success* (2007), Williams emphasizes the point that universally applicable efficient
movement patterns have not been identified, and that future research should concentrate on identifying how an individual’s structure and functional abilities influence performance, economy, and injury.

**Additional Considerations**

This study placed an emphasis on the lower-body movements of the FMA, attempting to identify any strength imbalances within an individual to see how these imbalances may affect both gait and metabolic measures during a 10k race-pace running economy test. A Pearson-product moment correlation table, which can be found in Appendix F, was utilized to identify 38 significant relationships meeting the \( r \) critical standard of 0.576. Of these 38 relationships, only two involved differences measured between the two legs, neither of them demonstrating a strong correlation.

Few strong correlations were found between variables explored, but it is interesting to note that the six strongest were related to Concentric Jump Peak Power, with the seventh, Concentric Jump Height, resulting from the same movement. All these strong correlations were found to be with parameters of gait. This is an extremely interesting finding, as most research has looked at the impact of plyometric exercises when looking at improving gait/running economy (Saunders et al, 2006). Arampatzis et al (2006) found that the most economical runners in their research exhibited a higher energy storage capacity during maximal voluntary contraction of the triceps surae and quadriceps femoris, along with a higher contractile strength of the triceps surae muscle tendon unit. With the focus of the concentric jump being to remove the elasticity-energy storage component from the muscle fiber (which plyometric exercises focus on training), these findings may encourage more research on the impact of elasticity on running economy.

The results of this study may support research such as that by Millet et al (2002), who found that concurrent heavy weight training program, along with endurance training, increased running economy in well-trained triathletes compared to endurance-only training, while \( \text{VO}_2 \) kinetics were not significantly affected for either group. The training between the two groups was similar, except the endurance+strength group performed two heavy weight training sessions per week, consisting of
hamstring curl, leg press, seated press, parallel squat, leg extension, and heel raise. These workouts consisted of two warm-up sets, followed by three to five sets to failure of 3-5 reps at a load calculated >90% one-rep max. Maximal concentric strength was also evaluated in the study utilizing the half-squat and heel raise, which did not differ significantly between groups at pretraining testing, but did show significant difference during final testing. To contradict these findings, it is important to note that the concentric jump also had three measures that had good negative correlations to RE Treadmill Speed and VT % of VO2max.

Single leg squat depth was the other measure that indicated a positive correlation to both gait and metabolic measures, with seven correlations showing good strength. Interestingly, none of these correlations were between the single leg squat and measures of gait for the same leg, and three of these correlations were with VT. The lack of data on the correlation between single leg squat performance and both metabolic and gait measures indicates the need for further analysis of potential relationships, as another single leg movement, the lunge, exhibited good correlation to some aspects of stride.

To date, there are no studies looking at a standardized functional screening tool that provides objective data and how the results correlate to any measures relating to running performance – i.e. VO2max, VT, RE, etc. The data gathered in this study is unique in the fact that it is based off objective measures provided by a FMA, making it extremely difficult to compare to previous research. The closest studies that resemble exploration of this type of information would be those using the FMS screening tool, including studies by Kiesel et al (2007), Chorba et al (2010), O’Connor et al (2011), Parchman and McBride (2011), Frost et al (2012), Lisman et al (2013), and Loudon et al (2014).

Chorba et al (2010) identified that compensatory movement patterns identified by the FMS can increase the risk of injury in female collegiate athletes, while the findings of Kiesel et al (2007) suggest professional football players with dysfunctional movement patterns as measures by the FMS are more likely to suffer injury than those scoring higher. In addition, Kiesel et al (2011) found that FMS scores do increase with a standardized intervention in professional football players. These studies are important to note in the context of the presented research as injuries can affect athletes of all types, including runners,
and can directly impact athletic performance. Although different in both the movements and scoring systems, the FMS and FMA are similar in the fact that they look at the ability of an individual to perform basic movement patterns. Parchman and McBride explored if the FMS is related to athletic performance in Division I golfers, with a lack of relationships between the FMS and measures of athletic performance suggesting it is not related to any aspect of athletic performance. Relating to the FMA, the subjective nature of the scoring with the FMS may play a role in the lack of it’s relation to athletic performance, and more research should be conducted to look at the relationship between the FMA and measures of athletic performance.

Lisman et al (2013) made an important observation in relation to the current study, as they found that in Marine Corps Officer Candidates, when FMS scores and 3 mile run-time were combined, subjects who scored poorly on both tests were 4.2 times more likely to suffer an injury. This study did not explore this, but relationships may exist between the FMA and metabolic measures if the results of the FMA are combined with aspects of gait.

**Conclusions**

The findings of this investigation suggest that few relationships exist between strength imbalances in legs from a functional motion analysis and running economy at 10k race pace in trained men. Additionally, the relationships that were the strongest were positive in nature. These findings refute Hypothesis 1, that there will be a negative relationship between strength imbalances in legs from a functional motion analysis and running economy in trained runners. Other relationships, both positive and negative, were identified between the results from the FMA and metabolic measures that were strong, suggesting that other relationships may exist between the results of a FMA and running economy.

The results of this study also suggest that strength imbalances in legs from a functional motion analysis are not significantly related to stride imbalances at 10k race pace in trained men. Positive relationships were found to exist between some of the strength imbalances measured by the FMA and aspects of gait, but three out of the eight strongest relationships were found to be negative in nature. These results also refute Hypothesis 2, which suggested a positive relationship between strength
imbalances in the legs from the FMA and stride imbalances during a 10k race pace treadmill run would exist.

Additionally, this study demonstrated no significant relationships exist between gait imbalances and running economy at 10k race pace in trained men. In relation to gait imbalances measured, only two relationships were identified with an r value above 0.20, and all relationships explored were positive in nature. Because significant negative relationships between stride imbalances and running economy were not identified, Hypothesis 3 was not supported.

Future Recommendations

The results of this investigation emphasize the need for further research into new technologies and their ability to predict running economy. In particular, there is currently no research regarding the ability of a FMA, or any standardized functional tests that provide objective data, to predict athletic performance of any kind. As technology continues to improve, and more data becomes readily available, and easily accessible, to individuals, future studies should investigate the correlation between data from functional testing and performance.

Relating specifically to the FMA and running economy, larger studies should be performed looking at the variables identified in Table 3. Although only a few of those correlations were found to be strong, the addition of more subjects would provide more insight on the true relationship between those variables. Additionally, a larger study may help identify variable that do have good to strong correlations but were not identified in this study.

Future research may also want to place an emphasis on standardizing the speeds the subjects run at. This could be done by either analyzing both metabolic and gait measures at pre-determined, set speeds, or basing the speeds off the results of a VO\textsubscript{2max} test, having subjects run at speeds producing the equivalent of a percentage of their VO\textsubscript{2max}. By doing so, researchers would not have to worry about accounting for the differences in racing intensities between individuals, which was a factor in this study.
Self reported 10k race pace speeds, as can be found in the Raw Data in Appendix E, ranged from 71% of \( \text{VO}_{2\text{max}} \) speed to 89% of \( \text{VO}_{2\text{max}} \) speed.

Research should focus on ways to normalize data from both the FMA and gait analysis to better account for differences in build between subjects and the effect those differences have on biomechanics. By placing a focus on accounting for these differences, such as leg length, femur length, and foot length, there is the potential to identify additional relationships that were previously undetectable, furthering understanding on performance measures that truly affect running performance.

Future research may also want to consider a training study to identify the effect increasing an individual’s performance in the FMA has on running economy. By having subjects participate in a training program specifically designed to increase performance in the FMA, researchers may be able to find measures of performance that can be directly influenced by a specific training program. This would expand upon current research on strength training and running economy, such as the study by Millet et al (2002). This type of study would be similar of that to Kiesel et al (2011), whose study demonstrated that fundamental movement characteristics in relation to the FMS do change with a standardized intervention. By tracking changes in movement patterns throughout the body, there would be the potential to identify specific movement patterns that may have an influence on running economy.

The efficiency with which data collection is collected for the FMA would make it an ideal tool to use for a longitudinal study of the course of a season or seasons for runners. Ideally, subjects would undergo FMA and metabolic testing once every 3 months over the course of a year, and track injuries, training, weight, and race performance. By tracking changes in FMA performance, along with running performance and injuries, researchers may be able to identify markers of performance, along with risk factors for injury.


Appendices
January 23, 2015

Philip Gallagher
philku@ku.edu

Dear Philip Gallagher:

On 1/23/2015, the IRB reviewed the following submission:

<table>
<thead>
<tr>
<th>Type of Review:</th>
<th>Initial Study</th>
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<tbody>
<tr>
<td>Title of Study:</td>
<td>Ability of a Functional Analysis to Predict Running Economy in Experienced Male Runners</td>
</tr>
<tr>
<td>Investigator:</td>
<td>Philip Gallagher</td>
</tr>
<tr>
<td>IRB ID:</td>
<td>STUDY00001952</td>
</tr>
<tr>
<td>Funding:</td>
<td>None</td>
</tr>
<tr>
<td>Grant ID:</td>
<td>None</td>
</tr>
<tr>
<td>Documents Reviewed:</td>
<td>• FMA Running Economy Informed Consent, • Initial Submission Form Running Economy, • FMA Running Economy Participant Flyer,</td>
</tr>
</tbody>
</table>

The IRB approved the submission from 1/23/2015 to 1/22/2016.

1. Before 1/22/2016 submit a Continuing Review request and required attachments to request continuing approval or closure.
2. Any significant change to the protocol requires a modification approval prior to altering the project.
3. Notify HSCL about any new investigators not named in original application. Note that new investigators must take the online tutorial at https://rgs.drupal.ku.edu/human_subjects_compliance_training.
4. Any injury to a subject because of the research procedure must be reported immediately.
5. When signed consent documents are required, the primary investigator must retain the signed consent documents for at least three years past completion of the research activity.

If continuing review approval is not granted before the expiration date of 1/22/2016 approval of this protocol expires on that date.

Please note university data security and handling requirements for your project: https://documents.ku.edu/policies/IT/DataClassificationandHandlingProceduresGuide.htm

You must use the final, watermarked version of the consent form, available under the “Documents” tab in eCompliance.

Sincerely,

Stephanie Dyson Elms, MPA
IRB Administrator, KU Lawrence Campus
APPROVAL OF PROTOCOL

February 25, 2015

Philip Gallagher
philku@ku.edu

Dear Philip Gallagher:

On 2/25/2015, the IRB reviewed the following submission:

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<td>Funding:</td>
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<td>Grant ID:</td>
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</tr>
</tbody>
</table>

Documents Reviewed:
- FMA Running Economy Informed Consent
- Initial Submission Form Running Economy

The IRB approved the submission from 2/25/2015 to 1/22/2016.

1. Before 1/22/2016 submit a Continuing Review request and required attachments to request continuing approval or closure.
2. Any significant change to the protocol requires a modification approval prior to altering the project.
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You must use the final, watermarked version of the consent form, available under the “Documents” tab in eCompliance.

Sincerely,

Stephanie Dyson Elms, MPA
IRB Administrator, KU Lawrence Campus
INTRODUCTION
You are invited to participate in a research study investigating the ability of a functional analysis to predict running economy in trained male runners. The functional analysis, developed by Dynamic Athletics, provides data on different movements and may be used to identify potential strength and range of motion imbalances that an individual may have. This study will be conducted at University of Kansas and Dynamic Athletics Research Institute, and 12-15 subjects are being sought to participate. The Department of Health, Sports, and Exercise Sciences at the University of Kansas supports the practice of protection for human subjects participating in research. The following information is provided to help you make an informed decision on whether or not to participate in the present study. Please feel free to ask any questions.

PURPOSE OF THE STUDY
The purpose of this study is to test the ability of a functional analysis to predict running economy in trained male runners. The study will compare the results of the Dynamic Athletics Functional Analysis to physiological and biomechanical data obtained during a VO2max test.

BASIS FOR SUBJECT SELECTION
You are eligible to participate in this study if you are a male runner who runs over 20 miles/week and/or regularly competes in races ranging in distance from 5k to 26.2 miles, and have been doing so for at least one year. Also, you must be between the ages of 18-35, healthy, non-obese (BMI <28 kg/m^2), non-smoking, and free of metabolic (diabetes) or cardiovascular diseases (congestive heart failure, high blood pressure). All subjects will be screened using a health-history questionnaire for contraindications to exercise by American College of Sports Medicine (ACSM) guidelines. Trained runner subjects will be selected to take part in 2 data collection sessions. One will be a functional analysis test at Dynamic Athletics in Lenexa, KS. The other will be performed at the Robinson Center on the University of Kansas campus.

PROCEDURES
A time-line of the testing procedures and an overview of the testing sequence for the pre-testing and test days are presented below. The pre-testing and functional analysis will be conducted at Dynamic Athletics in Lenexa, KS, with the VO2max testing being performed at the Applied Physiology Laboratory and the Athletic Training Laboratory at the University of Kansas. All procedures will be supervised by trained personnel.

Timeline of Testing Procedures

Pre-Testing and Functional Analysis at Dynamic Athletics:
- Consent Form
- Medical History Questionnaire
- Age, Height, and Weight Measurements
- Protocol Familiarization
  - Functional Analysis
Exercise testing equipment
-Heart Rate Monitor Fitting
Functional Analysis Screening

Running Economy and VO\textsubscript{2max} Test at Robinson Center, University of Kansas (within 7 days of initial testing session):
10 min warm up outdoors
Motion capture marker placement
8 min Running Economy Test at 10k race pace
20 min recovery
VO\textsubscript{2max} Test

1) Pre-testing Protocol and Functional Analysis (Dynamic Athletics Research Institute, 9535 Alden St, Lenexa KS 66215) – Consent form, medical history questionnaires; age, height, weight data, and Functional Motion Analysis. These procedures will take approximately 1 hr. The subject understands that they are responsible for providing their own transportation to and from the testing site. This FMA will have the subject perform 16 different functional movements in their marker-less 3D motion capture zone, and the data obtained will be processed and reported by Dynamic Athletics.

3) Running Economy and VO\textsubscript{2max} Testing – Each subject will undergo a Running Economy test and VO\textsubscript{2max} test. Subjects will need to fast for a minimum of three (3) hours prior to the test. Subjects will warm up for 10 minutes outdoors, not to exceed 80% perceived effort. Following the warm up, you will be fitted with markers on your feet and sacrum, along with a headpiece and mouthpiece, and then start the running economy test. The running economy test will be 8 min in length at a 1% incline, at each subject’s self-reported 10k race pace. After the running economy test, the markers and testing equipment will be removed and subjects will rest for 20 min. After resting, you will then undergo the VO\textsubscript{2max} test. The first stage will be 2 minutes at 7.0 mph (8:34 min/mile pace) at 1% incline. Subjects will continue to increase the intensity every 2 minutes by increasing the speed the equivalent of :30/mile in pace until they either reach exhaustion or the 4:30 min/mile pace limit of the exercise bout. The 1% incline will be maintained throughout the test unless the subject has not reached their VO\textsubscript{2max} level and the maximum speed of the treadmill is reached. In this case the treadmill speed will remain at 12mph and the incline will increase by 1% grade every 2 minutes until the subject has reached their VO\textsubscript{2max}. Exercising at 8:34 min/mile pace is equal to an easy to moderate run for a trained runner, while running at a pace of 4:30 min/mile would be equal to or near maximal effort for an elite runner. Once completed, you will perform a 5 min cool down on the treadmill. This testing session should take approximately 1 hr.

Testing Procedures

1) 3D Motion Capture- 3D motion capture will be utilized during the functional analysis, as well as during the data collection run. The motion capture system used during the functional analysis will utilize the Organic Motion Marker-less Motion Capture System (Organic Motion, New York, New York), and provides three-dimensional positional data necessary for Dynamic
Athletics software to provide kinematic and kinetic data on the subject. The motion capture system used during the VO2max testing will be the OptiTrack motion capture system (NaturalPoint, Corvallis, Oregon) and will provide the three-dimensional positional data necessary for Dynamic Athletics software to provide kinematic and kinetic running data on the subject. Neither of these motion capture systems collect pictures of the individual that would allow the subject to be identified by physical features, such as face, hair, and body size.

2) Heart Rate- Your heart rate will be constantly monitored an electronic Heart Rate monitor. Heart Rates will be recorded every 30 seconds during all treadmill runs.

3) Oxygen Consumption – Your oxygen consumption (VO2 via indirect calorimetry) will be monitored using the a metabolic cart from Parvo Medics (Parvo Medics, Sandy UT). For this measure, you will breathe through a lightweight mouthpiece that is attached to the Parvo Medics Cart. The oxygen consumption will be determined by the ratio of gases that are inhaled and expired while the subject is exercising. Oxygen consumption will be measured during the VO2max test and Test Run.

4) Rate of Perceived Exertion- You will be asked at the beginning of the 1st and 2nd minute of every stage to provide your level of exertion on the Borg Rating of Perceived Exertion (RPE). The scale is a 15 point scale starting at the number 6 and ending at the number 20 (shown below). This visual scale allows the subject an opportunity to rate how they are feeling during the different stages of their exercise bout.

6 No exertion at all
7 Extremely light
8
9 Very light - (easy walking slowly at a comfortable pace)
10
11 Light
12
13 Somewhat hard (It is quite an effort; you feel tired but can continue)
14
15 Hard (heavy)
16
17 Very hard (very strenuous, and you are very fatigued)
18
19 Extremely hard (You can not continue for long at this pace)
20 Maximal exertion

RISKS
1. Exercise Testing- You will undergo 2 exercise testing sessions, one in a marker-less motion capture system and one on a treadmill. In general, exercise does not provoke cardiovascular events in healthy individuals with normal cardiovascular systems, but, as with vigorous exercise, the risk of a cardiac event occurring during an exercise test does exist, and varies directly with the incidence of cardiovascular disease. According to the American College of Sports Medicine (ACSM), the absolute risk of sudden cardiac death during vigorous physical activity has been estimated at one per year for every 15,000-
18,000 people. Along with the risk of a cardiovascular event, there is also the risk of an acute musculoskeletal injury occurring during exercise. As a trained endurance athlete, the exercise testing protocol is no more physically demanding than a typical hard training session or a competition. You will be constantly monitored for abnormal heart rates including excessively high and excessively low heart rates. During each test you will constantly monitored by laboratory assistants and Dr. Gallagher, PhD. During the testing, athletic tape may be utilized to hold instruments in place, which carries a slight risk of irritation of the skin from the tape adherent.

FOLLOW UP CARE
Following the procedure you will be provided with contact information for Philip Gallagher, Ph.D, and Phillip Vardiman, PhD, ATC in case of any questions or concerns about the exercise test.

BENEFITS
Although you will not be receiving any monetary reimbursement for your participation in the study, you will receive valuable information regarding your body and ability to exercise. This information includes physiological data (Maximum Oxygen Consumption [Max VO₂], Ventilatory Threshold) and the associated pace for each of these data at no cost. From this, you will gain an increased understanding of your perceived effort during the various workloads of a typical running training session.
You will also receive the results of your functional test from Dynamic Athletics. This data will provide valuable information to you, allowing you to identify any range of motion, strength, or power imbalances you may have, as well as any tendencies to use one limb over another through certain bi-lateral movements. When applied to your training, this information will allow you to become a more balanced athlete, helping you to not only improve performance but also may allow you to avoid injury.

COMPENSATION FOR INJURY
The following information is provided in accordance with HEW regulations: “In the event of injury, the Kansas Tort Claims Act provides for compensation if it can be demonstrated that the injury was caused by the negligent or wrongful act or omission of a state employee acting within the scope of his/her employment.”

IN CASE OF EMERGENCY CONTACT PROCEDURE
In the event of a research related injury or adverse reaction, please contact Justin Maresh at (402) 802-6433 (cell), Phillip Gallagher, Ph.D. at 785-864-0772 (office) 785-550-6300 (cell), or Phill Vardiman at 785-864-0709 (office), 785-840-7447 (cell).

EMERGENCY CARE AND COMPENSATION IN CASE OF INJURY
In the unlikely event that any injury or illness occurs as a result of this research, the University of Kansas, their officers, agents, and employees, do not automatically provide reimbursement for medical care or other compensation. In cases of emergency, consistent with the Kansas Tort Claims Act, you would be responsible for payment of expenses related to treatments or associated with such complications except in a case where neglect can eventually be proven. You have been informed that payment for treatment of any injury or illness must be provided by your or your third-party payer, such as a health insurer. If any injury or illness occurs in the
course of research please notify the investigator in charge using the contact information found below.

INFORMATION TO BE COLLECTED
To perform this study, researchers will collect information about you. This information will be obtained from the Medical history form. Your name will not be associated in any way with the information collected about you or with the research findings from this study. The researchers will use a study identification number in place of your name. All of your data will be stored on a password protected computer, secure server, or in a locked filing cabinet located in a locked office of the applied physiology laboratory.

Dr. Gallagher, Justin Maresh, and the research team in the Applied Physiology Laboratory will use the information collected about you to examine the ability of a functional analysis (Dynamic Athletics Research Institute, Lenexa, KS) to predict running economy in trained runners. The researchers will not share information about you with anyone outside of the Applied Physiology Laboratory personnel unless required by law or unless you give written permission.

During the course of this study, the participants photograph and/or video may be taken during data collection for use during scientific presentations. By signing this consent form the subject hereby grants permission to the University of Kansas Department of Health, Sport, and Exercise Science to use any photographs or videos collected of the subject. The subject will not be compensated for such use.

Data collected through the use of 3D motion capture does not include pictures or video of the subject. Neither of the motion capture systems collect data that would allow for the subject to be identified by physical features, such as face, hair, and body size.

Permission granted on this date to use and disclose your information remains in effect indefinitely. By signing this form you give permission for the use and disclosure of your information for the purposes of this study at any time in the future.

REFUSAL TO SIGN CONSENT AND AUTHORIZATION
You are not required to sign this Consent and Authorization form and you may refuse to do so without affecting your right to any services you are receiving or may receive from the University of Kansas or to participate in any programs or events of the University of Kansas. However, if you refuse to sign, you cannot participate in this study.

CANCELLING THIS CONSENT AND AUTHORIZATION
You may withdraw your consent to participate in this study at any time. You also have the right to cancel your permission to use and disclose information collected about you, in writing, at any time, by sending your written request to: Philip Gallagher, Ph.D., University of Kansas, 1301 Sunnyside Avenue, Robinson Center Room 101DJ, Lawrence, Kansas 66045. If you cancel permission to use your information, the researchers will stop collecting additional information about you. However, the research team may use and disclose information that was gathered before they received your cancellation, as described above.

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PARTICIPANT CERTIFICATION
I have read this Consent and Authorization form. I have had the opportunity to ask, and I have received answers to, any questions I had regarding the study and the use and disclosure of information about me for the study. I understand that if I have any additional questions about this study you may call Justin Maresh (402-802-6433) or e-mail: justin.maresh@ku.edu; Dr. Philip Gallagher (785-864-0772) or e-mail: philku@ku.edu; or Dr. Phillip Vardiman (785-864-0709) or e-mail: pvardim@ku.edu. I understand that if I have any additional questions about my rights as a research participant, I may call (785) 864-7429 or write the Human Subjects Committee Lawrence Campus (HSCL), University of Kansas, 2385 Irving Hill Road, Lawrence, Kansas 66045-7563, email irb@ku.edu.

I agree to take part in this study titled ‘Ability of a Functional Analysis to Predict Running Economy in Experienced Male Runners’ as a research participant. I further agree to the uses and disclosures of my information as described above. By my signature I affirm that I am at least 18 years old and that I have received a copy of this Consent and Authorization form.

Print Subject’s Name
Signature of subject

Date

Print Name of Person Obtaining Consent
Signature of Person Obtaining Consent

Date

Print Name of Witness
Signature of Witness

Date

RESEARCHER CONTACT INFORMATION
Philip Gallagher
Principle Investigator
Applied Physiology Lab
101DJ Robinson Hall
University of Kansas
Lawrence, KS 66045
785-864-0772

Justin Maresh
Applied Physiology Lab
161 Robinson Hall
University of Kansas
Lawrence, KS 66045
402-802-6433
APPLIED PHYSIOLOGY LABORATORY
UNIVERSITY OF KANSAS

MEDICAL HISTORY FORM

NAME: ___________________________ DATE: __________
AGE: _______ HEIGHT: _______ WEIGHT: _______

A. Have you ever experienced any of the following conditions or procedures?

1. Myocardial Infarction YES NO
2. Angiography YES NO
3. Coronary Surgery YES NO
4. Chest Discomfort YES NO
5. Hypertension (high blood pressure) YES NO
6. Hypotension (low blood pressure) YES NO
   Systolic ≤ 100mmHg or Diastolic ≤ 60mmHg
7. Shortness of breath upon light exertion YES NO
8. Dizziness upon light exertion YES NO
9. Pulmonary disease YES NO
10. Heart palpitation YES NO
11. Heart murmur YES NO
12. Diabetes YES NO
   If “YES”, Type I or Type II
13. Extremity discomfort YES NO
14. Claudication (circulation problems cause leg pain) YES NO
15. Peptic Ulcers YES NO
16. Metal implants (including pins) YES NO
Does anyone in your family have a history of cardiovascular disease? YES NO
If “YES”, who? __________________________

B. Do you smoke? YES NO

C. Are you currently using any anti-asthmatic medications? YES NO

D. Are you currently using any anti-hypertensive medications? YES NO

E. Are you currently taking any anti-inflammatory medications? YES NO

F. Are you currently taking any blood thinners (i.e.: Coumadin, aspirin) YES NO

G. Are you currently taking any other kind of medication? YES NO
   If “YES”, please list below:
   __________________________________________
   __________________________________________
   __________________________________________
   __________________________________________

H. Have you ever been treated for a heat related illness (heat exhaustion, heat stroke)? YES NO

I. What is your current Cholesterol level? (If known) ___________

J. What is your current Blood-Pressure? (measured by APL staff or Nurse) ___________

K. Have you suffered any musculoskeletal injuries in the last 3 months? YES NO
   If “YES”, please list below:
   __________________________________________
   __________________________________________
   __________________________________________
   __________________________________________
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<th>TM Speed (mph)</th>
<th>Step Length (%)</th>
<th>Step Length (cm)</th>
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<th>Step Length (cm)</th>
<th>VO2max Step Length (%)</th>
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<td>8.2</td>
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<td>17%</td>
<td>8.2</td>
<td>0.7</td>
<td>8%</td>
<td>72.6</td>
<td>77.1</td>
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<td>RE % of VO2max</td>
<td>RE % of VT</td>
<td>RE Treadmill speed (mph)</td>
<td>Stride (cm)</td>
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Appendix F: Pearson-Product Moment Correlation Table
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VJ Loading Takeoff Force Difference R Vs L

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Con Jump Ht

|               | 0.145156964 | -0.325530717 | -0.570707471 | -0.21361625 | -0.41697306 | 0.133233327 | -0.629441269 | 0.548653583 |

CJ Peak Power

|               | 0.21079766 | -0.180526594 | -0.486493112 | -0.257220794 | -0.534837987 | -0.215474112 | -0.643183624 | 0.796343911 |

CJ RFD

|               | -0.299960481 | -0.187619536 | 0.186784853 | -0.064265073 | 0.158762439 | 0.035012081 | -0.234195224 | -0.048412432 |

CJ Peak Power/kg

|               | 0.30250758 | -0.205578052 | -0.651616092 | 0.265274835 | 0.103844569 | 0.451690927 | 0.262738835 | 0.056757985 |

Note: Denotes significant positive correlation.
Note: Denotes significant negative correlation.

Lunge Lt Distance

|               | 0.105249446 | -0.545948953 | -0.778949489 | -0.364692892 | -0.560017292 | -0.069993668 | -0.247709875 | 0.504125305 |

Lunge Lt % Ht

|               | 0.017184249 | -0.611374338 | -0.740110385 | -0.189230327 | -0.250510226 | 0.20187972 | -0.103137265 | 0.322386901 |

Lunge Rt Distance

|               | 0.163163327 | -0.261171087 | -0.511518075 | -0.40778399 | -0.680209279 | -0.340832041 | -0.293246241 | 0.580312066 |

Lunge Rt % Ht

|               | 0.108132335 | -0.351750702 | -0.544627182 | -0.31383162 | -0.50802641 | -0.156380534 | -0.218370474 | 0.506923997 |

Lunge Distance Difference R vs L

|               | 0.146808288 | 0.185207373 | -0.202995235 | -0.084701292 | -0.20369072 | -0.233449426 | 0.331425646 |

Note: Denotes significant positive correlation.
Note: Denotes significant negative correlation.
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<td></td>
<td>R Contact Time</td>
<td>Vert. Disp. (m)</td>
<td>L Vert Disp. (m)</td>
<td>Diff R/L Vert Disp. (m)</td>
<td>Broad Jump (cm)</td>
<td>Age</td>
<td>FMA Wt (kg)</td>
<td>HT (m)</td>
<td>L Vert Disps (m)</td>
<td>R Vert Disps (m)</td>
<td>% BW</td>
<td>Squat % BW</td>
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<td>VJ Takeoff Force Rt</td>
<td>VJ Loading Takeoff Force Difference R vs L</td>
<td>SLVJL Ht</td>
<td>SLVJL Net Force Impulse</td>
<td>SLVJR Ht</td>
<td>SLVJR Net Force Impulse</td>
<td>SLVJ Ht Difference R vs L</td>
<td>Lunge Lt Distance</td>
<td>Lunge Lt % Ht</td>
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