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Stability of Isometric Strength Asymmetry and Its Relationship to Sprint and Change-of-Direction Performance Asymmetry in Division-I Collegiate Athletes

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Stability of Isometric Strength Asymmetry and Its Relationship to Sprint and Change-of-Direction Performance Asymmetry in Division-I Collegiate Athletes

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Doctor of Philosophy in Sport Physiology and Performance
with a concentration in Sport Performance

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by
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ABSTRACT

Stability of Isometric Strength Asymmetry and Its Relationship to Sprint and Change-of-Direction Performance Asymmetry in Division-I Collegiate Athletes

by

Benjamin H. Gleason

The purpose of this dissertation was to evaluate the stability of strength asymmetry over a long-term period (1 year) and investigate the relationship of strength asymmetry to field test performance asymmetry in NCAA division-1 athletes. Isometric mid-thigh pull (IMTP) peak force asymmetry, ground contact time and finish time asymmetries on 10m sprint and 505 agility test performances were also observed. The impact of strength was also investigated in these studies to determine its effect on the magnitude of asymmetry.

In the first study, IMTP strength asymmetry was not related to symmetry indexes of 505 agility tests featuring right-leg plants or left-leg plants. Little connection was found between left or right-foot forward 10m sprint starts and strength asymmetry; only a large correlation (0.55) was found between symmetry index of dominant-leg force at 150ms and 10m sprint time asymmetry. All athletes reported being right-footed kickers; strength asymmetry was not related to functional sidedness, as half the athletes demonstrated strength asymmetry on either the left or right side. An interesting finding was that these athletes were significantly better at left turn 180° changes of direction (right leg cuts) compared to right turns (left leg cuts).

In the second study, peak force asymmetry over a one-year period was observed to be a rather volatile quality, with ranges between 16% or 8%, depending on the formula used. Based on this finding, it is possible that there may be a “normal” range of asymmetry that an individual athlete exhibits that could be linked to training adaptations along with other factors. Based on simple observation, an individual tendency toward symmetry existed in certain athletes. This relationship may be useful to explore in future study.

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To the athletes I have worked with at ETSU: Helping you attain your goals has been a privilege. Thank you for your trust. I hope you will look back on your time with me fondly.

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CHAPTER 1

INTRODUCTION

Several decades of research has been dedicated to the study of force production asymmetry between lower limbs in humans (Hewit, Cronin, & Hume, 2012; Knapik, Bauman, Jones, Harris, & Vaughan, 1991; Newton, Gerber, Nimphius, Shim, Doan, Robertson, Pearson, Craig, Hakkinen & Kraemer, 2006). Generally speaking, most studies have sought to investigate force production asymmetry as it relates to injury risk or lesser performance. With sufficient study, a threshold of performance asymmetry between limbs may be derived and associated with injury risk over time. Studies have been performed with a variety of testing methods, to include clinical, laboratory, and field tests. These testing methods have provided a variety of outcomes.

Previous initial research efforts on asymmetry were dedicated to investigating the influence of strength asymmetry observed in isokinetic machine tests on injury risk (Croisier 2004; Knapik et al., 1991). Factors such as hamstring to quadriceps strength ratios on the same leg and leg extension and flexion strength differences between legs have been widely used. In his review of isokinetic asymmetry research, Croisier (2004) proposed that a 15% strength asymmetry could be a relevant diagnostic threshold in the prediction of hamstring injury risk in soccer players, however at the time considerable debate existed on the exact threshold (evidence suggested between 10-20%). It is proposed that as fatigue occurs during game play or training, an unfavorable situation may result in a structural breakdown in the musculature of the weaker limb or ligament that results in injury. Not all studies support the use of isokinetic testing in the prediction of injury (Bennell, Wajswelner, Lew, Schall-Riaucour, Leslie, Plant, & Cirone, 1998). Because isokinetic testing involves the muscular actions about one joint, researchers and clinicians have proposed that isokinetic testing has limited relevance to athletic situations, as an athlete is rarely required to produce force in one joint alone. It is likely that performance decrements observed in athletic movements similar to those encountered in game play or training may be required to effectively assess any performance issues that could transfer to injury or performance deficit in game play. Recently studies have emerged that investigate the effects of strength asymmetry and/or limb preference on dynamic athletic movements such as jumping, running, changes of direction (COD) with short sprints, loaded squatting, and kicking (Bailey, 2014; Bell, Sanfilippo, Binkley, & Heiderscheit 2014; Chiang, 2014; Hart, Nimphius, Spiteri, & Newton 2014; Hart, Spiteri, Lockie, Nimphius, & Newton, 2014; Impellizzeri, Rampinini, Maffiuletti, & Marcora, 2007; Newton et al., 2006; Nimphius, McGuigan, & Newton, 2010; Spiteri, Nimphius, Hart, Specos, Sheppard, & Newton, 2014). It has been observed that changes of direction that feature the weaker limb may be slower (Nimphius et al., 2010). Several studies have demonstrated that strength asymmetry of >8% (or >15% depending on the formula used) resulted in a reduced jump height (Bailey, 2014; Bell et al., 2014). Research has yet to clearly associate a threshold of strength asymmetry using specific strength testing methods to a performance decrement in COD tasks or short sprint performance.

Previous injury appears to affect movement characteristics for a period of time following an injury. Brughelli, Cronin, Mendiguchia, Kinsella, & Nosaka (2010) investigated leg kinetics and kinematics during treadmill running at 80% maximum velocity (held for 8 seconds) in groups of non-injured and previously injured (within 2 years) Australian football players. Previously injured athletes demonstrated a reduction of horizontal force (49% asymmetry in previously injured vs. 4.9% asymmetry in non-injured) but not vertical force in the injured limb. Ground-foot contact times (GFCTs) were similar between limbs. It is unclear from the literature at this stage how long these asymmetries are maintained.

It is possible that assessing GFCT (either total ground contact time or contact time by step) in field tests may provide an indirect assessment of strength asymmetry, as a longer impulse may be required on a weaker limb to attain sufficient force to decelerate or push off in a COD, or during the stance phase in the acceleration phase of a sprint. To date, several studies have observed GFCT and ground reaction force asymmetry during CODs. Green, Blake, & Caulfield (2011) observed differences in cutting technique on a 45° COD task and reported rugby union starters exhibited longer GFCT in the plant leg and the push off leg during the non-dominant cut (both ≈5ms longer). Longer GFCTs were demonstrated for the nonstarters in the plant leg and push off leg during the dominant cuts (≈8ms and ≈3ms, respectively). Hart, Spiteri, et al. (2014) observed performances of regional Australian Football players on the AFL agility test (3 left cuts, 2 right cuts) and an alternative version with the opposite pattern (3 right cuts, 2 left cuts). Directional preference (sidedness) was observed in all athletes, with an inter-limb deficit completion time of 8% reported. Indeed, directional preference has been shown to improve with nine weeks of specific training on the insufficient limb in novice athletes (Salonikidis & Zafeiridis, 2008). At this time, little information exists in the literature as to the asymmetry threshold of directional preference in trained athletes, and very few studies have successfully tied strength asymmetry to performance on tasks involving locomotion.

For the purposes of this dissertation, testing was performed using IMTP peak force, along with the 10m sprint and 505 agility test. These are common tests used in sport performance testing. Infra-red timing gates are frequently used for evaluating speed during performance testing of sprint and CODs (Lockie, Schultz, Jeffriess, & Callaghan, 2012; Lockie, Schultz, Callaghan, Jeffriess, & Berry, 2013; Lockie, Callaghan, Berry, Cooke, Jordan, Luczo, & Jeffriess, 2014; Nimphius et al., 2010; Spiteri et al., 2014). The IMTP has been featured in multiple studies to date, including studies evaluating bilateral asymmetry (Bazyler, Bailey, Chiang, Sato, & Stone, 2014; Bailey, Sato, Alexander, Chiang, & Stone, 2013; Bailey, 2014; Chiang, 2014; Haff, Carlock, Hartman, Kilgore, Kawamori, Jackson, Morris, Sands, & Stone, 2005; Owens, 2011). The Optojump Next system was used in Coh, Tomazin, & Rausavljevic (2007), and was used to collect ground contact time of starts (20m as part of a 30m sprint). Though no significant differences existed during the acceleration, ground contact time by step and average ground contact time were reported. Interestingly, contact time of the faster sprinters shortened by ≈15ms over the 20m measured by Optojump, indicating the faster sprinters likely produced GRFs required for locomotion faster. Mann (2011) proposed GFCT observation as a relevant tool for the evaluation of sprinters, as GFCT is related to the amount of force an athlete can produce to enable locomotion at a high speed. As such, observing GFCT on a short or long-term basis, similar to the methods described in Coh et al. (2007) combined with key performance times may be a relevant monitoring tool to assess the outcome of training. To date, no studies have specifically evaluated GFCT to more than two steps of a COD. Because of the relationship between force production and GFCT, the use of GFCT to compare locomotion that highlights a particular limb in a COD may be a reasonable way to evaluate the performance impact of a strength asymmetry.

Statement of Purpose

1. To evaluate the relationship of bilateral force production asymmetry during the isometric mid-thigh pull and its relationship to asymmetry with:
    a. 10m sprint time
    b. Total 10m sprint ground-foot contact time
    c. 505 test performance time
    d. 7-step total 505 test ground-foot contact time
2. To evaluate the stability of bilateral lower extremity isometric force production asymmetry over a one-year period

Importance of the Study

To date, very little study has related strength asymmetry to athletic performance tests with the exception of those featuring jumping. Motor control aspects tend to confound findings, therefore additional studies are required to weed out the factors involved in locomotion on sport-relevant tasks. It is possible that a combination of laboratory and field testing methods may provide adequate means to assess the performance impact of strength asymmetry observed in athletes. A proper understanding of performance asymmetry is required so that practitioners may address (or not address) it through the use of appropriate training methods.

Assumptions

It was assumed that NCAA Division 1 collegiate men's & women's soccer, men's & women's tennis, women's softball, and men's baseball at East Tennessee State University are representative of athletes at other mid-level Division 1 institutions competing in the same sports. It is also assumed that self-reported lack of injury and the existence of data in the archive indicates a lack of injury in participating athletes were indeed accurate. It is further assumed that effort provided was maximal on all tests included in this study (10m sprint, 505 test, and isometric mid-thigh pulls).

Limitations

Athletes in the first study conducted testing on a rest day following the preseason camp. It is possible that residual fatigue may have been a factor in some or all of the measurements; all measurements intended to observe performance differences between sides were alternated (i.e. left cut then right cut) to alleviate any chances of fatigue affecting data collected from one side. In the second study, data sets were chosen based on availability over the selected time period. As such, some athletes were assessed during two preseason test sessions and one post-season session, while others may have been assessed during two postseason and one preseason session. It is unclear if this had any bearing on the quality of data acquired for analysis.

Delimitations

This study included a sample of collegiate athletes who participated in the Sport Performance Enhancement Consortium (SPEC) program at East Tennessee State University. Performance capacity of individuals in general or special populations are not of interest to the present investigation, as it relates to the performance capability of athletes. Short-term access to a limited subset of collegiate athletes was available at the time of study one (based on competitive schedule and sport practices). Long-term data sets from athletes included in study two were chosen based on the availability of laboratory data from three time points, with the first and last being one calendar year apart. The tests chosen represent methods that exist in the literature for comparison, or are a means of comparison that possesses potential merit. The tests were also ones that could be performed on the laboratory instrumentation available.

Definition of Terms

1. Absolute strength—maximal strength value that does not account for body mass

2. Asymmetry—difference in force production between lower limbs during a strength test or difference in time to complete a closed course test between trials that isolate a particular plant leg or start leg.
3. Dynamic—a muscle action that occurs involving joint movement
4. Ground reaction force—the resistive forces of the ground when forces are applied to it (by a limb)
5. Isokinetic—a specific velocity of movement (predetermined in clinical tests)
6. Isometric—a muscle action that occurs without joint movement
7. Peak force—the maximum force applied during a contraction
8. Relative strength—maximal strength value that accounts for body mass
9. Symmetry index—a formula that creates a percentage difference between right and left limbs and enables comparison between different qualities (i.e. time and force)

CHAPTER 2

LITERATURE REVIEW

Because strength asymmetry may have complex origins, a survey of topics within the area of asymmetry research was performed to discuss relevant physiological, motor control, and practical aspects for consideration relevant to strength asymmetry, 10m sprints, and 505 test performance. To appropriately set the stage for the studies included in this dissertation, discussion of common testing methods has been included. As it relates to several common testing and/or training tools used by practitioners, this study may be helpful in providing solutions to a current sport training debate.

A Very Brief Outline of the Unilateral vs. Bilateral Training Debate

At this time the performance impact of strength asymmetry is not well known despite some volume of study. Little is known about whether bilateral training—as seen in traditional lower body strength training (squats, weightlifting derivatives, etc.)—or unilateral training—as seen in single leg exercises (i.e. rear-leg elevated split squats, step ups, etc.)—reduce asymmetry as the athlete develops strength over time. It is possible that asymmetry may be reduced using bilateral training tools with attention to proper technique. No training study has yet compared or contrasted the two strength training approaches in athletes. Only two short-term studies have compared these training tools in untrained individuals—subjects included college-aged individuals and middle-aged and older individuals (see Hakkinen, Kraemer, Kallinen, Linnamo, Pastinen, & Newton, 1996 and

McCurdy, Langford, Doscher, Wiley, & Mallard, 2005). As such, there remains a substantial debate among coaches and practitioners as to the superiority of either approach, or most effective blend of these training tools (for a comprehensive review of the debate see Nijem & Galpin, 2014). Some practitioners have promoted unilateral training as an appropriate method to reduce strength asymmetry or provide more effective sport-specific adaptations citing only anecdotal evidence or theory to support the purported effectiveness of these methods (Bosch, 2014; Boyle, 2010). It is important to point out that laboratory analysis of training methods over a long-term period is required to evaluate the adaptations to sport training tools so that a framework for effective implementation may be derived. It is important to reiterate that laboratory study of these training tools has yet to occur using current training methods. Many individuals with a unilateral-is-best mindset may fail to realize that some sports have specific asymmetries that may be advantageous to performance, and the exact profiles for establishing injury risk related to asymmetry have yet to be developed for particular sports. To further elaborate on this concept, to date there is no detailed, well-established sport-specific threshold to determine the magnitude of asymmetry that may lead to performance deficit or increase/decrease injury risk. Furthermore, position-specific asymmetries may exist between athletes in a particular sport. For instance an 800m runner may be more asymmetrical than a cross-country runner, as the bulk of track-specific training might include more turns on a track and result in a greater training stress to one side. Specific architectural adaptations have been found to occur based on the most frequent sport training tools employed, and these may change in the short term (over the course of a training macrocycle or in-season period) according to programming (Blazevich, Gill, Bronks, & Newton, 2003; Nimphius, McGuigan, & Newton, 2012). These may be sport-specific adaptations, as one would expect during the in-season period. With such a volume of challenges for the sport science researcher, establishing such a threshold of performance or injury risk for one sport alone would likely require a substantial research commitment.

Major Biological Factors of Performance

In the pursuit of enhancing sport performance, many physical factors have been observed and evaluated by sport and exercise scientists and coaches—the most obvious choices are often measures of strength, power, and speed in sport-relevant tasks with sport-relevant distances. Multiple additional factors may also be of considerable importance implementing successful technical aspects of game play, such as the potential performance decrement imposed by strength asymmetry, lower limb dominance (also called limb preference or sidedness), and agility. These factors are likely inter-related with many common underpinnings. Lower extremity asymmetry may be observed in performance differences between legs during some form of locomotion. Studies have demonstrated asymmetry in athletes during athletic tasks such as jumping, changes of direction, running, kicking tasks, and resistance training, along with clinical strength assessment tasks (Bailey, 2014; Hart, Nimphius, et al., 2014; Knapik et al., 1991; Lockie et al., 2012; Newton et al., 2006; Nimphius et al., 2010). Before detailing these concepts, we must first discuss common laboratory and field test methods of measurement and formulas used in the diagnosis of asymmetry.

Common Instrumentation Used in the Measurement of Asymmetry

Open-Chain Methods

Previous research efforts investigating lower limb asymmetry have predominantly involved open chain exercises such as quadriceps and hamstring contractions using isokinetic dynamometers with dynamic and isometric methods to identify bilateral asymmetry (Amato, Afriat, Croisier, Legros, Desnuelle, & Bernard, 2003; Knapik et al., 1991; Markou & Vagenas, 2006; Read & Bellamy, 1990; Ruas, Minozzo, Pinto, Brown, & Pinto, 2015; Schmitt, Paterno, & Hewett, 2012; Schiltz, Lehance, Maquet, Bury, Crielaard, & Croisier, 2009). Researchers who have posed reliability and validity questions of the use of open chain methods—specifically over motor unit activation that may not transfer to sport situations—suggest that it may be inappropriate to solely base return to play decisions and assessments of individuals from healthy populations on tests using this type of instrumentation (Augustsson & Thomee, 2000; Lephart, Perrin, Fu, Gieck, McCue, & Irrgang, 1992; Impellizzeri, Bizzini, Rampinini, Cereda, & Maffiuletti, 2008). Many of these concerns are highlighted in the work of Read and Bellamy (1990), who evaluated isokinetic asymmetry of advanced and elite tennis, squash, and track athletes. Researchers found no significant differences to exist in hamstring/quadriceps torque ratio asymmetry between legs between types of athlete, however a large difference in the torque ratio was demonstrated between the preferred and non-preferred legs at 300°·sec^{-1} for all athletes. Similar torque ratios existed between legs only at lower speeds. The hamstrings produced more force compared to the quadriceps as speed of movement increased, particularly in the non-preferred leg, indicating that a complex relationship exists between lower limb musculature during high-speed single joint movement, potentially due to neural factors, muscle architecture or mechanical advantage. Further demonstrating difficulty establishing relationships between isokinetic measurements and dynamic performance, Farrar and Thorland (1987) found low correlations (range -0.01 to -0.22) between isokinetic strength (at 60°·sec^{-1} and 300°·sec^{-1}) and sprint speed (36.6m and 91.4m) in a sample of active college physical education (PE) students.

Closed-Chain Methods

Studies have investigated asymmetry using closed-chain methods such as jumping and isometric pulls or squats performed on force plates (Bailey, 2014; Bell et al., 2014; Chiang, 2014; Newton et al., 2006; Nimphius et al., 2010; Spiteri et al., 2014). Laboratory-based and field tests using closed chain testing methods appear to be more appropriate than open chain methods for use with non-clinical populations because they are similar to movements used in athletics. Isometric strength assessment using the mid-thigh pull (Kraska, Ramsey, Haff, Fethke, Sands, Stone, & Stone, 2009) is a time-efficient method that is used in several sport science laboratories across the globe. This method presents a considerable advantage, as coaches and sport scientists may evaluate athletes' force characteristics exhibited during maximal effort pulling performed from the universal athletic position—a balanced stance commonly used in sports (Plisk, 2006) (Figure 2.1).

Figure 2.1. Universal Athletic Position

A variant of the universal athletic position has been shown to be the most mechanically advantageous for maximal force production during the mid-thigh pull in strength-trained athletes (Beckham, Lamont, Sato, Ramsey, Haff, & Stone, 2012). The force data provided by a custom analysis program provides the researcher with the ability to observe peak force (PF), along with a variety of relevant factors to performance (rate of force development, impulse, etc.). This method has been used in the past to identify isometric strength asymmetry in collegiate athletes (Owens, 2011; Bailey, 2014; Chiang, 2014). Because the position is fixed, more control is possible on the evaluation of muscle contraction without complications from motor control aspects of changing joint angles. Equivalent force data is not produced using common open-chain testing methods.

Locomotion

Several studies have observed asymmetry with respect to time to complete one-legged plant change-of-direction (COD) tasks (Chiang, 2014; Green et al., 2011; Lockie et al., 2014; Nimphius et al., 2010). Most studies compared some strength-related task to one or more COD performances that included multidirectional movements that somehow isolated the force generating capacity of a particular limb (i.e. 505 test compared to unilateral isometric squat). Due to the complexity of analyzing biomechanical aspects of COD tasks, many analyses are limited to finish time and force production of a plant leg (i.e. Spiteri et al., 2014).

Only a few studies have investigated ground contact force or time asymmetry in able-bodied individuals during running. Divert, Mornieux, Baur, Mayer, & Belli (2004) observed multiple mechanical parameters of gait in recreational distance runners during four minutes of treadmill running. The authors reported asymmetry <2% between limbs on all mechanical factors observed over 60 steps (to include ground contact time, vertical and horizontal force). Buckalew, Barlow, Fischer, & Richards (1985) observed ground contact time of elite female marathon runners during a race and noted no differences in asymmetry between top ten and bottom ten finishers. A review by Carpes, Mota, & Faria (2010) highlighted that a range of asymmetry has been observed to vary according to the individual. Cavagna (2006) observed that stiffness increases as speed increases (running >14 km/h^{-1}), with the elastic qualities of tendons being responsible for conserving a greater proportion mechanical force. It is not yet clear what the relationship of ground contact time is in COD running; few observations have been made, which are usually limited to a few steps within the closed course (i.e. Green et al., 2011).

Movement Screening

Many practitioners have endorsed the utility of "functional movement" screening tools in the assessment of movement quality of athletes. Though a thorough review of these methods is beyond the scope of this discussion (for methods see Cook et al., 2006a and Cook et al., 2006b), briefly highlighting their use is appropriate. Atkins, Hesketh, & Sinclair (2015) reported peak ground reaction force asymmetry ranged between 4-13% (right vs. left) during an unloaded overhead deep squat in a sample of talented youth and adolescent soccer players (12-16 years old). As this was an acute study, any determinations of asymmetry changes over time should be made with caution for this population, similar to Voutselas, Papanikolaou, Soulas, & Famisis (2007). Questions still remain if the application of unloaded clinical tools included in the Functional Movement Screen (Cook, Burton, & Hogenboom, 2006; Cook et al., 2006) is appropriate to assess performance decrements or injury risk. Lockie, Schultz, Jordan, Callaghan, Jeffriess, & Luczo (2015) evaluated the efficacy of the Functional Movement Screen® (FMS) to identify deficiencies on a battery of performance tests in male recreational team sport athletes. Four significant differences were reported. The unloaded overhead deep squat correlated moderately and negatively with differences between sides in 505 performance—a higher squat score was negatively correlated to time difference between right and left 505 (r = -0.423, $p < 0.050$). Also modified T test time differences between left and right tests correlated strongly with hurdle step score of left and right legs (left r = 0.511, $p < 0.015$; right r = 0.582, $p < 0.05$). Modified T test also correlated moderately with overall FMS score (r = 0.432, $p < 0.045$)—indicating that a better FMS score was related to a greater performance differences between sides on the modified T test. Similar to other clinical tools such as open chain strength testing, so-called "functional movement" assessment tools, very little evidence supports any association with better performance on sport-related and loaded tasks or injury risk, generally based on lack of specificity (Frost, Beach, Callaghan, & McGill, 2013; Beardsley & Contreras, 2014).

A Brief Introduction to Instrumentation Used to Evaluate Running Mechanics

Today biomechanical evaluations of running mechanics are typically performed using computer-modeling software that provides a 3-dimensional model of the athlete wearing reflective markers moving through a field of view (i.e. VICON Nexus, v 1.85, Centennial, CO, USA). For coaching applications this technology is not always practical, as a considerable amount of time is required for system calibration, data collection, and analysis. Other systems also include the use of reflective markers and video analyzed to provide joint angles two-dimensions (i.e. Slawinski, Dorel, Hug, Couturier, Fournel, Morin, & Hanon, 2008), however similar time demands exist with data analysis. Marker-based systems have a considerable limitation in COD movement analysis, as often markers are hidden by moving arms or the trunk, etc. during the COD. As a result these systems require several cameras to assess high velocity CODs, which may make their use cost-prohibitive to all but very well funded laboratories. Other methods of indirectly observing mechanics have recently been developed. The OptoJump Next system (Microgate, Bolzano, Italy), evaluates foot contact over time using a series of linked instruments laid down on a flat surface like railroad tracks (see Figure 3.2). A continuous series of light-emitting diodes (LEDs) and sensors are aligned down the rails that are interrupted during the contact phase as the athlete moves through the course. Reliability and validity of this system has been assessed in several studies during jumping and running (Glatthorn, Gouge, Nussbaumer, Impellizzeri, & Maffiuletti, 2011; Glazier & Irwin, 2001). In the first study to use such a system for long-term monitoring, Mattes, Habermann, Schaffert, & Muhlbach (2014) used Optojump Next to evaluate running mechanics qualities exhibited during a flying-30m sprint protocol in a long-term observational study of national and international level sprinters and jumpers.

Common Formulas Used to Measure Lower Limb Strength Asymmetry

In the extant literature, versions of four common formulas have been used to provide relative strength asymmetry. The first formula has been used to calculate bilateral force production differences of isokinetic and dynamic (jumping) tasks (Impellizeri et al., 2007; Newton et al., 2006; Lockie et al., 2014).

SI = [(stronger limb – weaker limb)/(stronger limb)]*100

Impellizzeri et al. (2007) pointed out that this formula may be altered for specific purposes, comparing strength values between stronger vs. weaker limbs, right vs. left, and injured vs. non-injured limbs. In addition, they pointed out that using this formula as listed below may introduce different values for the same relative asymmetry because of the size of the numerator. This formula is also used to calculate percent change when assessing pre- & post-intervention performance testing data (Vincent & Weir, 2012).

One alternative formula is also found in the extant literature; variations have been used to assess bilateral force production asymmetry and performance during isometric, squatting, and jumping tasks (Bailey et al., 2013; Bazyler et al., 2014; Sato & Heise, 2012):

SI = [(stronger limb – weaker limb)/(stronger limb + weaker limb)]*100

As it has been applied in several studies, this formula does not provide specific direction of asymmetry, and always yields a positive number. Therefore it is only used in the above context to present a picture of strength asymmetry magnitude. If the purpose of a study is to compare asymmetry values (strength dominance) between groups or between different tests, a formula must be used that indicates direction. A formula that achieves this goal is found in Schiltz et al. (2009):

SI = (1 – non-dominant limb/dominant limb)*100

Or

SI = (1 – limb with injury history/limb without injury history)*100

This formula has been used to compare uninjured and injured limbs and strength dominance, generally in rehabilitation settings following anterior cruciate ligament reconstruction.

Recently Bell et al. (2014) used the following formula to evaluate leg mass and force asymmetry during jumping in collegiate athletes:

SI = [(right limb – left limb)/0.5(right limb + left limb)]*100

Because this formula includes data from both limbs in the numerator, absolute asymmetry may be acquired to compare magnitude of asymmetry without compromising the scale of the data. The Bell et al. (2014) formula was selected for use in this dissertation because it may be applied to data from specific limbs (right and left vs. stronger and weaker) and normative directional asymmetry data were recently proposed for a collegiate athletic population based on their findings. It also may be altered according to strength dominance, similar to several of the previous formulas.

Considerations for Agility Performance

For the vast majority of sports, agility is an important factor to consider in assessment of an athlete's improvement or ability to optimally perform. Agility is defined as a whole body change of direction in response to a stimulus within a small area, usually 4-10m (Roozen & Suprak, 2012). Agility has two components, the physical (the body's ability to decelerate, change direction, and accelerate in another direction) and the cognitive (the brain's ability to detect a relevant stimulus, process it efficiently and accurately, and direct the body to act in accordance with potential sporting advantage) (Sheppard & Young, 2006; Nimphius, 2014). Many tests have been developed to assess athletes' agility over the last several decades. Most of these have been developed with intent to assess the physical aspect of agility, such as a timed, closed course test including single or multiple pre-planned CODs between short sprints. Several tests of this nature have been developed and applied to common distances used in court/field sports, including the 505 agility test (Draper & Lancaster, 1985). The 505 test is unique, as it is the only established test to include a single 180° COD. Observing details of agility testing such as overall times, time the foot is in contact with the ground, and comparing these factors between trials may allow sport scientists to evaluate limb specific asymmetries in an athlete's movement that could expose him/her to tactical disadvantage or even risk of injury. From an athlete development and coaching perspective, an athlete should ideally possess as few movement deficiencies as possible in the context of the sport situation they are likely to encounter. Recent efforts by sport scientists to develop sport-specific tests to evaluate movement capacity have resulted in the linkage of video stimuli to timed agility testing with sport-relevant circumstances (distances, cutting angles, speeds, etc.). Such advanced testing methods may never be available to coaches at most levels of sport, therefore simpler tools such as closed drills should be thoroughly evaluated to assess their relevance to performance, and implemented in an appropriate context.

The ability to change direction, as assessed by closed drills, is likely influenced by multiple, and often inter-related factors, to include: technique (and motor control factors), strength factors (maximal strength, reactive strength, power, and rate of force development), leg stiffness (and ground contact time), limb dominance (sidedness or preference), body size and anthropometrics (McMahon, Comfort, & Pearson, 2012; Roozen & Suprak, 2012; Young, James, & Montgomery, 2002; Young, Miller, & Talpey, 2015).

Technical Components

Despite their common use in sport practice and conditioning settings, the technique exhibited during COD movements has received minimal attention in the scientific literature. One group of researchers recently evaluated several common techniques observed during the 90° turn and sprint test using a high speed camera and reported them in a coaching context (Hewit, Cronin, Button, & Hume, 2010). Common factors of "successful" performance on this test were reported to be (in order) a lowering of the center of mass (COM) before the turn (assumption of the universal athletic position as discussed by Plisk, 2006) (Figure 2.1), moving the COM toward the target, maintaining arm and leg position close to the body when turning, establishing COM position past the takeoff foot, full extension of the takeoff leg, and aggressive arm action. The most successful strategy for performance on the 90° turn and sprint test, as observed in their laboratory, was reported to be the pivoting crossover. No data or details of the population sampled were reported in this article.

The same research group observed CODs in female under-21 national level netball athletes (Hewit, Cronin, & Hume, 2012). Athletes began in the UAP and performed 180° turns into a 2.5m sprint. Researchers qualitatively evaluated the turns for common best practices. Similarly to the previous study, the best performances involved a hip drop, followed by the head leading the body and a push off the pivot foot, arm action close to the body, full extension of the takeoff leg, and a large takeoff distance. Mechanics of this turn more closely resemble the mechanics of a 505 agility test, in that a sidestep cut was employed. Andrews, McLeod, Ward, & Howard (1977) first outlined the mechanics of the sidestep cut, where an athlete approaches a point and makes a decisive COD. As the athlete approaches the COD point, the center of mass is dropped, the plant leg is extended with the hips flexed and the plant foot makes contact with the ground. As forward momentum is stopped and reversed, the torso and pelvis are rotated and weight is transferred to the opposite leg as the athlete accelerates out of the turn. Sasaki, Nagano, Kaneko, Sakurai, & Fukubayashi (2011) evaluated trunk lean angles and ground contact during performances in a modified 505 test (no run-up) in male collegiate soccer players. Greater forward lean during the foot contact and maximum trunk inclination phase correlated strongly with time and ground contact time ($r = 0.61$, $p < 0.04$ and $r = 0.65$, $p < 0.02$ respectively). Moderate correlations between these variables during foot-off phase did not reach statistical significance. Similarly, moderate correlations between time and contact time and lateral angular displacement were found, but these also failed to reach statistical significance. Excessive forward lean during the COD may decrease mechanical advantage. Efficiency appears to be of utmost importance in COD activities.

Nimphius, Spiteri, Seitz, Haff, & Haff (2013) evaluated pacing strategy employed by adolescent athletes during a 505 test. Some athletes slowed in preparation for the COD, however strength was not evaluated in this study. Individual strategies have been observed in the literature, however it is not clear how common pacing strategies may occur in highly trained athletes.

Relationship Between Strength and Power Factors on COD and 10m Sprint Performance

Several studies have evaluated the relationship between absolute or relative strength and COD performance. Peterson, Alvar, & Rhea (2006) found 1RM back squat significantly correlated (strong and negative) to T test performance (r = -0.78, p < 0.01) in a large sample of male and female first-year collegiate athletes. The correlation was higher when the 1RM back squat was related to body mass (r = -0.80; p < 0.01). Sprint acceleration also correlated strongly with absolute and relative 1RM back squat strength in this sample (r = 0.82, p < 0.01 and r = 0.876, p < 0.01, respectively). Chiang (2014) investigated the relationship between allometrically scaled IMTP strength and performance on a modified 505 test and found a strong negative correlation (r = -0.65, p < 0.01). The author reported partial time asymmetry (total time - acceleration time at 3m) was related to strength asymmetry at 50ms and 90ms (*r* = 0.42 to 0.60, *p* not reported). Results of this study indicated that 3m may be a short enough distance that strength asymmetry measurements are not negated by the influence of bilateral steps. Chaouachi, Brughelli, Chamari, Levin, Ben Abdelkrim, Aurencelle, & Castagna (2009) tested national level basketball players and found 1RM back squat correlated significantly and negatively with 10m sprint time ($r = -0.68$, $p < 0.05$), but was not related to T test time ($r = -0.22$, $p > 0.5$). Spiteri et al. (2014) observed the relationship between multiple strength and power variables on COD performance on several tests in female professional basketball players. Isometric strength correlated strongly and negatively with performance on the 505 and T test (*r* = -0.79 and -0.85 respectively, $p < 0.001$). Dynamic strength also correlated strongly and negatively with 505 and T test (*r* = -0.80 and -0.80 respectively, $p < 0.001$). Vescovi and McGuigan (2008) put female high school and collegiate athletes through a battery of power, speed and agility tests. Moderate to strong correlations were found between countermovement jump (CMJ) performance and 9.1m sprints (-0.49 to -0.68). A moderate correlation was observed between CMJ and Illinois test (-0.48, $p <0.0001$), however a weak-moderate correlation (-0.36) was noted between CMJ and pro-agility test in high school athletes. Strong correlations were found between CMJ and Illinois and pro-agility tests in collegiate athletes (-0.55 to -0.70). Markovic (2007) observed low correlations between explosive strength, maximal strength (both absolute) and COD performance in a heterogeneous group of male collegiate physical education (PE) majors, some of which were national-level athletes. Elastic strength tests correlated -0.33. Nimphius et al. (2010) also found strength related to

505 performance in a group of regional-level female softball players. Relative back squat (1RM/BW) strength correlated to non-dominant 505 across a season (r = -0.73 to -0.85, $p < 0.05$), however correlation with the dominant side was lower and failed to reach significance in two of three testing sessions (r = -0.50 to -0.75). Results of this study demonstrate potentially population-specific adaptations based on sport training adaptations.

Research with college PE majors supports the notion that some populations may have unique relationships between strength (or strength-power) and performance. Jones, Bampouras, & Marrin (2009) found speed (flying 5m from 20-25m) and eccentric knee flexor strength (isokinetic dynamometer) were the best correlates of 505 test performance.

A few studies have related reactive strength to COD performance. Lockie et al., (2014) put recreational males through various performance tests and found reactive strength index from a 40cm drop jump correlated strongly and negatively with change of direction and agility test performance ($r = -0.64$, $p < 0.008$) and 10m sprint performance ($r = -0.68$, $p < 0.004$), and moderately and negatively with T test performance ($r = -0.54$, $p < 0.032$). Castillo-Rodriguez, Fernandez-Garcia, Chinchilla-Minguet, & Carnero (2012) reported weak to strong correlations (r = -0.34 to -0.88, $p < 0.05$) in male collegiate physical education students (amateur soccer players) between drop jump height (30cm and 15cm drop height) and a series of short 1-turn COD tests (90° and 180° turn).

Power has been specifically observed in a number of studies in relationship to CODs. Spiteri et al. (2014) found moderate and weak correlations between 505, T test performance and power derived from CMJ (0.47 and 0.17 respectively, $p < 0.001$) in female professional basketball players. Another study investigated the relationship between unilateral CMJ power asymmetry and performance on the 3-cone drill in Division III collegiate football players (Hoffman, Ratamess, Klatt, Faigenbaum, & Kang, 2007). A power asymmetry of 9.7 ± 6.9% was reported, however a negligible difference between sides was observed on the 3-cone drill. Also reported was a low-moderate correlation between bilateral power and 3-cone drill performance ($r = -0.34$ to -0.39, $p < 0.05$). Young et al. (2002) investigated the relationship between power and strength variables and COD performance at single 20°, 40°, 60°, and four 60° cuts in club level athletes. Correlation between finish time and unilateral concentric power were low to moderate (0.07 to -0.33, $p > 0.05$). The relationship between reactive strength and finish times was stronger, with correlations ranging from -0.29 to -0.61. This relationship achieved statistical significance only on right and left 60° multiple turns and 20° turn to the right and straight sprint ($p < 0.05$). Marshall, Franklyn-Miller, King, Moran, Strike, & Falvey (2014) found peak concentric ankle power to be the factor most related to finish times of a 5+5m sprint with 75° COD in high level Gaelic hurlers ($r = 0.77$).

Sport-specific performance asymmetry has been observed in novice and recreational athletes with respect to strength factor asymmetry. Salonikidis and Zafeiridis (2008) observed lateral movement speed differences between right and left tennis-specific 4m shuffling and 4m sprinting in novice tennis players. Athletes in this training study showed reduction in asymmetry and performance improvement as a result of a 9-week plyometric and COD training program. Drop jump (DJ) performance and reactive strength index (DJ height/ground-foot contact time) were the best predictors of 4m and 12m sprints in this study (r = -0.60 to -0.75, $p < 0.05$). Spiteri et al. (2013) compared the relationship between multiple performance variables observed during 45° CODs and isometric strength in recreational athletes. Stronger subjects displayed greater angles of knee flexion and hip abduction during the stance phase than weaker athletes. Stronger athletes produced greater braking and propulsive forces during the COD task compared to weaker athletes. Relative isometric strength was also suggested to be a quality related to change of direction performance, however a correlation was not provided.

Superior unilateral jumping performances have been observed in the stronger leg of athletes who typically have fixed start positions. Regional and national sprinters underwent a test battery with a variety of jumps and 10m sprints (Habibi, Shabani, Rahimi, Fatemi, Najafi, Analoei, & Hosseini, 2010). Researchers reported longer single and three-hop distances (0.04m and 0.13m) with the leg that they typically used in front during a block start. Vagenas and Hoshizaki (1986) observed the relationship between leg strength asymmetry (as diagnosed with unilateral static-start jumps) and short sprint performance variables in regional and national level sprinters. The stronger leg was strongly predictive in determining the best start leg ($\Phi = 0.87$, $p < 0.01$). The stronger leg in the front block was the determinant of superior sprint performances (takeoff velocities and sprint times) at 5m, 10m, and 20m. Interestingly, an average asymmetry of 8% was reported in this study. Mean asymmetry in their sample was 28.85N (8%).

Body Size and Anthropometrics on COD and 10m Sprint Performance

Differences have been observed in 505 performances and 10m sprints in heterogeneous athletes from several sports. Swinton, Lloyd, Keogh, Agouris, & Stewart (2014) noted a negligible correlation between stature, 10m and 505 performance (r = 0.23 and 0.22 respectively, $p > 0.05$), in a group of well-trained club rugby athletes. Body mass correlated strongly with 10m and 505 performance in this population (r = 0.55 and 0.56 respectively, $p < 0.05$), indicating larger athletes did not perform as well as smaller athletes on these tests. Chaoachi et al. (2009) found T test performances of national level basketball athletes correlated moderately with height ($r = 0.40$, $p > 0.11$) and strongly with mass ($r = 0.58$, $p < 0.03$), again indicating an inverse relationship between size and performance on COD tests. Results from Nimphius et al. (2010) support the notion that larger athletes tend to perform slower on COD tests. Strong correlations were found between 505 performance and body mass in regional level female softball players (r = 0.70 to 0.93, $p < 0.05$). Athletes from strength-power sports illustrate the expected effects of size on performances in short sprint and COD tests based on the requirement of a variety of body types to support different skill requirements within these sports.

Performance Asymmetry Observed in Dynamic CODs

Green et al. (2011) observed leg kinematics and kinetics of semi-professional rugby players during a 45° cut after a 5m run-up on a closed course and observed that the sidestep cut was the preferred choice for all athletes. The starter group initiated knee extension in the push-off leg faster than the nonstarter group in the dominant-leg cut (greater ground reaction forces), likely as a result of a greater deceleration by the dominant leg before the plant leg push-off. Plant leg ground-foot contact times were shorter for the starter group only on the dominant leg cut, and similar between groups for non-dominant leg cuts. Strength asymmetry was not specifically observed in this study, therefore only asymmetry trends related to locomotion in a COD test may be gleaned from this work. Hart, Spiteri, et al. (2014) observed performance asymmetry based on cutting direction preference in Australian football players. Using the AFL agility test, athletes demonstrated ≈8% performance difference between preferred and non-preferred sides. Because the AFL agility test (in its current form) involves three cuts to the left, right leg-dominant athletes (61%) were found to perform better in trials featuring more cuts to the left. The remaining athletes performed better in the alternative version of the test, which featured three cuts to the right and two to the left. It is interesting that trials featuring more cuts to the left (associated with a right leg plant) featured better performances in the majority of athletes in this sample.

Potential Motor Control-Related Considerations for 10m and COD Performance

Leg Stiffness and Ground-Foot Contact Time (GFCT)

The forces encountered during dynamic movements require substantial leg stiffness to enable efficient movement (Chelly & Denis, 2001; McMahon et al., 2012). Leg stiffness is frequently obtained using hopping or horizontal locomotion tasks where peak vertical ground reaction force is divided by change in displacement of the center of mass during ground contact (McMahon et al., 2012). Leg stiffness (K_{leg}) enables the limb to absorb and release energy efficiently after the onset of ground contact through the effective use of the stretch-shortening cycle—a natural muscle action where a pre-activated muscle is lengthened in the eccentric phase then shortened in the concentric phase (Butler, Crowell, & Davis, 2003; Brazier, Bishop, Simons, Antrobus, Read, & Turner, 2014; Taube, Leukel, & Gollhofer, 2012). Bret, Rahmani, Dufour, Messonnier, & Lacour (2002) observed that K_{leg} of regional and national-level sprinters was strongly related to greater velocities observed at the later stages (last two-thirds) of a competitive 100m sprint. Leg stiffness has been shown to vary according to the task being performed (Farley, Houdijk, Van Strien, & Louie, 1998; Arampatzis, Bruggemann, & Metzler, 1999), and is adjusted quickly (particularly at the ankle) according to the surface, to enable efficient movement (Farley et al., 1998; Ferris, Liang, & Farley, 1999). Studies combining ultrasound and electromyography have observed specific muscle fascicle shortening to maximize tendon elasticity during faster running paces and jumping tasks (Ishikawa & Komi, 2008). Therefore, it appears that a specific range of K_{leg} may be optimal for a given task (Brazier et al., 2014; Ishikawa & Komi, 2008; McMahon et al., 2012). This stiffness is modulated by the central nervous system by a complex interaction of pathways, with stretch reflexes recently proposed to be a major sensory mechanism that drives control (Taube et al., 2012). The motor cortex and corticospinal system may also contribute substantially to movement efficiency by implementing pre-set motor programs—particularly in fast movements, however this relationship is not well understood (Taube et al., 2012). The capacity for leg stiffness, as observed in a unilateral hopping test, has been shown to not change substantially over the course of a season in male professional athletes from at least one football code (Pruyn, Watsford, Murphy, Pine, Spurrs, Cameron, & Johnston, 2013). It is not clear the extent to which leg stiffness is involved in CODs, however it is one factor that should be evaluated in future studies particularly as it relates to strength. It may be possible that dexterity is an additional inter-related factor that enables stiffness to occur in a COD (Lyle, Valero-Cuervas, Gregor, & Powers, 2013).

Mauroy (2014) observed changes in leg stiffness in recreational runners running to and jumping over a 0.65m-high obstacle. During the two steps preceding a jump, the subjects decreased K_{leg} (preparatory step), then increased K_{leg} (jumping step) compared to K_{leg} observed during running. This demonstrates some of the motor control aspects of negotiating changes of direction. The same research group also compared the K_{leg} of hurdlers to recreational athletes, and noted a similar pattern of K_{leg} change, however the change was less pronounced in hurdlers (Mauroy, Schepens, & Willems, 2014).

A measurable performance quality likely related to leg stiffness and performance is ground-foot contact time (GFCT). Both field and laboratory-based observation of this factor may be relevant to indirectly assess the dynamic movements of athletes, provided technique is stable. Ground-foot contact time during CODs has been observed in a few studies, however this factor has not yet been directly evaluated in vivo in connection to leg stiffness. Chiang (2014) reported longer ground contact time (≈0.05s) in male vs. female collegiate soccer athletes during the 180° turn of a modified 505 test (no runup) despite faster COD times in men. Marshall et al. (2014) observed performance times in a 75° COD task, where strong and moderate correlations were observed between performance times and peak ankle flexor moment (r = 0.65) along with performance times and ground contact time (r = -0.48). Green et al. (2011) observed high level Gaelic hurlers performing a 75° cutting task; plant leg GFCTs were ≈15-30 ms shorter in starters vs. non-starters, while minimal push-off leg GFCT differences were observed between starters and non-starters (≈3-5ms). The starters were older and about 8kg heavier on average, demonstrating that small increases in body mass—particularly lean mass—may not negatively affect COD time. Korhonen, Suominen, Viitasalo, Liikavainio, Alen, & Mero (2010) observed kinetic and kinematic variables for asymmetry during sprinting in high-level young and old sprinters. Very small GFCT asymmetry (≈1-2ms) was found at top speed (30m and 60m sprints), with slightly greater mean GFCTs observed on the dominant leg (perceived preferred jumping leg) steps.

Limb Preference (Sidedness), Sprint and COD Performance

Relationship between sidedness and performance is unclear. It would stand to reason that in sport activities such as kicking a football different skills may be developed in each leg (stiffness in the plant leg and tension in one or more muscle groups through a range of motion in the kicking leg) that may result in specific structural adaptations over time. Hart, Nimphius, et al. (2014a) found leg mass asymmetry in AFL athletes. This was related to strength asymmetry (deficit in the post leg) that reduced kicking accuracy. Such adaptations could lead to asymmetry in COD activities based on force production differences between legs (similar to Chiang, 2014).

A tool commonly used to diagnose a skill-dominant lower limb in humans is the 12-question Waterloo Footedness Questionnaire (Steenhuis & Bryden, 1989). Study in state-level swimmers found sidedness as assessed with a revised WFQ was not strongly tied to 5m speed in a swim track start (Hardt, Benjamuvatra, & Blanksby, 2009). It may be that the population was not well trained enough to demonstrate a sufficient leg drive difference. However, it is possible that any performance decrement based on skill may be negated by the bilateral nature of locomotion beyond a certain distance.

Asymmetry Threshold Observations from Clinical and Laboratory Settings

Rehabilitation researchers have suggested mobility asymmetry or strength asymmetry thresholds between 10-20% may be used for assessing injury risk and return to play following knee anterior cruciate ligament and musculoskeletal sport injuries (Croisier, 2004; Knapik et al., 1991; Schmitt et al., 2012). Bell et al. (2014) indicated that the 15% asymmetry threshold (Croisier, 2004) may be too high, as performance decrements were observed on vertical jumps with power asymmetry of 15%. This was supported by Bailey (2014), who indicated that 8% (or 16% using the same formula as Bell et al., 2014) may be a more appropriate threshold to observe a performance decrement, however the impact of strength asymmetry on injury risk remains unclear despite considerable study.

CHAPTER 3

RELATIONSHIP BETWEEN ISOMETRIC FORCE, 10M SPRINT, AND 505 AGILITY TEST PERFORMANCE ASYMMETRY IN DIVISION-1 COLLEGIATE SOCCER PLAYERS

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Abstract

The purpose of this study was to determine the relationships between strength asymmetry and performance asymmetry on common athletic performance field tests (10m sprint and 505 agility test). Subjects included 17 collegiate soccer players who performed isometric strength testing, 10m sprints and 505 agility tests under conditions that may detect asymmetry. Pearson correlations were performed on symmetry indices of force production at various time frames from isometric mid-thigh pull (IMTP), 10m sprint performance using right and left-foot forward stances, and 505 tests with turns to the right and left. Paired samples *t*-tests were performed on the data sets to evaluate differences between sides on performance measures and establish reliability between trials. A large correlation (*r* = 0.55) was found between force asymmetry at 150ms and asymmetry between 10m sprints. Negligible relationships existed between factors on 505 performance. Averaged performance times (R + R)/2 vs. (L + L)/2 were best on the left turn (right leg plant) of the 505 agility test in this sample, with no apparent explanation based on strength asymmetry.

Abstract word count: *172*

Key words:

Bilateral strength asymmetry, field test performance asymmetry, 10m sprint, 505 agility test, isometric strength

Introduction

Factors related to strength asymmetry have been studied for decades and related to performance and injury risk (Knapik, Bauman, Jones, Harris, & Vaughan, 1991; Newton, Gerber, Nimphius, Shim, Doan, Robertson, Pearson, Craig, Hakkinen & Kraemer, 2006; Lockie, Schultz, Jeffriess, & Callaghan, 2012; Nimphius, McGuigan, & Newton, 2010). Recent efforts to further evaluate performance on common tests have investigated the relationships of a variety of strength qualities (power, reactive strength, etc.) to outcomes of the tests. Peak force and strength asymmetry have been related to lesser performance in jumping and changes of direction (CODs) in previous study of athletic populations (Bailey, Sato, Alexander, Chiang, & Stone, 2013; Chiang, 2014; Lockie et al., 2012; Nimphius et al., 2010). Sprint performance has also been observed to vary according to the position of the stronger or preferred leg in the start stance of trained sprinters (Habibi, Shabani, Rahimi, Fatemi, Najafi, Analoei, & Hosseini, 2010; Vagenas & Hoshizaki, 1986). Ground-foot contact time (GFCT) has also been observed in athletic populations during sprinting and CODs (Green, Blake, & Caulfield, 2011; Mattes, Habermann, Schaffert, & Muhlbach, 2014). Because GFCT has only been evaluated in a few key steps of a COD (plant step and push-off step), it is unclear if GFCT of additional steps in the COD are related to performance in the COD. Several studies have evaluated performance of competitive sprinters in part based on GFCT (Coh, Tomazin, & Rausavljevic, 2007; Mattes et al. 2014). Observations of GFCTs in CODs may also be a useful tool for monitoring or assessing performance improvements over time. To date, no study to our knowledge has included evaluation of the summed total GFCT ($GFCT_{total}$) during a 10m sprint or

COD. Because GFCT limits the force production capacity during locomotion, observing $GFCT_{total}$ may be useful as an indirect evaluation of an athlete's force production capability. The purposes of this study were to evaluate the relationship of finish time and GFCT asymmetry in both 505 and 10m sprints using opposite direction cuts and opposite start stances to peak force asymmetry observed in the isometric mid-thigh pull (IMTP).

Methods

Subjects

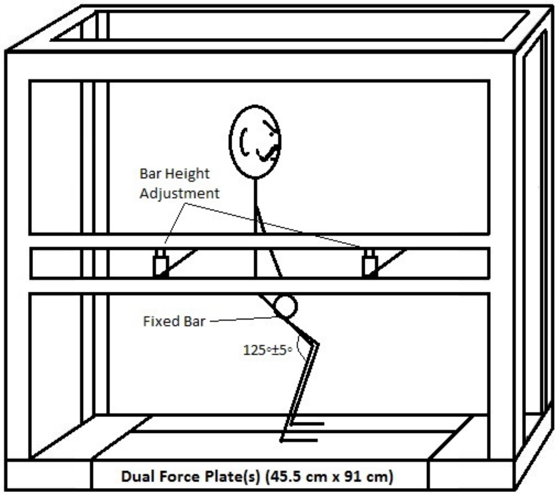
The methods for this study were approved by the East Tennessee State University Institutional Review Board (Appendix A). Male subjects from a NCAA Division-1 soccer team volunteered for the study (n = 17, age 18-22 years, height 178.3 ± 6.33, mass 76.79 ± 9.43). The athletes were new (6) or returning participants (11) in an athlete monitoring program.

Data Collection

Participants reported to the laboratory during a rest day after the completion of preseason soccer camp for participation in a standardized athlete monitoring program (Kraska, Ramsey, Haff, Fethke, Sands, Stone, & Stone, 2009). Height was recorded to the nearest 0.5 cm with a stadiometer (Detecto ProDoc, Detecto Scale Company, Webb City, MO, USA). Mass was recorded with a digital scale to the nearest 0.1 kg (Tanita BF-350, Arlington, Heights, IL, USA). Following seven-site skinfold body composition measurements and a standardized dynamic warmup, bar height was recorded at the beginning of the second pull position (knee angle of 125

± 5°). Previously recorded bar height information was used for returning athletes. Following a series of jumps, the participants conducted at least two maximal isometric mid-thigh pulls (IMTP) to assess maximal strength on a custom rack using dual force plates (RoughDeck® HP, Rice Lake Weighing Systems, Rice Lake, WI, 0.91m x 0.45m) sampling at 1,000Hz. Individualized bar height was attained (knees at 125 ± 5°) on the custom rack using hydraulic jacks to adjust bar height (Figure 3.1). The athletes' hands were held in place using weightlifting straps and secured with several layers of athletic tape. Warmup trials at 50% and 75% maximal effort were performed with about 1 minute in-between. Athletes were instructed to place light tension on the bar, stabilize for ≈2 seconds, then directed to pull as fast and hard as possible. Two maximal-effort trials were performed. If a countermovement occurred or a 250N difference existed between peak force measurements on the first and second effort, a third effort was performed. Data were collected and analyzed using custom software (LabVIEW, version 12.0, National Instruments, Austin, TX, USA), which collected vertical ground reaction forces at 90, 150, 200, 300, 400, 500, and 600 milliseconds (ms), along with peak ground reaction force. These times were chosen based on common GFCTs observed during pilot testing. A 2nd-order low pass Butterworth filter with a cutoff frequency of 10Hz was applied to smooth the data.

Figure 3.1. Isometric Mid-Thigh Pull Position.



Following the standard monitoring battery, athletes completed the field testing sequence on AstroTurf® surface (for equipment setup see Figure 3.2). This protocol began with 10m warmup runs of 50% and 75% effort beginning in a three-point sprint stance. About 30 seconds of rest was provided between warm-up efforts. Two 10m sprints with alternating right foot-forward (RFF), then left foot-forward (LFF) three-point sprint stances were performed. To maximize consistency of the times, no coaching was provided during testing beyond the initial instructions. A 10m OptoJump Next (Microgate, Bolzano, Italy) system was used to collect GFCT. Infrared timing gates (TC Timing System, Brower Timing Systems, Draper, UT) were used to collect the finish times. This system included an infrared start pod placed by the rear foot (Motion Start, Brower Timing Systems, Draper, UT), so the athletes' first foot movement started the clock for greater accuracy. Following the 10m sprints, the athletes conducted 50% and 75% warmup run-throughs of a standard 505 test (Draper & Lancaster, 1985), turning to the right, then left. About 30 seconds rest was provided between warm-ups. A total of four maximal-effort 505 tests were performed, alternating between right and left turns. Athletes rested at least 30 seconds between trials. The maximal-effort trials were video recorded from the side (perpendicular to running direction) at 240 frames per second (Casio Exilim EX-ZR1000, Casio Computer Co., Ltd. Tokyo, Japan).

Figure 3.2. Field Testing Equipment Setup.

Data Processing

Finish times for the 10m and 505 test, and GFCT data from OptoJump Next were recorded and logged in an Excel spreadsheet (Microsoft Excel for Mac 2011, Version 14.4.6, Microsoft, Redmond, WA). Video clips from the 505 test were analyzed using a digital media player (Microsoft Media Player, Microsoft, Redmond, WA) to count the number of frames the foot was in contact with the ground. Ground-foot contact time for a total of seven steps were analyzed from each 505 test: the three deceleration steps leading into the COD, the plant step, and the three acceleration steps out of the COD; these data were summed to produce $\text{GFCT}_{\text{total}}$. Ground-foot contact time for the deceleration steps was determined to begin when an athlete clearly depressed the turf with his shoe and ankle plantar flexion was observed; foot contact ended when the toe-off was clearly visible in the video (Figure 3.3).

Figure 3.3. Start (a) and End (b) of Foot Contact for 505 Deceleration Step.

a. b.

Onset of ground-foot contact time for the acceleration steps was determined to begin when turf depression was observed and ended when the toe clearly left the ground (Figure 3.4). The number of frames counted during foot contact was multiplied by 1/240 to yield the GFCT in seconds. Based on technique differences, some athletes maintained both feet in contact with the ground during the COD. If this occurred, the first acceleration step was determined to begin when the athlete was still crouched during the COD, the hand touching the line had left the ground, and the lead leg shank angle decreased relative to the ground, indicating further weight transfer to the lead leg and increased force production resulting in acceleration (ending step 3, beginning step 5) (Figure 3.5).

Figure 3.4. Start (a) and End (b) of Foot Contact for Acceleration Steps.

a.

b.

Figure 3.5. Balanced Stance Indicating End of 3rd Step (a) and Transfer of Weight Indicating Start of Step 5 (b) in Athletes Who Kept Both Feet on Ground During COD.


a. b.

Symmetry index was calculated between left and right sides using the symmetry index formula from Bell, Sanfilippo, Binkley, & Heiderscheit (2014). The formula yields a positive number for a right-side strength dominance, and a negative number for a left-side strength dominance:

$$SI = [(\text{right limb} - \text{left limb})/0.5(\text{right limb} + \text{left limb})]*100$$

This formula was modified to evaluate data based on strength dominance, wherever practical, using the following formula:

$$SI = [(\text{dominant limb} - \text{nondominant limb})/0.5(\text{dominant limb} + \text{nondominant limb})]*100$$

SI values were modified using absolute value to enable comparisons between SIs and times and forces. For instance, any comparisons between IMTP values and force or time show comparison between magnitude of asymmetry and force or time, and therefore do not reflect sidedness. This was done to prevent erroneous comparison of data on two different scales—for example, comparing finish time directly to SI would be comparing time to right or left-sidedness, not asymmetry.

Allometric scaling of IMTP data was performed using the following formula (Jaric, Mirkov, & Markovic, 2005):

$a = \text{Force}/\text{body mass}^{2/3}$

An alternative measure of relative strength was calculated by dividing peak force by body mass.

Statistical Analysis

Data were analyzed using Microsoft Excel and SPSS (Version 22, IBM, Inc. New York, NY). Coefficients of variation (CV) were acquired to examine the magnitude of variation in the data sets collected on each side for force variables, 10m and 505 times, and GFCTs. Intraclass Correlation Coefficients (ICC) were calculated for IMTP variables and 505 test variables. To assure trial-trial consistency, two-tailed paired-sample *t*-tests were performed to examine statistical differences between trials. Zero-order Pearson product-moment correlation coefficients were also performed to determine if relevant relationships existed between aforementioned variables; this analysis was performed according to strength dominance. Bilateral and unilateral peak force values were allometrically scaled (Table 3.2) and relative strength was calculated. Data were screened for normality using the Kolmogorov-Smirnov test. A two-way repeated-measures ANOVA (Right and left strength dominance X right and left turns) was performed to determine the effects of strength asymmetry on 505 test performance.

Results

IMTP Data

The results from IMTP testing are included on Tables 3.1-3.3. For reliability purposes, a series of paired-samples *t*-tests were performed, which did not reveal any statistically significant differences between left and right isometric strength variables within this sample (Appendix C, Table 3.7-3.8). ICCs ranged between 0.77-0.97. No significant correlations were observed between symmetry indices of (right-left) strength variables, 10m time, 10m $\text{GFCT}_{\text{total}}$, 505 time, and 505 $\text{GFCT}_{\text{total}}$ (Appendix C, Table 3.9). All 17 athletes declared that their best kicking foot was their right foot, however no apparent relationship was observed between peak force SI and potential leg preference factors attributed to kicking skill. Nine athletes in this sample were right-footed kickers that were right-side strength dominant (PF L<R), while eight were right-footed kickers who were left-side strength dominant (PF L>R). Magnitude of force production asymmetry varied considerably (within subjects), with mean range 21.21 ± 8.25% (Table 3.4).

Table 3.1. Mean IMTP Force Data (Unilateral Comparison)

Athlete	F90 L	F90 R	F150 L	F150 R	F200 L	F200 R	F300 L	F300 R	F400 L	F400 R	F500 L	F500 R	F600 L	F600 R	Peak Force L	Peak Force R
1	452.50	517.18	783.14	789.34	1317.74	1260.19	1581.13	1510.65	1520.93	1622.23	1569.30	1530.42	1666.55	1468.39	1815.66	1640.90
2	737.36	797.66	873.63	936.78	1145.08	1175.11	1336.60	1344.88	1757.15	1608.54	1934.89	1822.16	2011.90	1970.94	2454.88	2388.48
3	342.93	360.22	512.88	546.40	680.81	739.55	830.07	957.96	1197.75	1301.58	1257.76	1351.48	1341.15	1497.17	1847.18	1946.50
4	489.32	681.40	829.57	1002.00	1254.05	1441.86	1478.73	1667.01	1528.06	1775.81	1569.19	1871.28	1557.71	1914.76	1929.26	2526.22
5	538.27	583.85	650.68	684.74	880.90	886.61	1095.07	1060.52	1418.69	1363.82	1510.52	1468.86	1584.95	1577.73	2040.50	2186.15
6	738.45	619.81	1380.33	1256.91	1668.42	1607.13	1690.53	1714.89	1754.41	1702.71	1808.68	1766.64	1853.06	1835.89	1925.85	1922.59
7	319.32	285.89	519.24	486.76	693.73	629.26	787.78	699.34	1077.71	800.73	1216.98	925.43	1236.99	1009.52	1595.42	1226.29
8	438.92	386.72	935.07	755.57	1382.53	889.05	1664.14	1107.75	1515.02	1299.87	1603.71	1105.89	1631.61	1049.15	1848.54	1341.03
9	452.85	574.35	636.68	824.50	961.82	1058.25	1146.87	1170.60	1460.31	1374.38	1525.36	1465.40	1619.71	1475.75	1867.56	2082.16
10	706.26	685.55	1148.73	1105.26	1677.86	1749.16	1956.53	2115.46	1967.25	2382.87	2068.05	2492.98	2179.08	2506.58	2585.92	2872.89
11	671.42	750.06	802.41	858.55	1110.69	1205.48	1401.71	1539.42	1706.17	1911.71	1832.21	2017.24	1840.09	2003.47	2709.56	2983.99
12	347.61	349.48	597.70	495.16	940.01	685.25	1244.22	905.24	1457.19	1254.05	1513.64	1369.55	1658.76	1414.59	2035.11	1803.58
13	998.37	834.53	1152.06	998.65	1359.21	1220.02	1523.40	1428.73	1692.71	1676.58	1753.95	1697.19	1819.92	1714.76	1946.68	1830.25
14	503.46	481.54	624.48	647.85	803.55	932.48	999.13	1186.53	1178.82	1382.62	1264.81	1458.99	1349.49	1449.65	1604.73	1840.59
15	528.39	474.39	615.56	595.44	838.71	792.05	1088.54	1020.58	1369.10	1137.09	1397.84	1200.03	1375.57	1200.97	1609.30	1424.08
16	534.14	436.57	613.08	522.57	774.83	728.01	928.96	980.32	1358.23	1344.89	1445.81	1367.19	1583.00	1466.64	1880.95	1718.29
17	483.70	665.41	587.51	795.77	725.39	994.71	855.44	1162.41	907.22	1299.45	883.70	1300.67	941.37	1340.64	1550.05	1699.34

Table 3.2. Bilateral Allometrically Scaled IMTP Force Values

Athlete	Total PF (N)	Total PFa (N/kg)*
1	3456.56	211.73
2	4843.36	224.40
3	3793.68	192.59
4	4455.48	222.20
5	4226.65	243.95
6	3848.43	220.24
7	2821.71	180.41
8	3189.57	195.18
9	3949.71	223.74
10	5458.81	277.13
11	5693.56	306.33
12	3838.69	210.51
13	3776.93	198.49
14	3445.32	186.65
15	3033.38	162.10
16	3599.25	192.01
17	3249.40	185.09

Table 3.3. IMTP Symmetry Index Values at Key Timepoints

Athlete	SI90	SI150	SI200	SI300	SI400	SI500	SI600	SIPF
1	-13.34	-0.79	4.47	4.56	-6.45	2.51	12.64	10.11
2	-7.86	-6.98	-2.59	-0.62	8.83	6.00	2.06	2.74
3	-4.92	-6.33	-8.27	-14.30	-8.31	-7.18	-10.99	-5.24
4	-32.81	-18.83	-13.93	-11.97	-15.00	-17.56	-20.56	-26.80
5	-8.12	-5.10	-0.65	3.21	3.94	2.80	0.46	-6.89
6	17.47	9.36	3.74	-1.43	2.99	2.35	0.93	0.17
7	11.05	6.46	9.75	11.89	29.49	27.22	20.25	26.16
8	12.64	21.23	43.45	40.15	15.29	36.75	43.45	31.82
9	-23.66	-25.71	-9.55	-2.05	6.06	4.01	9.30	-10.87
10	2.98	3.86	-4.16	-7.81	-19.11	-18.63	-13.98	-10.51
11	-11.07	-6.76	-8.19	-9.36	-11.36	-9.61	-8.50	-9.64
12	-0.54	18.76	31.35	31.54	14.98	9.99	15.89	12.06
13	17.88	14.27	10.79	6.41	0.96	3.29	5.95	6.17
14	4.45	-3.67	-14.85	-17.15	-15.91	-14.26	-7.16	-13.69
15	10.77	3.32	5.72	6.44	18.51	15.23	13.55	12.21
16	20.10	15.94	6.23	-5.38	0.99	5.59	7.63	9.04
17	-31.63	-30.11	-31.32	-30.43	-35.55	-38.18	-34.99	-9.19

Note: a positive number indicates L > R, 0 = symmetrical, a negative number indicates R > L.

Table 3.4. Number of Athletes Exhibiting IMTP Asymmetry

Time	<-15%	-14.99 – -8%	-7.99 – 0 %	0 – 7.99%	8 – 14.99%	>15%
90 ms	3	3	2	3	3	3
150 ms	3	2	3	6	0	3
200 ms	2	2	4	3	5	1
300 ms	2	1	4	5	3	2
400 ms	3	2	5	1	2	4
500 ms	3	1	7	1	2	3
600 ms	3	3	5	1	3	2
Peak Force	2	4	3	2	5	1

Strength Asymmetry, 10m Time and 10m GFCT

Reliability analysis, performance times and GFCT times for the 10m sprints are located in Appendix C, Tables 3.10-3.11 and Figure 3.13. ICCs for 10m time and $GFCT_{total}$ were 0.96 and 0.78, respectively. Demonstrating that the performances were consistent, paired-samples *t*-tests found no significant differences between RFF and LFF finish times (two-tailed, $t = -0.910$, $p = 0.376$, Cohen's $d = 0.09$) or RFF and LFF $GFCT_{total}$ (two-tailed, $t = -0.411$, $p = 0.687$, $d = 0.09$). During pre-data analysis screening, two athletes were outside the normal distribution, however a normal distribution was found for 10m $GFCT_{total}$ (see Appendix C, Figure 3.12). Comparisons of force values with 10m time and GFCT were reported with and without these two data sets (GFCT "outliers") (see Figures 3.6 and 3.7). When data were re-organized according to strength dominance, a large correlation was found between SI of force at 150ms and 10m SI ($r = 0.55$, $p < 0.021$) (Hopkins, 2002). This indicated a relationship between strength dominance at 150ms and performance differences between stances. Other correlations performed on symmetry indices were ≤0.44 and did not reach significance. Relative and allometrically scaled peak force did not correlate well with 10m performance in this sample (*r* = -0.33 and -0.40, respectively, $p > 0.05$).

Figure 3.6. 10m Time and Mean GFCT$_{total}$.

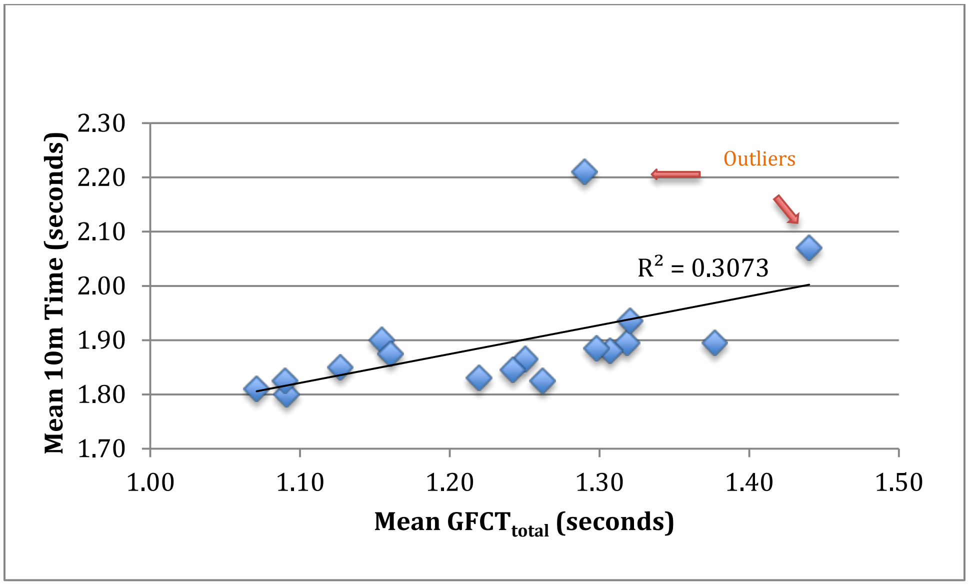
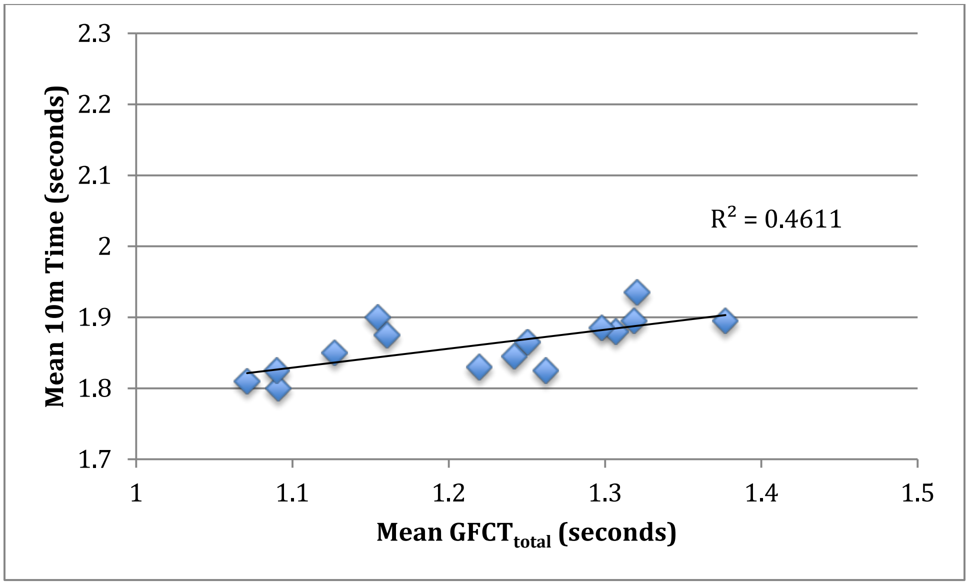


Figure 3.7. 10m Time and $GFCT_{total}$ with Outliers Removed



Strength Asymmetry, 505 Time and GFCT

No significant differences were found in 505 time or $GFCT_{total}$ between first and second trials (same side) using a paired samples *t*-test, indicating consistency of both trials (two-tailed paired samples *t*-tests; left plant trials—$t = 1.062$, $p = 0.304$, $d = 0.24$; right plant trials—$t = -0.678$, $p = 0.507$, $d = 0.097$), as were $GFCT_{totals}$ between first and second trials (two-tailed, paired samples *t*-tests; left plant trials—$t = 1.423$, $p = 0.174$, $d = 0.32$; right plant trials—$t = -0.909$, $p = 0.377$, $d = 0.22$). ICCs for 505 time were 0.69 (left) and 0.84 (right), and ICCs for $GFCT_{total}$ were 0.65 (left) and 0.58 (right). CVs for 505 time were <4.5%, while CVs for 505 $GFCT_{total}$ were 0-71.26% (Appendix C, Tables 3.13-3.15). Performance and GFCT times for the 505 test are located in Table 3.5 and Appendix C, Tables 3.16-3.17.

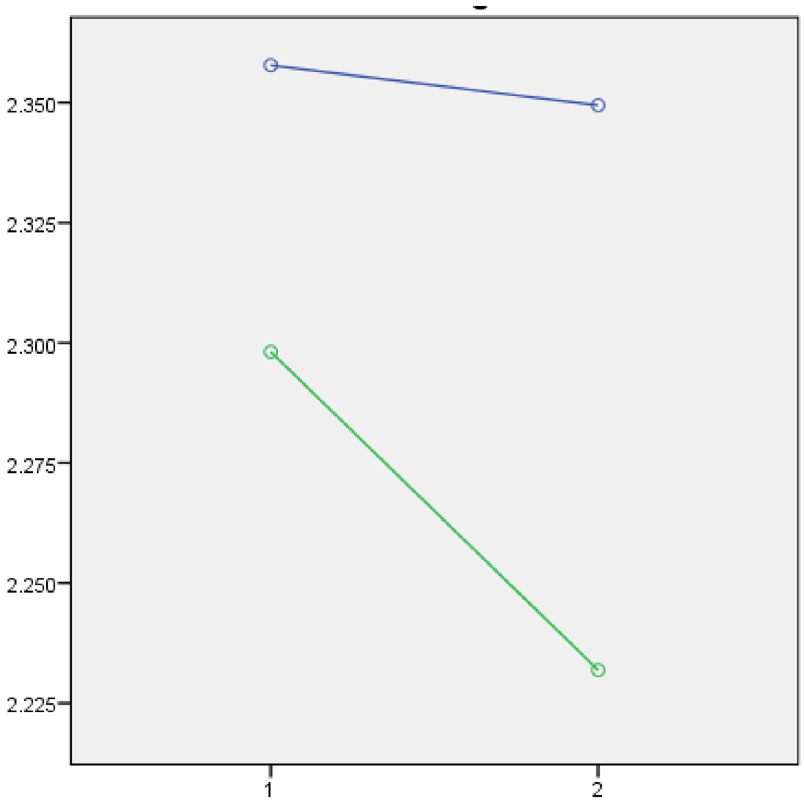
Table 3.5. 505 Test Time and 10m Runup Time (seconds).

Athlete	10m runupL1	505L1	10m runupL2	505L2	10m runupR1	505R1	10m runupR2	505R2	mean L505	meanR505	Avg time
1	1.78	2.46	1.81	2.38	1.82	2.28	1.84	2.31	2.42	2.295	2.36
2	1.95	2.46	1.89	2.32	1.98	2.4	1.95	2.45	2.39	2.425	2.41
3	1.86	2.49	1.88	2.41	1.86	2.37	1.84	2.38	2.45	2.375	2.41
4	1.86	2.34	1.88	2.31	1.86	2.23	1.9	2.22	2.325	2.225	2.28
5	1.78	2.24	1.8	2.32	1.78	2.19	1.81	2.17	2.28	2.18	2.23
6	1.84	2.33	1.86	2.33	1.83	2.27	1.86	2.35	2.33	2.31	2.32
7	1.84	2.23	1.97	2.31	1.88	2.26	1.89	2.33	2.27	2.295	2.28
8	2.0	2.33	2.04	2.3	2.02	2.32	2.05	2.32	2.315	2.32	2.32
9	2.23	2.33	1.94	2.34	2.26	2.33	2.2	2.29	2.335	2.31	2.32
10	1.88	2.28	1.86	2.26	1.82	2.17	1.83	2.18	2.27	2.175	2.22
11	1.84	2.19	1.8	2.17	1.79	2.21	1.78	2.16	2.18	2.185	2.18
12	1.93	2.41	1.91	2.28	1.88	2.17	1.83	2.28	2.345	2.225	2.29
13	2.1	2.45	2.06	2.42	2.05	2.42	2.01	2.52	2.435	2.47	2.45
14	2.15	2.3	2.2	2.37	2.14	2.3	2.17	2.13	2.335	2.215	2.28
15	1.92	2.28	1.88	2.38	1.93	2.38	1.9	2.48	2.33	2.43	2.38
16	1.92	2.42	1.94	2.35	1.89	2.38	1.93	2.37	2.385	2.375	2.38
17	1.81	2.22	1.83	2.2	1.78	2.22	1.83	2.16	2.21	2.19	2.20

Note: mean 505 time = 2.31 ± 0.09s; mean 10m run-up = 1.92 ± 0.12s

A paired-samples *t*-test on the mean left and right 505 test trials yielded significant differences between finish times ($t = 2.184$, $p < 0.044$), with the left-foot plant being slower (left plant 2.33 ± 0.07s vs. right plant 2.29 ± 0.10s). Effect size was moderate ($d = 0.42$) (Becker, 1999; Hopkins, 2002). No statistical differences were found between mean left and right 505 $\text{GFCT}_{\text{total}}$. Levene's test indicated greater variation in the right plant 505 time for right-dominant athletes ($F(1,15) = 4.567$, $p < 0.049$). A two-way, repeated measures ANOVA (right and left strength dominance X left and right turns) yielded a significant difference between times on right and left 505 trials, with no interaction effect between strength dominance and 505 time or 505 GFCT ($F(4,12) = 2.674$, $p = 0.084$, partial $\eta^2 = 0.47$). Both groups (left and right-side strength dominant) performed better on the right leg plant (Figure 3.8).

Figure 3.8. Repeated-Measures ANOVA Results for 505 Time



Note: Blue = left strength dominant, green = right strength dominant, 1 = left plant, 2 = right plant turn

Discussion

Because all 17 athletes reported their right foot being the dominant kicking foot, we expected to observe in this sample some asymmetry trends toward greater strength in the left leg based on the persistent training demands of consistent posting on the left leg during right-footed kicks. No trends to support this expectation were demonstrated by this sample (Tables 3.3-3.4). Within-athlete isometric strength asymmetries in the sampling timeframes observed in this study were inconsistent, with individual athletes' ranges of SI observed within the time points selected varying between 4.60-35.01%. No significant correlation was observed between PF and SI range (r = -0.42, p = 0.091), indicating stronger athletes did not possess less asymmetry. Allometrically scaled peak force also correlated poorly with absolute SI_{PF} (r = -0.21, p = 0.414), indicating very little relationship between relative strength and asymmetry in this sample. This finding differs from previous observations from this laboratory based on data from recreational (Bazyler, Bailey, Chiang, Sato, & Stone, 2014) and athletic (Bailey, 2014) samples. Individual trends in asymmetry were observed (i.e. the strongest athlete in this sample demonstrated the lowest range in SI (4.6%) throughout the IMTP).

Large negative correlations were found between measures of relative strength and 505 time (PFa r = -0.52; $p < 0.033$; PF/BdM r = -0.60, $p < 0.01$). These points support the importance of relative strength on acceleration and deceleration in COD performance—based on the ability to produce more relative force, a stronger athlete should perform better on a COD task than a weaker one with a similar build. However, the impact of relative strength on COD performance appears to be independent of isometric strength asymmetry, as the impact of relative strength differences between limbs may disappear over a certain distance because the athlete travels on both legs.

The use of $GFCT_{total}$ appears to be of use in evaluating 10m sprint performance, particularly within subjects. Differences observed between start stances in this study indicated a direct relationship to asymmetry. With regard to 10m performance, $GFCT_{total}$ correlated strongly with performance time (r = 0.56, $p <$ 0.019). After removing both GFCT outliers, correlation improved (r = –0.68, $p <$

0.005). However, $GFCT_{total}$ does not appear to be a useful tool to evaluate 180° COD performance possibly because of individual differences in COD technique.

Interestingly, our COD results supported the findings of Castillo-Rodriguez, Fernandez-Garcia, Chinchilla-Minguet, & Carnero (2012), who found superior COD performances in turns to the left among college students who were amateur soccer players. The athletes in Castillo-Rodriguez et al. (2012) performed better in the right unilateral countermovement jump, indicating that a potential mechanism for COD performance asymmetry observed in this study may be reactive strength asymmetry. Further research may be valuable to evaluate motor aspects of soccer athletes—this indicates a potential common technique or training effect that could exist in soccer players during CODs. Five athletes demonstrated inconsistency regarding 505 finish times between trials, as defined by a CV >3% (Hopkins, 2004); however all athletes demonstrated CVs ≤5.43% between trials in this study. Finish times were likely affected by technique differences between 505 trials, with CVs of GFCTs up to 52.5%, as shown in Appendix C, Tables 3.14-3.15. Future study may be useful to assess ranges of acceptable variability for finish time and GFCT between trials for the 505 agility test in collegiate athletes and other populations.

Practical Application

In this study it was demonstrated that isometric strength asymmetry, as diagnosed in a well-controlled laboratory setting, has little relationship to performance in field tests such as the 10m sprint and 505 agility tests. Other factors (complex biomechanical patterns, joint stiffness, anthropometric measurements, etc.) are likely to be important determinants of performance on these tests. It has been demonstrated in similar populations that collegiate athletes and college-aged males who possess lower peak force asymmetry (<8%) may perform better on dynamic tasks such as jumping. Because performance differences in the right and left stance 10m sprint and right and left plant 505 tests were not explained by isometric strength asymmetry or strength in this sample, other factors such as technique and muscle stiffness, etc. should be evaluated to establish a common source for performance differences.

Recent criticisms of common clinical movement and flexibility/mobility asymmetry tests such as the Functional Movement Screen™ have included proposals that the velocity of movement may be a critical factor of accurate assessment of asymmetry. A slower movement in a clinical environment may not transfer to sport performance, as velocity of movement may be highly dependent on motor skills required for the movement—not necessarily strength asymmetry (see Frost, Beach, Callaghan, & McGill, 2013). Lockie, Schultz, Jordan, Callaghan, Jeffriess, & Luczo (2015) supported this criticism in general, finding many clinical screening tests did not predict performance deficiencies in CODs.

Because peak voluntary isometric force usually requires ≈3-4 s of continuous effort to attain, one may argue that IMTP PF is not a relevant factor to observe asymmetry based on the observation that sufficient time is not available in vivo during athletic events to demonstrate asymmetry that may be found by a PF IMTP test. This point is supported by at least one study that found low or low-moderate correlations between PFa and jumping performance in recreational subjects (Young, James, & Montgomery, 1999). Based on the results of the present study, any prediction of performance decrements in the 10m sprint or 505 test based on isometric strength asymmetry testing in this population would be inappropriate. It is likely that technique is of primary importance to field test performance. Future research should be focused on: the relationship of isometric strength testing to starting strength, the relationship of isometric strength asymmetry to dynamic performance testing in other athletic populations, the relationship of dynamic strength and reactive strength asymmetry to dynamic performance testing methods, and the relationship of all these factors within athletes of different training ages. Training studies are also required to determine if reducing asymmetry improves performance on athletic tasks.

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CHAPTER 4

LONG-TERM STABILITY OF ISOMETRIC MAXIMAL STRENGTH ASYMMETRY IN DIVISION-1 COLLEGIATE ATHLETES

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Abstract

Lower body strength asymmetry has been linked to lesser performance and increased injury risk in athletes. To date, no studies have specifically observed stability of lower extremity strength asymmetry over a long-term period (≥1 year). Archived data collected in three testing sessions over a 1-year period were evaluated to determine the stability of isometric peak force asymmetry between left and right lower limbs. Subjects were 53 Division-1 NCAA athletes (25 male, 28 female) who participated in field/court sports. A large variation in asymmetry was observed (mean range 16 ± 10%) over a one-year period. No significant difference in strength asymmetry was observed between testing sessions, despite a statistically significant increase in strength following the initial test session. Based on the findings of this study, strength asymmetry appears to be independent of gains in strength.

Abstract word count: *134*

Key Words:

Bilateral strength asymmetry, isometric maximal strength

Introduction

Lower body strength asymmetry has been previously linked to lesser performance and increased injury risk in athletic populations (Bailey, 2014; Bell, Sanfilippo, Binkley, & Heiderscheit, 2014; Knapik, Bauman, Jones, Harris, & Vaughan, 1991). Studies investigating asymmetry have typically involved acute testing sessions, with the test results applied to indexes comparing the strength of one limb to the other. Very little research has been performed to observe the stability (carryover or reliability) of asymmetry over time. Stability of strength asymmetry using closed chain testing methods over a long-term period has yet to be studied in any population. Before it is known how much asymmetry can be reduced, a basic profile of asymmetry should be acquired within multiple populations.

Studies observing asymmetry have included both open and closed kinetic chain methods (Fousekis, Tsepis, & Vagenas, 2010; Knapik et al., 1991; Newton, Gerber, Nimphius, Shim, Doan, Robertson, Pearson, Craig, Hakkinen & Kraemer, 2006). Open chain methods, such as isokinetic dynamometry, typically have a limb placed in a machine that evaluates the forces produced by a specific muscle group in isolation at a specific contraction velocity or isometric contraction (Greenberger & Paterno, 1995; Ramos & Knapik, 1978; Read & Bellamy, 1990). Closed chain methods are generally performed in tasks using multiple muscle groups with the support limb on the ground, and include movements such as jumping or isometric strength testing methods performed in an athletic position (Greenberger & Paterno, 1995; Nuzzo, McBride, Cormie, & McCaulley, 2008). Closed chain methods, such as those used in the present study, may have a distinct advantage, as motor units are engaged in more realistic ways to provide theoretically similar muscle activation to situations in vivo.

One study associated lesser asymmetry detected using an isokinetic dynamometer in an acute testing session to a longer training age in professional soccer players (Fousekis et al., 2010). Authors proposed from their results that players who enjoyed longer careers may experience lesser injury rates based on improved symmetry. Interestingly, asymmetry did not hold constant through speeds (angular velocities) used in isokinetic testing. The sample changed sidedness across the spectrum of speeds tested. Amato, Afriat, Croisier, Legros, Desnuelle, & Bernard (2003) also used isokinetic dynamometry to assess injury risk in soccer players and gymnasts at two testing points one year apart. For the purposes of comparison, the authors of the present study calculated SI from the mean values reported by Amato et al. (2003). In context of previously proposed meaningful thresholds of ≈15% (Croisier, 2004), highly variable results were observed over time for various angular velocities over the course of a year (range of 0.38 – 36.5% asymmetry from year 1 to year 2 for various angular velocities tested). Newton et al. (2006) compared asymmetry using back squats, jumps and isokinetic dynamometry. Mean sidedness did not change across the sample, however the magnitude of asymmetry was different between the closed chain tests and open chain test. A number of training studies have employed isometric mid-thigh pull (IMTP) testing periodically to assess the strength gains of collegiate athletes over brief training periods (<6 months) as part of the long-term athlete monitoring program (Hornsby, 2013; Painter, 2012). Additionally, several studies in the same setting have observed asymmetry using the IMTP in athletes using one-time data collection (Bailey 2014, Chiang, 2014, Owens 2011). Only one training study from this athlete monitoring setting observed strength asymmetry in a recreationally trained male population. Bazyler, Bailey, Chiang, Sato, & Stone, (2014) found a ≈2% decrease of isometric squat peak force asymmetry (at 120° knee angle) among weaker subjects (mean allometrically-scaled isometric PF 172.85 ± 19.86 $N/kg^{0.67}$ pre-training) compared to stronger subjects (mean allometrically-scaled isometric PF 227.96 ± 17.45 $N/kg^{0.67}$ pre-training) over the course of a 7-week strength training program. To date, no studies observing long-term strength asymmetry using IMTP have been performed on athletic populations. The purpose of this study was to observe isometric peak force asymmetry over a long-term period (1 year) in collegiate athletes.

Methods

Subjects

Subjects were male (25) and female (28) Division-1 NCAA athletes (18-22 years old, n = 53) who participated in a long-term athlete monitoring program (see Kraska, Ramsey, Haff, Fethke, Sands, Stone, & Stone, 2009). Subjects competed in men's soccer (n = 11), women's soccer (n = 11), men's tennis (n = 3), women's tennis (n = 6), men's baseball (n = 11), and women's volleyball (n = 11). The methods for this retrospective study were approved by the East Tennessee State University Institutional Review Board (Appendix B).

Archived isometric mid-thigh pull test results were considered from athletes who participated in at least three testing sessions over the course of a year as part of an athlete monitoring program. Based on differences in team sporting seasons and testing schedules, timeframes of data collection did not fit the same schedule for all athletes. The first and third data sets selected for this study were collected 52 ± 2 weeks apart, with the second data sets selected from testing sessions at least 3 months from the first or third sessions. Data sets for athletes competing in the same sport were chosen from the same timeframe when possible.

Data Collection

Subjects reported to the laboratory in the early morning for testing. Height was recorded to the nearest 0.5 cm with a stadiometer (Detecto ProDoc, Detecto Scale Company, Webb City, MO, USA). Mass was recorded with a digital scale to the nearest 0.1 kg (Tanita BF-350, Arlington, Heights, IL, USA). Following body composition measurements and a standardized dynamic warmup, bar height was recorded at the beginning of the second pull position (knee angle of 125 ± 5°). Previously recorded bar height information was used for returning athletes. Following a series of jumps, the participants conducted maximal IMPT to assess maximal strength on a custom rack using dual force plates (RoughDeck® HP, Rice Lake Weighing Systems, Rice Lake, WI, 0.91m x 0.45 m) sampling at 1,000 Hz. Individualized bar height was attained (knees at 125 ± 5°) on the custom rack using hydraulic jacks to adjust bar height. The athletes' hands were held in place using weightlifting straps and secured with several layers of athletic tape. Warmup trials at 50% and 75% maximal effort were performed with about 1.5-2 minutes in-between. Athletes were instructed to place light tension on the bar, maintain it for ≈2 seconds, then directed to pull as fast and hard as possible. Two maximal-effort trials were performed. If a countermovement occurred or a >250N difference existed between peak force measurements on the first and second effort, a third effort was performed. Data were collected and analyzed using custom software (LabVIEW, version 12.0, National Instruments, Austin, TX, USA), which evaluated vertical peak ground reaction forces. A 2nd-order low pass Butterworth filter with a cutoff frequency of 10Hz was applied to smooth the data.

Data Processing

Symmetry index (SI) was calculated between left and right sides using the same formula as Bell et al. (2014). This formula yields a positive number for a right side higher value, and a negative number for a left side higher value:

SI = [(right limb – left limb)/0.5*(right limb +left limb)]*100

Statistical Analysis

Data were analyzed using Excel (Microsoft, Redmond, WA) and SPSS (Version 22, IBM, Inc. New York, NY). Kolmogorov-Smirov tests for normality were performed on peak force and absolute SI. Two data sets outside the normal curve were found for absolute peak force in the first testing session, however the data sets were within normal ranges for the following testing sessions. Several athletes were outside the normal curve at one period over a year, while only one athlete demonstrated abnormal asymmetry on all three testing sessions. As a result, no data were excluded in the analysis based on the variance of the data and the indication that SI trends of a few individuals were somewhat consistent (see Appendix C, Table

4.4). Coefficients of variation (CV) were calculated using (standard deviation/mean)*100 (Vincent & Weir, 2012). Range of asymmetry was obtained by acquiring the high and low scores of the three SI values for each athlete; then low score was subtracted from high score to yield the range for each athlete. Average and standard deviation was calculated for range scores. Absolute SI was acquired using the "ABS" function in Excel, so that magnitude of asymmetry could be compared to absolute peak force. A two-tailed Pearson correlation was performed between absolute peak force and SI across all data points. Two repeated-measures ANOVAs were performed to evaluate the changes in absolute SI and absolute peak force over these three time points. Following this analysis, the athletes' data were sorted by strength values from session 1, and data from the strongest (n = 17) and weakest (n = 17) thirds of the sample were compared. Two repeated measures ANOVAs were applied to these absolute force and absolute SI values, respectively, to determine any differences based on strength.

Results

Intra-session CV for absolute peak force values from trials 1 and 2 averaged 4.12 ± 1.57% (see Appendix C, Table 4.3 for individual athlete CVs), indicating very small variation between trials. Interclass correlation coefficient for absolute SI was 0.52. Interclass correlation coefficients of peak force values were 0.84 (left) and 0.89 (right). Sample means of PF and absolute SI from each testing session are presented in Figures 4.1 and 4.2.

Figure 4.1. Mean Peak Force per Testing Session

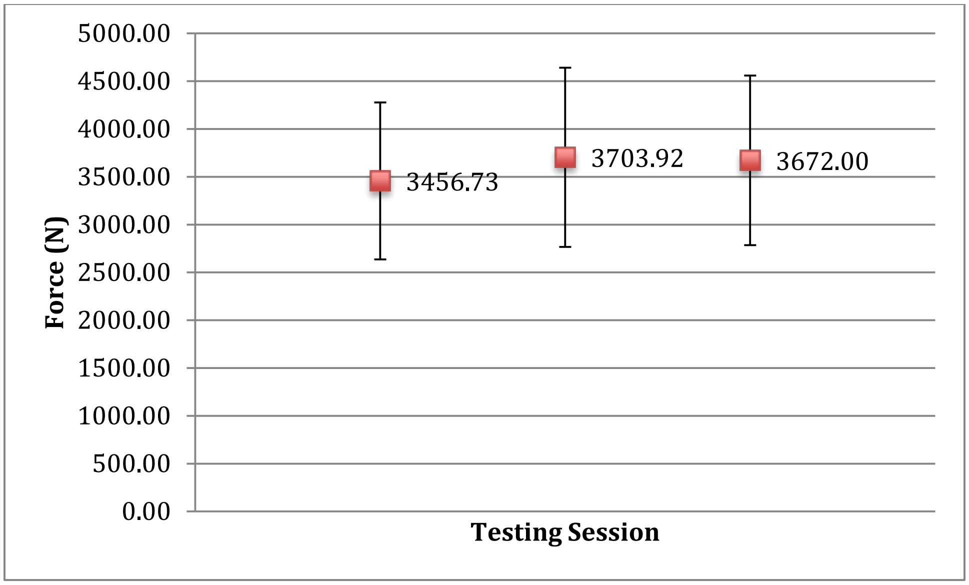
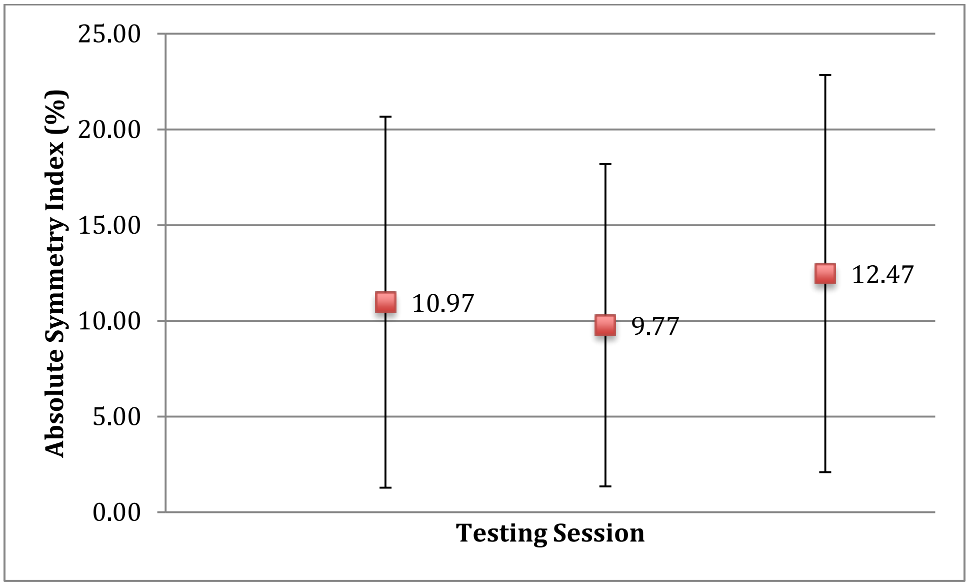


Figure 4.2. Mean Absolute Symmetry Index per Testing Session



The mean range of absolute isometric peak force asymmetry demonstrated by this sample of athletes over a year was 16 ± 10.7% (Appendix C, Table 4.4). A weak (Hopkins, 2004), non-significant negative correlation was observed among data from all testing sessions between absolute peak force and absolute SI ($r = -0.30$,

$p > 0.707$). A significant improvement in absolute peak force was found between the first session (mean 3456.7 ± 820.5 N) and the second and third sessions (mean 3703.9 ± 936.7 N and 3672 ± 886.2 N, respectively) ($F(1,52) = 10.01$, $p < 0.003$). No significant difference in absolute SI was found between the sessions ($F(1,52) = 0.859$, $p = 0.385$). Sample details by testing session are reported in Tables 4.1 and 4.2, with and information regarding SI range per athlete in Appendix C (Table 4.4).

Table 4.1. Mean Peak Force (N), 95% Confidence Intervals, and CV by Session

		95% Confidence Intervals		
Testing Session	Mean ± SD	Lower Bound	Upper Bound	CV
1	3456.73 ± 820.46	3230.58	3682.88	23.73%
2	3703.92 ± 936.68	3445.74	3962.10	25.29%
3	3672.0 ± 886.20	3427.73	3916.26	24.13%

Table 4.2. Descriptives and 95% Confidence Intervals for Absolute Symmetry Index

		95% Confidence Intervals		
Testing Session	Mean ± SD (%)	Lower Bound	Upper Bound	CV
1	10.97 ± 9.69	8.30	13.65	88.33%
2	9.77 ± 8.50	7.43	12.12	87.02%
3	12.47 ± 10.38	9.61	15.33	83.20%

The two-way repeated-measures ANOVAs applied to the data from the strongest and weakest groups revealed no significant differences between groups in terms of strength gain or SI changes. No significant differences were found between groups for strength gains over time ($F(2,32) = 1.549$, $p = 0.220$). Similarly, no significant differences were found between groups in terms of SI ($F(2,32) = 0.750$, $p = 0.476$) (see Tables 4.1 & 4.2 for means and standard deviations).

Discussion

The purpose of this study was to evaluate the stability of IMTP asymmetry over a long-term period (1 year). Despite a significant improvement in strength over this time period, athletes did not demonstrate significant changes in the magnitude of strength asymmetry. Based on the low correlation between magnitude of asymmetry and strength, the results of this study demonstrate that in this sample of athletes the magnitude of asymmetry between limbs was not related to strength. Comparison of SI between the strongest third to the weakest third of this sample further demonstrated that asymmetry was unrelated to strength. Thus it is possible that gaining or losing strength may not affect the level of asymmetry.

Of the two formulas typically used for asymmetry evaluation, mean absolute peak force asymmetry range observed over the course of a year in this heterogeneous sample of collegiate athletes would be 16 ± 10.7% (Bell et al., 2014) or 8 ± 5.4% (Sato & Heise, 2012). Part of the lack of association between strength and magnitude of asymmetry is rooted in the fact that considerable variation (with respect to the previously proposed ≈15% threshold) between legs in isometric absolute peak force production among athletes was observed over the course of the one-year period in this study. This is further demonstrated by an interclass correlation coefficient of 0.52 for absolute SI in the present study, indicating substantial rank-order differences over time in the magnitude of asymmetry. Such instability of a variable makes drawing comparisons between asymmetry and other variables difficult. Our results indicate that it may be common for strength asymmetry to vary substantially over the course of a year. Independent observation of individual data sets indicated individual trends in asymmetry stability (see Appendix C, Table 4.4).

Our results contradict the findings of Bazyler et al. (2014), who observed statistically significant ($p < 0.05$) ≈2% reductions in asymmetry (isometric squat at 120° knee angle) of weaker recreationally trained males as a result of bilateral training over the course of a 7-week program. It may be possible that short-term fluctuations occur based on a number of factors (sport-specific muscle architecture changes, cumulative fatigue, etc.). As a result, regular testing or monitoring over a long-term period may be required to accurately assess asymmetry and establish reliable trends for each athlete. Population-specific differences may also exist; sufficient evidence is required to extrapolate trends observed in one population to another.

Of note, exercise selection for the strength training programs these teams conducted varied throughout the year and generally included a combination of bilateral (squatting, weightlifting derivatives, etc.) and unilateral exercises (step-ups, etc.). Specific corrective exercise programming was not employed to reduce strength asymmetry.

Unfortunately the sample size was not sufficient to analyze trends according to each individual sport. Injury status was not specifically observed, however athletes did not participate in the long-term monitoring program if suffering from a current injury—the availability of data in the archive for isometric mid-thigh pull indicates a lack of current injury status.

Future research should evaluate the role of dynamic strength asymmetry over long-term periods, and attempt to relate the results of the studies to sport performances or performance in sport-specific tests. Studies observing asymmetry in larger samples of athletes within individual sports may allow sport scientists to establish norms for ranges of asymmetry and attempt to evaluate injury risk and performance decrements on sport-specific skills accordingly.

Practical Application

The results of this study suggest that maximal isometric force production, as diagnosed in a well-controlled laboratory setting, is not related to the magnitude of strength asymmetry in a large heterogeneous sample of Division-1 collegiate athletes. Furthermore we observed considerable variation in asymmetry over the course of a training year that was apparently unrelated to improvements in strength. Without further research to establish a clear relationship between asymmetry and strength, practitioners should be cautious and conservative interpreting the results of acute tests observing asymmetry—no pattern of asymmetry reduction was seen over long-term typical strength and sport training in these athletes.

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CHAPTER 5

SUMMARY

Despite several decades of research dedicated to the study of strength asymmetry, much is still unknown about the effects of strength asymmetry on performance during locomotion. Much of the complication in studying this topic may be a result of the observation that strength asymmetry appears to be relatively plastic quality in most athletes, while in others it may be somewhat stable. Without relative stability or expectations of trends in asymmetry for a particular population or body type, predictability of asymmetry-related training adaptations may be limited.

Based on the findings of the present investigations, peak force asymmetry was minimally related to performance asymmetry on the 505 agility test and 10m sprint with right leg forward and left leg forward stances. Interestingly, collegiate soccer players performed better on a 180° cut to the left (right leg plant) than they did on a cut to the right (left leg plant). This supported the results of Castillo-Rodriguez et al., 2012), who also observed better performance times on cuts to the left in a group of college PE majors who were also recreational soccer players. Better performances on right-legged jumps may have explained better results on CODs including left turns (Castillo-Rodriguez et al., 2012). No explanation for the observations made in the present comparison between peak force asymmetry and COD asymmetry is yet available, however the differences may have motor-learning origins or be related to dynamic strength, not isometric strength.

The average range of long-term asymmetry was found to be 16% (or 8% depending on the formula used), similar to the percentage of asymmetry found in previous study in athletic populations using multiple methods. If this value constitutes either normal measurement error or typical variability, measurement of asymmetry may present considerable challenges for the practitioner and sport scientist alike. Reliability of asymmetry may indeed be a construct that is difficult to define or attain.

As a result of these findings, future research should investigate the individual relationship between technical factors of short sprint and 505 performance and their impact on GFCT. Measurement of ground reaction forces during multiple steps is needed to determine the relevance of GFCTs in the context of overall performance; therefore the use of laboratory instrumentation such as in-floor force plates are required to provide answers to this question. Further use of 3-D biomechanical analysis is also necessary to evaluate joint angles and the relationship of joint stiffness to COD performance. It is the opinion of the authors that measuring GFCT is a useful tool for athlete monitoring in most sports (sprinting, court and field sports, push sports, etc.), therefore future studies should be performed that relate GFCT measurements to training techniques and fatigue accumulation over time as demonstrated in short sprints. Future study should also be performed on body lean and leg placement in COD movements to determine the range of most mechanically efficient positions that enable optimal performance. Another potential tool for the monitoring of fatigue may be establishing a normal range of GFCT for a specific athlete in a common sport-specific drill. Additionally, further study is required to elucidate the stability of dynamic strength asymmetry, particularly within a timeframe that is relevant to GFCT during athletic locomotion (≈150-250ms). As of this point, the reasons for the wide range of strength asymmetry variation in most athletes over the one-year period in this study are not yet known. Investigation into individual trends are necessary, as groups of relatively strength stable and strength unstable athletes may be compared by observing muscle pennation angles in an attempt to account for some of the strength asymmetry variation over time. Finally study of the variation of force asymmetry over a long-term period during dynamic movements (such as jumping) may be of use in defining the normal ranges of the stability (or instability) of asymmetry.

The impact of accurate assessment of athlete movement asymmetry may be considerable for the sport coach, in that injury risk and detailed performance profiling may eventually be available with the work of a sport science team. This information should help guide training methods and reduce the incidence of injury through the use of evidence-based programming and agile scientific investigation.

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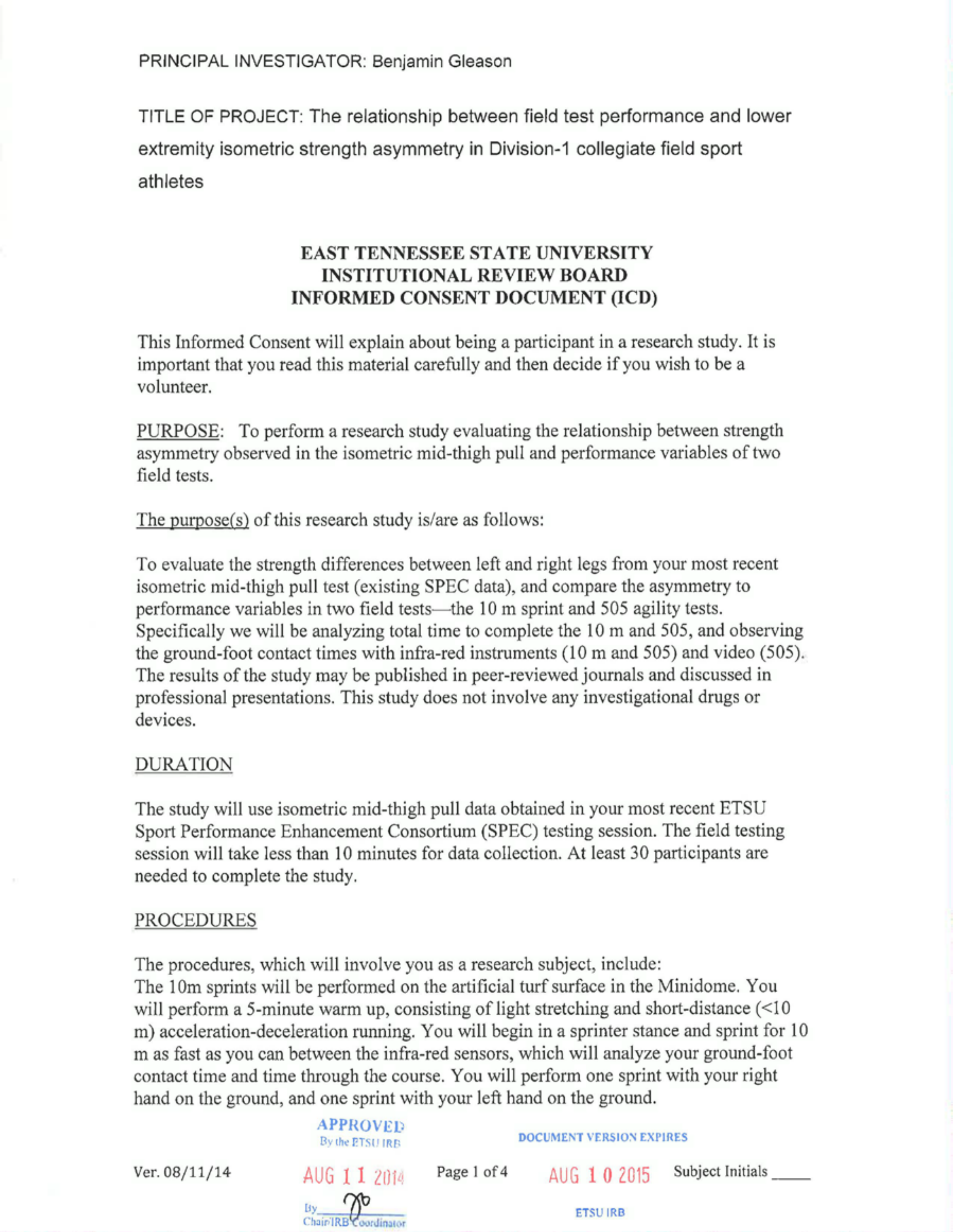
APPENDICES

Appendix A

ETSU IRB Approval/Informed Consent Document



PRINCIPAL INVESTIGATOR: Benjamin Gleason

TITLE OF PROJECT: The relationship between field test performance and lower extremity isometric strength asymmetry in Division-1 collegiate field sport athletes

EAST TENNESSEE STATE UNIVERSITY
INSTITUTIONAL REVIEW BOARD
INFORMED CONSENT DOCUMENT (ICD)

This Informed Consent will explain about being a participant in a research study. It is important that you read this material carefully and then decide if you wish to be a volunteer.

PURPOSE: To perform a research study evaluating the relationship between strength asymmetry observed in the isometric mid-thigh pull and performance variables of two field tests.

The purpose(s) of this research study is/are as follows:

To evaluate the strength differences between left and right legs from your most recent isometric mid-thigh pull test (existing SPEC data), and compare the asymmetry to performance variables in two field tests—the 10 m sprint and 505 agility tests. Specifically we will be analyzing total time to complete the 10 m and 505, and observing the ground-foot contact times with infra-red instruments (10 m and 505) and video (505). The results of the study may be published in peer-reviewed journals and discussed in professional presentations. This study does not involve any investigational drugs or devices.

DURATION

The study will use isometric mid-thigh pull data obtained in your most recent ETSU Sport Performance Enhancement Consortium (SPEC) testing session. The field testing session will take less than 10 minutes for data collection. At least 30 participants are needed to complete the study.

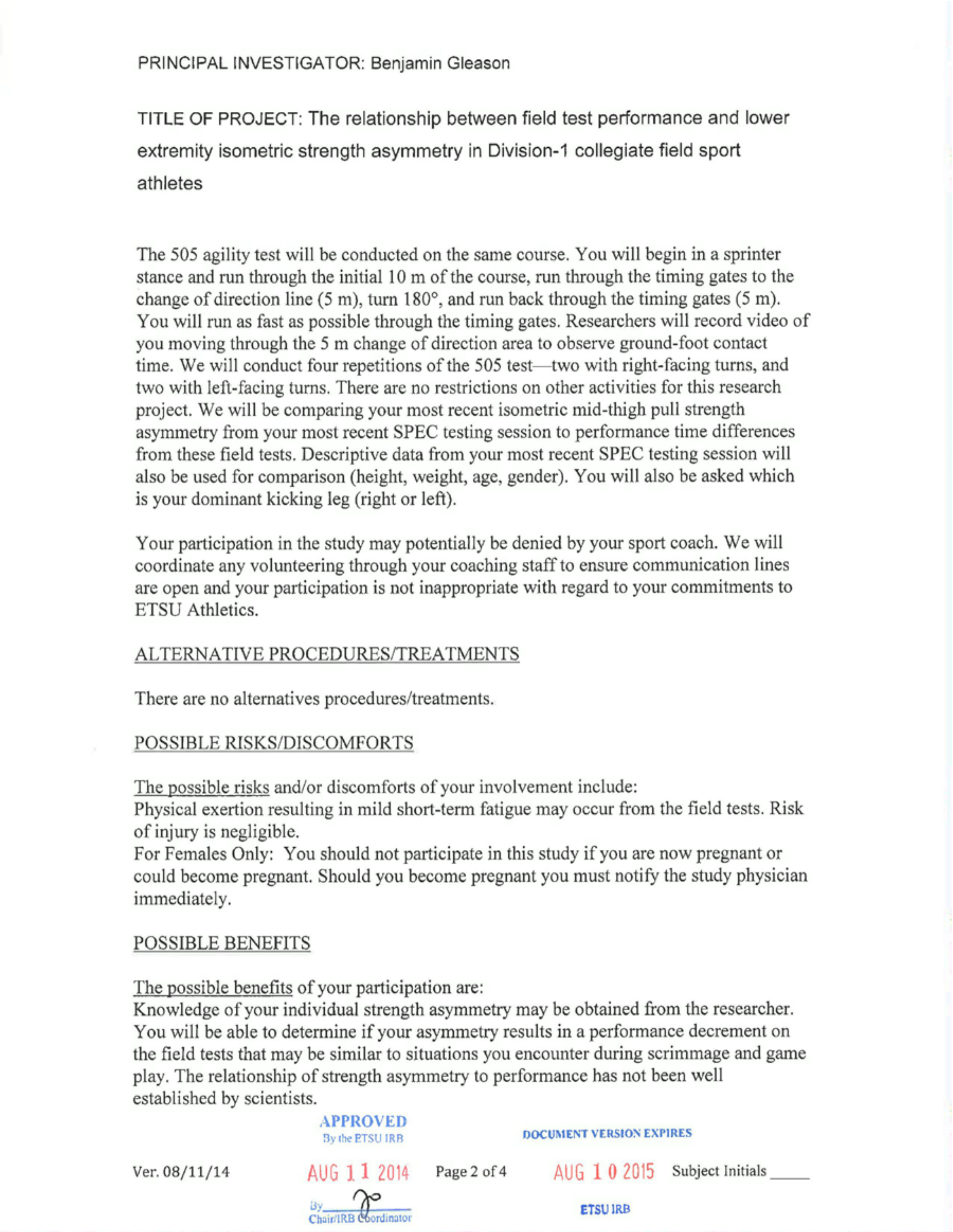
PROCEDURES

The procedures, which will involve you as a research subject, include:
The 10m sprints will be performed on the artificial turf surface in the Minidome. You will perform a 5-minute warm up, consisting of light stretching and short-distance (<10 m) acceleration-deceleration running. You will begin in a sprinter stance and sprint for 10 m as fast as you can between the infra-red sensors, which will analyze your ground-foot contact time and time through the course. You will perform one sprint with your right hand on the ground, and one sprint with your left hand on the ground.

APPROVED
By the ETSU IRB
AUG 11 2014
By Chair/IRB Coordinator

DOCUMENT VERSION EXPIRES
AUG 10 2015
ETSU IRB

Ver. 08/11/14 Page 1 of 4 Subject Initials _____



The 505 agility test will be conducted on the same course. You will begin in a sprinter stance and run through the initial 10 m of the course, run through the timing gates to the change of direction line (5 m), turn 180°, and run back through the timing gates (5 m). You will run as fast as possible through the timing gates. Researchers will record video of you moving through the 5 m change of direction area to observe ground-foot contact time. We will conduct four repetitions of the 505 test—two with right-facing turns, and two with left-facing turns. There are no restrictions on other activities for this research project. We will be comparing your most recent isometric mid-thigh pull strength asymmetry from your most recent SPEC testing session to performance time differences from these field tests. Descriptive data from your most recent SPEC testing session will also be used for comparison (height, weight, age, gender). You will also be asked which is your dominant kicking leg (right or left).

Your participation in the study may potentially be denied by your sport coach. We will coordinate any volunteering through your coaching staff to ensure communication lines are open and your participation is not inappropriate with regard to your commitments to ETSU Athletics.

ALTERNATIVE PROCEDURES/TREATMENTS

There are no alternatives procedures/treatments.

POSSIBLE RISKS/DISCOMFORTS

The possible risks and/or discomforts of your involvement include:
Physical exertion resulting in mild short-term fatigue may occur from the field tests. Risk of injury is negligible.
For Females Only: You should not participate in this study if you are now pregnant or could become pregnant. Should you become pregnant you must notify the study physician immediately.

POSSIBLE BENEFITS

The possible benefits of your participation are:
Knowledge of your individual strength asymmetry may be obtained from the researcher. You will be able to determine if your asymmetry results in a performance decrement on the field tests that may be similar to situations you encounter during scrimmage and game play. The relationship of strength asymmetry to performance has not been well established by scientists.

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By the ETSU IRB
AUG 11 2014
By Chair/IRB Coordinator

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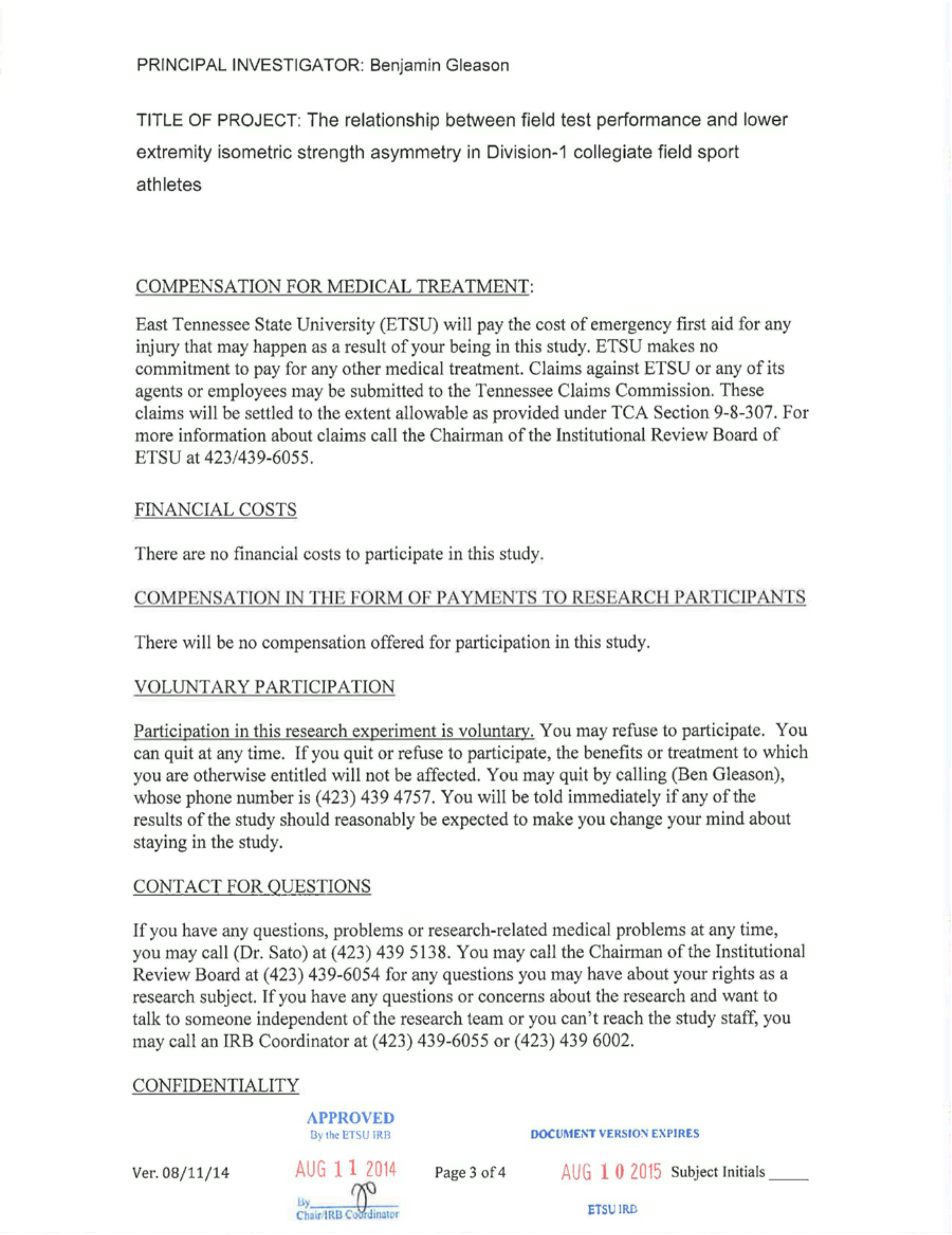

PRINCIPAL INVESTIGATOR: Benjamin Gleason

TITLE OF PROJECT: The relationship between field test performance and lower extremity isometric strength asymmetry in Division-1 collegiate field sport athletes

COMPENSATION FOR MEDICAL TREATMENT:

East Tennessee State University (ETSU) will pay the cost of emergency first aid for any injury that may happen as a result of your being in this study. ETSU makes no commitment to pay for any other medical treatment. Claims against ETSU or any of its agents or employees may be submitted to the Tennessee Claims Commission. These claims will be settled to the extent allowable as provided under TCA Section 9-8-307. For more information about claims call the Chairman of the Institutional Review Board of ETSU at 423/439-6055.

FINANCIAL COSTS

There are no financial costs to participate in this study.

COMPENSATION IN THE FORM OF PAYMENTS TO RESEARCH PARTICIPANTS

There will be no compensation offered for participation in this study.

VOLUNTARY PARTICIPATION

Participation in this research experiment is voluntary. You may refuse to participate. You can quit at any time. If you quit or refuse to participate, the benefits or treatment to which you are otherwise entitled will not be affected. You may quit by calling (Ben Gleason), whose phone number is (423) 439 4757. You will be told immediately if any of the results of the study should reasonably be expected to make you change your mind about staying in the study.

CONTACT FOR QUESTIONS

If you have any questions, problems or research-related medical problems at any time, you may call (Dr. Sato) at (423) 439 5138. You may call the Chairman of the Institutional Review Board at (423) 439-6054 for any questions you may have about your rights as a research subject. If you have any questions or concerns about the research and want to talk to someone independent of the research team or you can't reach the study staff, you may call an IRB Coordinator at (423) 439-6055 or (423) 439 6002.

CONFIDENTIALITY

APPROVED
By the ETSU IRB
AUG 11 2014
By Chair/IRB Coordinator

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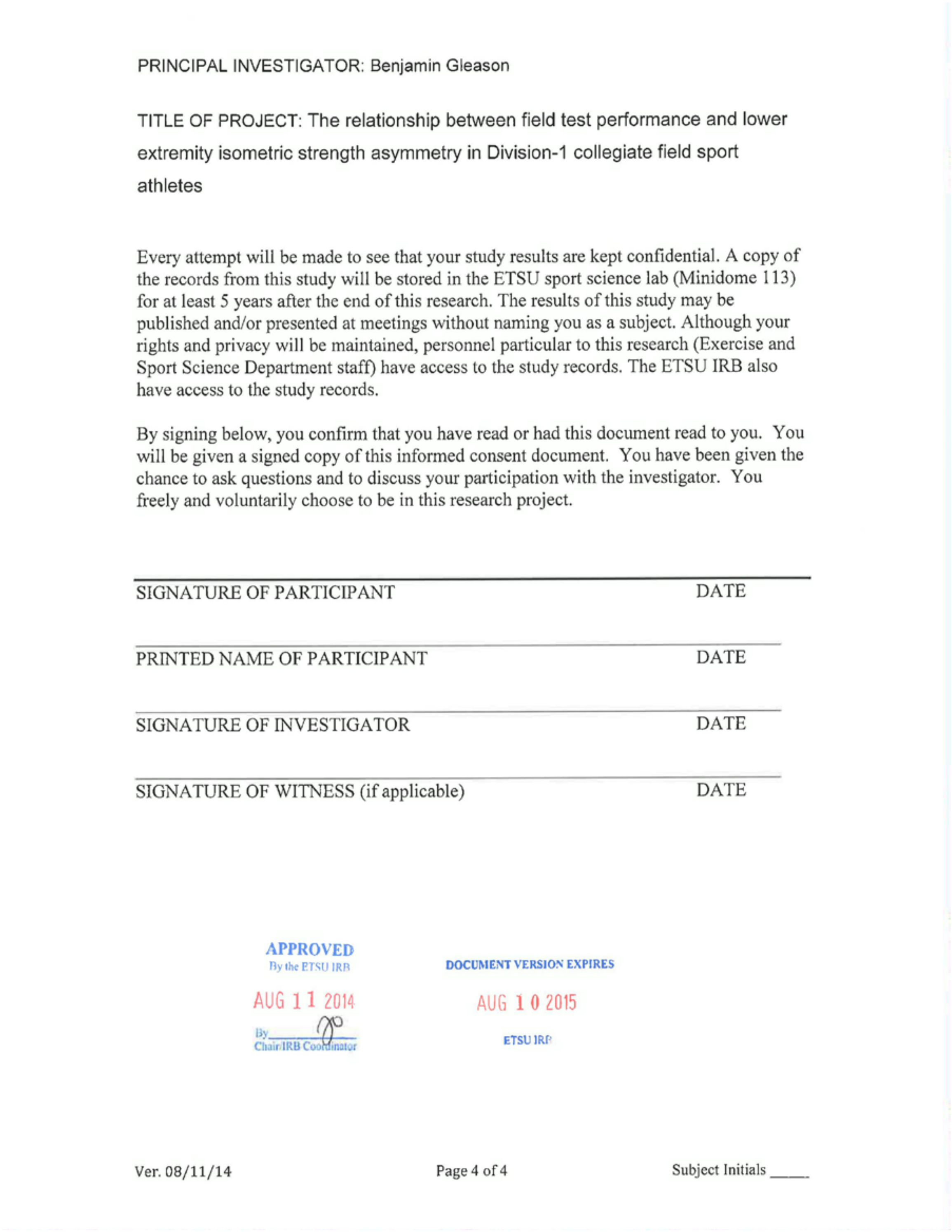
Ver. 08/11/14 Page 3 of 4 Subject Initials _____



PRINCIPAL INVESTIGATOR: Benjamin Gleason

TITLE OF PROJECT: The relationship between field test performance and lower extremity isometric strength asymmetry in Division-1 collegiate field sport athletes

Every attempt will be made to see that your study results are kept confidential. A copy of the records from this study will be stored in the ETSU sport science lab (Minidome 113) for at least 5 years after the end of this research. The results of this study may be published and/or presented at meetings without naming you as a subject. Although your rights and privacy will be maintained, personnel particular to this research (Exercise and Sport Science Department staff) have access to the study records. The ETSU IRB also have access to the study records.

By signing below, you confirm that you have read or had this document read to you. You will be given a signed copy of this informed consent document. You have been given the chance to ask questions and to discuss your participation with the investigator. You freely and voluntarily choose to be in this research project.

SIGNATURE OF PARTICIPANT DATE

PRINTED NAME OF PARTICIPANT DATE

SIGNATURE OF INVESTIGATOR DATE

SIGNATURE OF WITNESS (if applicable) DATE

APPROVED
By the ETSU IRB
AUG 11 2014
By
Chair/IRB Coordinator

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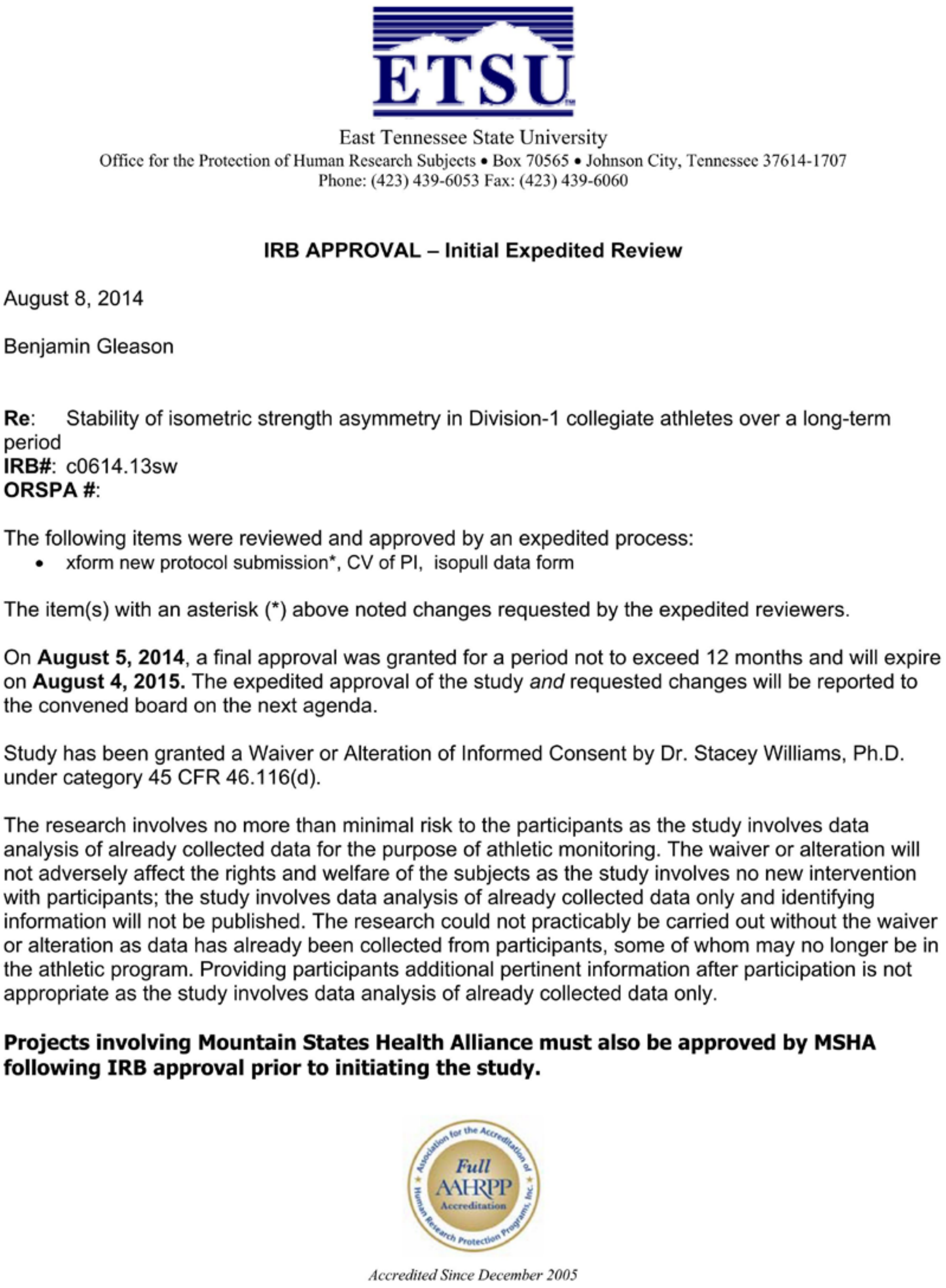
Appendix B

ETSU IRB Approval



ETSU

East Tennessee State University
Office for the Protection of Human Research Subjects • Box 70565 • Johnson City, Tennessee 37614-1707
Phone: (423) 439-6053 Fax: (423) 439-6060

IRB APPROVAL – Initial Expedited Review

August 8, 2014

Benjamin Gleason

Re: Stability of isometric strength asymmetry in Division-1 collegiate athletes over a long-term period
IRB#: c0614.13sw
ORSPA #:

The following items were reviewed and approved by an expedited process:

- xform new protocol submission*, CV of PI, isopull data form

The item(s) with an asterisk (*) above noted changes requested by the expedited reviewers.

On **August 5, 2014**, a final approval was granted for a period not to exceed 12 months and will expire on **August 4, 2015.** The expedited approval of the study *and* requested changes will be reported to the convened board on the next agenda.

Study has been granted a Waiver or Alteration of Informed Consent by Dr. Stacey Williams, Ph.D. under category 45 CFR 46.116(d).

The research involves no more than minimal risk to the participants as the study involves data analysis of already collected data for the purpose of athletic monitoring. The waiver or alteration will not adversely affect the rights and welfare of the subjects as the study involves no new intervention with participants; the study involves data analysis of already collected data only and identifying information will not be published. The research could not practicably be carried out without the waiver or alteration as data has already been collected from participants, some of whom may no longer be in the athletic program. Providing participants additional pertinent information after participation is not appropriate as the study involves data analysis of already collected data only.

Projects involving Mountain States Health Alliance must also be approved by MSHA following IRB approval prior to initiating the study.

Accredited Since December 2005

Unanticipated Problems Involving Risks to Subjects or Others must be reported to the IRB (and VA R&D if applicable) within 10 working days.

Proposed changes in approved research cannot be initiated without IRB review and approval. The only exception to this rule is that a change can be made prior to IRB approval when necessary to eliminate apparent immediate hazards to the research subjects [21 CFR 56.108 (a)(4)]. In such a case, the IRB must be promptly informed of the change following its implementation (within 10 working days) on Form 109 (www.etsu.edu/irb). The IRB will review the change to determine that it is consistent with ensuring the subject's continued welfare.

Sincerely,
Stacey Williams, Ph.D., Vice-Chair
ETSU Campus IRB

cc: Kimitake Sato

Appendix C. Data from Studies I and II.

Table 3.6. Reliability Test Data for IMTP; Two-Tailed Paired Samples *t*-test Results & Pearson Correlations for IMTP Trials (Mean Right vs. Mean Left Side Data)

Force at Time	*t* =	*p* >	*r* =	*p* <
90 ms	-0.493	0.628	0.832	0.000
150 ms	-0.083	0.935	0.888	0.000
200 ms	0.306	0.764	0.856	0.000
300 ms	0.043	0.966	0.827	0.000
400 ms	-0.420	0.680	0.794	0.000
500 ms	-0.055	0.957	0.761	0.000
600 ms	0.341	0.737	0.746	0.001
Peak Force	-0.163	0.872	0.847	0.000

Table 3.7. Unilateral Allometrically Scaled IMTP Force Values

Athlete	PFaLeft	PFaRight
1	112.77	101.92
2	115.49	112.37
3	95.18	100.29
4	97.66	127.88
5	119.45	127.98
6	111.79	111.60
7	103.41	79.48
8	114.70	83.21
9	107.31	119.64
10	133.24	148.03
11	147.92	162.90
12	113.23	100.35
13	103.81	97.61
14	88.21	101.17
15	87.26	77.22
16	101.82	93.01
17	89.56	98.19

Table 3.8. Correlation Matrix of IMTP SI and Field Test SI Values

		TimeSI 505	GFCTSI 505	TimeSI 10m	GFCTSI 10m	IMTPSI 90	IMTPSI 150	IMTPSI 200	IMTPSI 300	IMTPSI 400	IMTPSI 500	IMTPSI 600	IMTPSI PF
TimeSI 505	Pearson Correlation	1	-.281	.227	.033	-.358	-.132	-.148	-.140	-.438	-.404	-.292	-.441
	Sig. (2-tailed)		.274	.381	.900	.158	.613	.571	.591	.079	.108	.256	.077
	N	17	17	17	17	17	17	17	17	17	17	17	17
GFCTSI 505	Pearson Correlation	-.281	1	-.225	.016	.048	-.093	-.140	-.134	.204	-.025	-.090	-.015
	Sig. (2-tailed)	.274		.384	.951	.855	.722	.593	.609	.432	.925	.730	.954
	N	17	17	17	17	17	17	17	17	17	17	17	17
TimeSI 10m	Pearson Correlation	.227	-.225	1	.419	.082	.060	.079	.083	.152	.239	.299	.105
	Sig. (2-tailed)	.381	.384		.094	.753	.819	.764	.751	.561	.355	.243	.688
	N	17	17	17	17	17	17	17	17	17	17	17	17
GFCTSI 10m	Pearson Correlation	.033	.016	.419	1	.089	.064	.017	-.012	.110	.192	.163	.028
	Sig. (2-tailed)	.900	.951	.094		.735	.807	.950	.964	.673	.461	.532	.914
	N	17	17	17	17	17	17	17	17	17	17	17	17
IMTPSI 90	Pearson Correlation	-.358	.048	.082	.089	1	.876**	.610**	.458	.528*	.586*	.569*	.628**
	Sig. (2-tailed)	.158	.855	.753	.735		.000	.009	.065	.029	.013	.017	.007
	N	17	17	17	17	17	17	17	17	17	17	17	17
IMTPSI 150	Pearson Correlation	-.132	-.093	.060	.064	.876**	1	.855**	.722**	.562*	.662**	.689**	.714**
	Sig. (2-tailed)	.613	.722	.819	.807	.000		.000	.001	.019	.004	.002	.001
	N	17	17	17	17	17	17	17	17	17	17	17	17
IMTPSI 200	Pearson Correlation	-.148	-.140	.079	.017	.610**	.855**	1	.967**	.729**	.848**	.889**	.810**
	Sig. (2-tailed)	.571	.593	.764	.950	.009	.000		.000	.001	.000	.000	.000
	N	17	17	17	17	17	17	17	17	17	17	17	17
IMTPSI 300	Pearson Correlation	-.140	-.134	.083	-.012	.458	.722**	.967**	1	.783**	.867**	.904**	.777**
	Sig. (2-tailed)	.591	.609	.751	.964	.065	.001	.000		.000	.000	.000	.000
	N	17	17	17	17	17	17	17	17	17	17	17	17

IMTPSI 400	Pearson Correlation	-.438	.204	.152	.110	.528*	.562*	.729**	.783**	1	.936**	.849**	.740**
	Sig. (2-tailed)	.079	.432	.561	.673	.029	.019	.001	.000		.000	.000	.001
	N	17	17	17	17	17	17	17	17	17	17	17	17
IMTPSI 500	Pearson Correlation	-.404	-.025	.239	.192	.586*	.662**	.848**	.867**	.936**	1	.964**	.843**
	Sig. (2-tailed)	.108	.925	.355	.461	.013	.004	.000	.000	.000		.000	.000
	N	17	17	17	17	17	17	17	17	17	17	17	17
IMTPSI 600	Pearson Correlation	-.292	-.090	.299	.163	.569*	.689**	.889**	.904**	.849**	.964**	1	.848**
	Sig. (2-tailed)	.256	.730	.243	.532	.017	.002	.000	.000	.000	.000		.000
	N	17	17	17	17	17	17	17	17	17	17	17	17
IMTPSI PF	Pearson Correlation	-.441	-.015	.105	.028	.628**	.714**	.810**	.777**	.740**	.843**	.848**	1
	Sig. (2-tailed)	.077	.954	.688	.914	.007	.001	.000	.000	.001	.000	.000	
	N	17	17	17	17	17	17	17	17	17	17	17	17

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

Table 3.9. CVs for GFCT During Each Step of 10m Sprint (RFF vs. LFF)

Athlete	step1	step2	step3	step4	step5	step6	step7	step8
1	10.04	0.83	4.85	0.92	5.66	0.47	1.03	
2	10.30	2.38	10.64	4.02	0.44	1.80	6.11	9.60
3	4.15	0.35	1.46	2.10	2.11	0.86		
4	21.18	6.93	2.12	1.55	4.99	0.83	6.45	
5	10.88	0.00	5.51	4.88	7.97	0.50	0.49	
6	12.43	3.99	8.81	7.14	9.23	1.41	7.00	
7	0.00	0.77	3.75	8.00	0.44	11.22	5.27	
8	0.38	2.59	3.70	6.29	7.91	4.39	10.62	8.73
9	4.52	3.78	2.94	1.71	0.00	0.00	0.00	26.48
10	16.07	2.15	17.46	2.93	6.94	2.14	5.66	7.63
11	1.72	0.65	4.65	3.20	5.52	2.09		
12	8.90	2.03	3.94	2.64	13.64	3.35	6.08	
13	5.41	4.06	3.31	4.56	4.54	0.00	4.88	2.60
14	5.49	3.31	6.45	6.15	0.96	1.43	1.91	2.97
15	11.45	15.22	11.55	2.99	2.90	0.41	8.56	
16	1.70	2.28	1.52	2.05	5.66	5.89	1.33	
17	9.97	4.47	3.23	3.18	0.44	0.91		

Table 3.10. 10m Sprint Times (seconds)

Athlete	RFF	LFF	10m mean time
1	1.78	1.82	1.80
2	1.88	1.91	1.90
3	1.90	1.90	1.90
4	1.90	1.89	1.90
5	1.83	1.79	1.81
6	1.83	1.82	1.83
7	1.86	1.87	1.87
8	1.87	1.88	1.88
9	1.93	1.94	1.94
10	1.86	1.80	1.83
11	1.84	1.81	1.83
12	1.89	1.87	1.88
13	2.08	2.06	2.07
14	2.16	2.26	2.21
15	1.91	1.86	1.89
16	1.85	1.84	1.85
17	1.88	1.82	1.85
		Mean	1.89 ± 0.10

Note: RFF = right foot forward start stance, LFF = left foot forward start stance.

Table 3.11. 10m Sprint GFCTs (seconds)

	Step1	Step2	Step3	Step4	Step5	Step6	Step7	Step8
RFF	0.2088 ± 0.0314	0.1851 ± 0.0187	0.1749 ± 0.0191	0.1636 ± 0.0156	0.1591 ± 0.0150	0.1569 ± 0.0135	0.1525 ± 0.0187	0.1385 ± 0.0208
LFF	0.2029 ± 0.0237	0.1844 ± 0.0167	0.1769 ± 0.0187	0.1605 ± 0.0141	0.1574 ± 0.0143	0.1564 ± 0.0141	0.1486 ± 0.0214	0.1519 ± 0.0197
Mean GFCT	0.2059 ± 0.0276	0.1847 ± 0.0175	0.1759 ± 0.0186	0.1621 ± 0.0147	0.1582 ± 0.0145	0.1567 ± 0.0136	0.1506 ± 0.0199	0.1452 ± 0.0205

Note: Mean $\text{GFCT}_{\text{total}}$ = 1.24 ± 0.11s; RFF = right foot forward, LFF = left foot forward

Table 3.12. CVs for Mean Right and Mean Left Plant 505 Test Times.

Athlete	CV Lplant	CV Rplant	CVtotal
1	2.34	0.92	3.40
2	4.14	1.46	2.66
3	2.31	0.30	2.25
4	0.91	0.32	2.60
5	2.48	0.65	3.00
6	0.00	2.45	1.49
7	2.49	2.16	2.00
8	0.92	0.00	0.54
9	0.30	1.22	0.95
10	0.62	0.33	2.50
11	0.65	1.62	1.02
12	3.92	3.50	4.30
13	0.87	2.86	1.92
14	2.12	5.43	4.49
15	3.03	2.91	3.43
16	2.08	0.30	1.24
17	0.64	1.94	1.29

Table 3.13. CVs for 505 Test GFCTs (left foot plant).

Athlete	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7
1	9.43	10.25	6.94	7.39	11.79	0.00	17.32
2	20.74	1.75	6.90	18.68	16.83	7.58	8.76
3	13.16	1.46	47.14	13.72	52.66	2.48	11.31
4	3.82	0.00	6.85	0.74	3.14	1.40	4.56
5	8.32	7.44	33.53	9.56	9.90	7.29	1.63
6	7.44	1.94	4.79	0.00	6.49	1.43	4.66
7	0.00	4.16	8.59	2.45	5.66	7.44	12.86
8	9.96	10.88	23.06	3.14	11.86	7.29	1.52
9	27.67	5.24	39.86	3.12	15.08	6.26	6.73
10	6.73	6.90	16.57	27.92	2.36	8.13	9.64
11	3.29	3.72	2.44	7.37	1.96	5.94	12.65
12	19.58	9.18	13.37	22.44	1.00	1.35	3.14
13	16.07	2.89	2.97	0.00	11.72	5.14	0.00
14	1.94	3.93	2.29	8.89	11.79	2.62	6.73
15	5.51	5.77	12.64	2.18	13.97	16.56	2.57
16	3.29	5.11	42.85	20.05	6.47	6.49	2.89
17	2.67	9.75	12.09	14.54	8.32	1.17	2.67

Table 3.14. CVs for 505 Test GFCTs (right foot plant).

Athlete	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7
1	1.99	7.64	2.48	0.54	5.40	11.26	1.30
2	5.98	3.82	43.39	28.02	40.41	9.43	2.83
3	5.51	7.44	20.83	1.10	7.79	8.92	13.40
4	0.00	1.89	10.96	5.99	6.73	5.14	4.47
5	5.81	0.00	17.77	0.75	2.21	17.09	13.69
6	27.55	11.93	12.99	5.73	1.13	4.99	7.29
7	0.00	4.77	5.72	0.76	4.49	0.00	3.01
8	3.63	1.99	8.54	7.50	0.00	4.47	3.21
9	1.75	7.19	11.98	12.20	2.11	9.08	1.43
10	6.15	8.08	15.27	2.18	14.38	9.43	7.60
11	5.51	1.89	13.07	6.15	5.44	2.36	1.23
12	5.51	1.84	4.04	9.12	41.37	0.00	3.69
13	14.97	33.86	4.88	5.95	19.45	0.00	3.97
14	3.63	17.25	10.71	1.85	5.93	7.71	3.21
15	10.35	9.87	43.24	3.82	9.56	1.30	12.41
16	71.26	19.00	2.34	13.22	4.99	3.69	0.00
17	5.66	8.95	6.43	4.69	8.13	6.87	0.00

Table 3.15. 7-Step GFCT for 505 Test (seconds).

Lplant								Rplant						
	step1	step2	step3	step4	step5	step6	step7	step1	step2	step3	step4	step5	step6	step7
1	0.1250	0.1438	0.5521	0.5583	0.2500	0.2208	0.2042	0.1479	0.1542	0.5938	0.5438	0.2729	0.2354	0.2271
2	0.1563	0.1688	0.1708	0.4417	0.6479	0.2333	0.2354	0.1479	0.1542	0.3667	0.4521	0.4083	0.2188	0.2083
3	0.1792	0.2021	0.4125	0.4938	0.4979	0.2375	0.2083	0.1604	0.1583	0.5375	0.5375	0.2646	0.2313	0.1979
4	0.1542	0.1583	0.4729	0.3979	0.2813	0.2104	0.1938	0.1667	0.1563	0.5646	0.4917	0.2625	0.2292	0.1979
5	0.1771	0.1188	0.2021	0.3083	0.4167	0.2021	0.1813	0.1521	0.1667	0.3813	0.3938	0.2667	0.1896	0.1938
6	0.1583	0.1521	0.4917	0.3208	0.2271	0.2063	0.1896	0.1604	0.1729	0.4083	0.3083	0.2604	0.1771	0.2021
7	0.1583	0.1417	0.5146	0.3604	0.2083	0.2375	0.2063	0.1583	0.1854	0.3604	0.3896	0.2625	0.2000	0.1958
8	0.1479	0.1083	0.3833	0.3750	0.3229	0.2021	0.1938	0.1625	0.1479	0.6208	0.5104	0.2875	0.1979	0.1833
9	0.1917	0.1688	0.4583	0.4729	0.3125	0.2354	0.2188	0.1688	0.1229	0.3688	0.4104	0.2792	0.2271	0.2063
10	0.1313	0.1708	0.5333	0.3271	0.2500	0.1813	0.1833	0.1438	0.1458	0.4438	0.4063	0.2458	0.1875	0.1938
11	0.1792	0.1583	0.4833	0.4000	0.3000	0.2479	0.2563	0.1604	0.1563	0.4958	0.4313	0.3250	0.2500	0.2396
12	0.1354	0.1604	0.4188	0.5646	0.2938	0.2188	0.1875	0.1604	0.1604	0.3646	0.3875	0.3063	0.2167	0.2396
13	0.1833	0.2042	0.2979	0.4542	0.3771	0.2292	0.2208	0.1771	0.1479	0.3625	0.3958	0.3333	0.2375	0.2229
14	0.1521	0.1500	0.3854	0.3646	0.3500	0.2250	0.2188	0.1625	0.1708	0.5229	0.4771	0.3479	0.2292	0.1833
15	0.1604	0.2042	0.4896	0.4063	0.3375	0.2313	0.2292	0.1708	0.1792	0.5042	0.3854	0.3083	0.2271	0.2375
16	0.1792	0.1729	0.5500	0.5438	0.3188	0.2271	0.2042	0.2688	0.1396	0.5042	0.4458	0.3542	0.2396	0.2333
17	0.1104	0.1208	0.4875	0.4458	0.3542	0.2521	0.2208	0.1563	0.1646	0.4583	0.4396	0.3625	0.2146	0.2042

Table 3.16. Mean GFCT for 505 Test (seconds).

Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7
0.1619 ± 0.0366	0.1585 ± 0.0244	0.4460 ± 0.1193	0.4306 ± 0.0792	0.3204 ± 0.0946	0.2208 ± 0.0222	0.2094 ± 0.0224

Note: mean $GFCT_{total}$ for seven steps was 1.94 ± 0.13s

Table 4.3. CV Values per Limb by Testing Session & CV Average

Athlete	CVL1	CVL2	CVL3	CVR1	CVR2	CVR3	CV Average
1	0.29	2.27	2.31	0.88	0.04	3.60	1.56
2	10.96	6.86	0.76	11.72	7.78	0.21	6.38
3	1.72	14.14	2.05	0.65	5.22	0.92	4.11
4	1.10	3.40	3.56	8.72	0.94	0.49	3.03
5	5.54	3.86	5.65	4.19	12.13	10.18	6.93
6	3.65	3.93	16.23	1.26	8.37	0.30	5.62
7	4.35	2.33	8.72	2.81	7.19	10.35	5.96
8	2.62	1.48	0.07	4.56	3.21	1.58	2.25
9	0.73	1.78	3.75	3.72	2.04	2.32	2.39
10	1.48	9.32	5.85	1.25	13.29	5.63	6.14
11	4.92	4.13	1.60	1.68	2.83	6.26	3.57
12	4.57	0.60	1.44	0.57	2.56	2.11	1.97
13	3.55	1.09	1.07	0.71	2.52	2.15	1.85
14	3.14	4.99	0.80	0.14	0.62	2.31	2.00
15	3.78	0.67	1.46	3.37	2.49	5.62	2.90
16	3.62	5.38	11.29	2.35	4.96	5.48	5.51
17	6.00	0.11	1.06	0.46	3.84	6.21	2.95
18	2.38	4.27	2.64	6.10	8.01	1.68	4.18
19	4.35	0.77	0.60	1.76	0.85	2.01	1.72
20	2.19	6.81	4.40	7.78	4.58	3.84	4.93
21	2.48	2.99	6.28	5.27	0.23	3.31	3.43
22	0.01	5.04	2.02	10.70	4.90	4.60	4.54
23	7.37	0.46	5.00	6.14	4.48	2.65	4.35
24	8.07	6.02	8.16	3.31	5.02	6.40	6.16
25	6.07	1.30	5.50	2.95	5.51	1.38	3.79
26	5.23	7.85	7.56	2.85	9.09	12.26	7.47
27	3.28	1.27	0.19	2.37	1.77	0.80	1.61
28	0.55	12.05	5.33	3.58	9.69	1.78	5.50
29	3.45	3.06	1.87	0.72	0.96	5.95	2.67
30	5.30	4.89	0.09	9.28	4.13	5.90	4.93
31	5.64	2.55	2.00	8.05	11.37	12.69	7.05
32	1.66	3.15	2.05	4.25	0.53	6.31	2.99
33	0.39	2.61	6.90	1.61	4.49	8.29	4.05
34	6.63	2.65	0.62	2.35	4.33	5.02	3.60
35	11.67	2.27	6.27	12.93	5.93	6.39	7.57
36	0.08	7.59	1.28	1.51	1.69	6.95	3.18
37	0.02	3.70	7.27	6.01	9.38	7.34	5.62
38	1.27	0.76	3.36	0.50	0.57	2.64	1.51
39	4.77	0.97	1.37	0.18	3.61	7.92	3.14
40	2.57	4.79	3.96	3.72	7.05	1.17	3.88

41	6.75	4.35	0.32	4.13	1.98	9.57	4.51
42	2.84	4.89	9.58	8.53	0.43	1.36	4.60
43	6.87	0.47	4.11	0.65	11.70	7.42	5.20
44	10.15	2.40	2.90	2.03	2.09	1.25	3.47
45	0.08	6.31	6.55	2.60	3.03	4.71	3.88
46	4.29	4.35	3.95	0.01	0.98	8.17	3.63
47	3.46	3.82	0.54	12.46	5.72	4.91	5.15
48	2.47	0.98	3.88	10.14	2.65	4.77	4.15
49	4.61	2.26	4.05	8.07	1.37	4.12	4.08
50	0.61	4.00	11.88	9.19	1.25	3.60	5.09
51	9.61	0.59	6.45	3.53	0.80	3.95	4.16
52	3.94	0.05	4.10	10.44	1.79	3.31	3.94
53	3.26	1.28	6.62	2.19	4.39	1.93	3.28
							4.12 ± 1.57%

Table 4.4. High and Low SI Scores and SI Range.

Athlete	SI High	SI Low	SI Range (%)
1	-12.38	-16.58	4.20
2	-4.10	-16.04	11.95
3	15.60	-2.19	17.80
4	17.39	9.73	7.66
5	12.12	-6.28	18.40
6	34.45	20.14	14.30
7	16.33	14.92	1.41
8	5.10	-0.84	5.94
9	-1.87	-16.25	14.38
10	14.65	-17.24	31.89
11	1.31	-1.38	2.69
12	13.59	0.90	12.69
13	12.53	-0.13	12.66
14	2.29	-14.71	17.00
15	6.87	-28.36	35.23
16	14.00	-16.09	30.09
17	26.46	22.49	3.97
18	-3.13	-15.87	12.74
19	9.65	-4.70	14.34
20	0.75	-18.43	19.18
21	7.11	-0.78	7.89
22	-6.19	-14.72	8.53
23	11.31	3.32	7.98
24	24.86	-2.15	27.01
25	12.37	-21.79	34.16
26	5.98	2.48	3.50
27	24.58	-6.30	30.88
28	35.16	1.71	33.45
29	1.68	-4.18	5.85
30	-34.87	-37.39	2.52
31	2.93	-27.29	30.22
32	16.83	-8.35	25.19
33	-0.15	-13.22	13.08
34	26.54	-14.17	40.71
35	11.74	6.94	4.80
36	39.59	14.54	25.05
37	16.76	12.29	4.47
38	16.31	3.27	13.03
39	17.25	7.35	9.91
40	0.74	-1.19	1.94
41	19.48	5.26	14.21
42	9.72	-17.05	26.78
43	10.84	3.74	7.10
44	15.22	-2.62	17.84

45	16.06	-1.68	17.75
46	4.42	-10.92	15.34
47	1.47	-4.85	6.32
48	18.72	-2.81	21.53
49	40.14	4.28	35.86
50	-0.78	-4.86	4.08
51	31.55	12.85	18.70
52	37.51	5.44	32.07
53	11.05	-2.96	14.00
		Mean SI Range	16.04 ± 10.72

Figure 3.9. Kolmogorov-Smirov Test Results for 10m Time Data Points Outside Normal Curve.

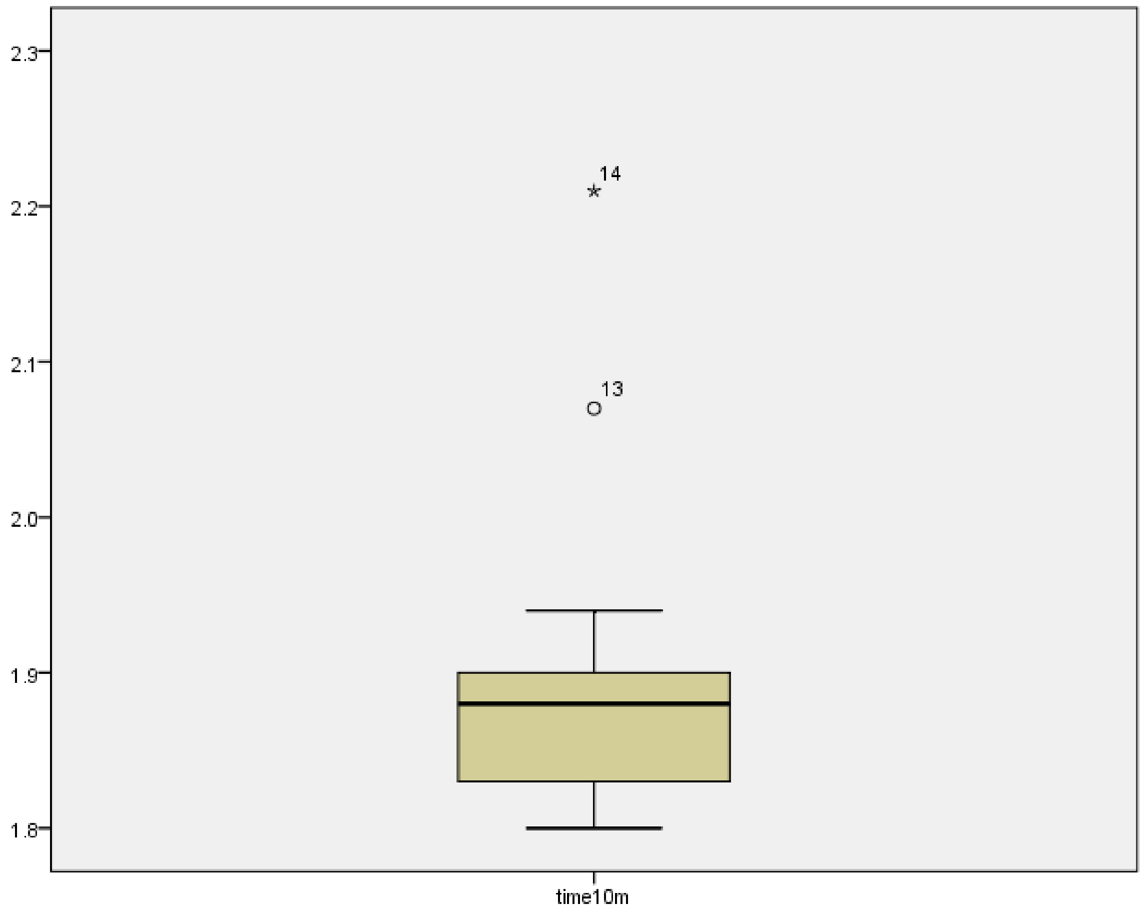
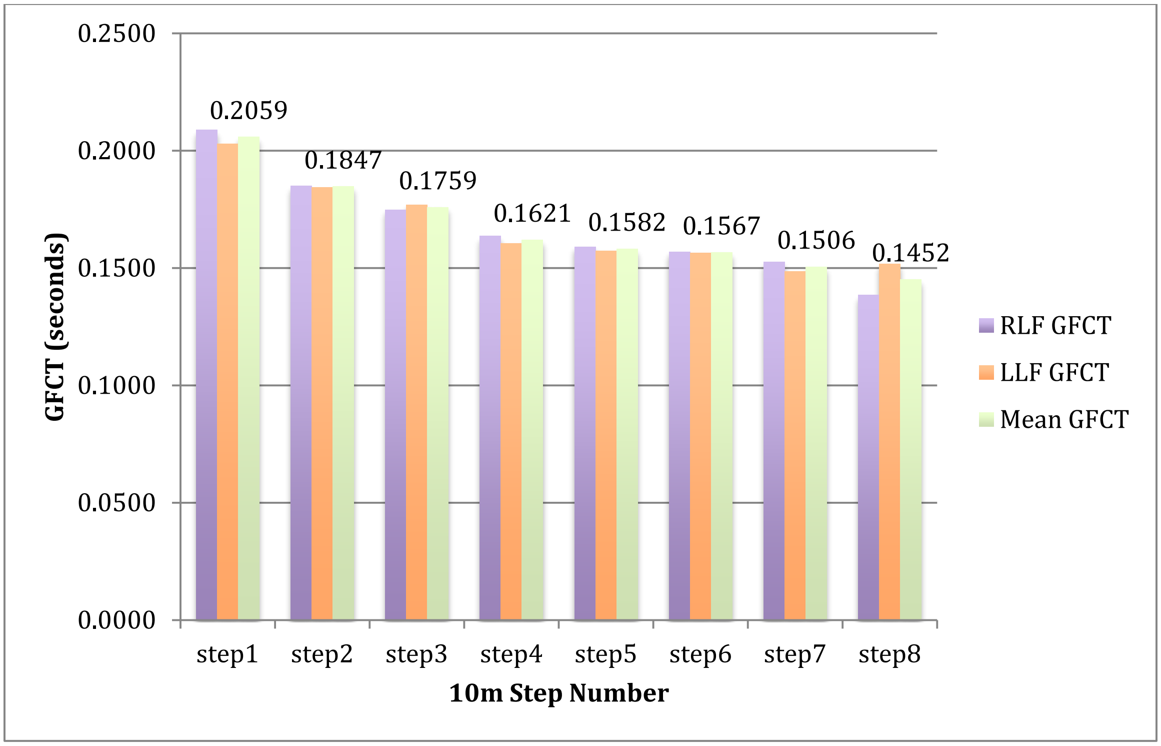


Figure 3.10. Group Mean GFCTs for 10m Sprint by Step



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