THESIS

RELATIONSHIPS BETWEEN ASYMMETRIES IN FUNCTIONAL MOVEMENTS AND THE STAR EXCURSION BALANCE TEST

Submitted by

Grant Overmoyer

Department of Health and Exercise Science

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Master's Committee:

Advisor: Raoul Reiser II

Ray Browning
David Gilkey

ABSTRACT

RELATIONSHIPS BETWEEN ASYMMETRIES IN FUNCTIONAL MOVEMENTS AND THE STAR EXCURSION BALANCE TEST

Lower extremity functional asymmetries (LEFA) as well as the Star Excursion Balance Test (SEBT) have been used to screen for injury risk and assess post-injury function. Both have also been shown to relate to physical performance. However, the relationships between LEFA, observed during different tasks, are not well understood, nor are the relationships between LEFA and side-to-side asymmetries in SEBT scores. As a result, it is difficult to determine which methods are most appropriate to assess detrimental asymmetries and whether they might be interchangeable. **PURPOSE:** The goal of this investigation was to examine the correlation in LEFA using measurement of vertical ground reaction forces (GRFv) during quiet standing, body weight squats, maximal effort counter-movement jumps (CMJ) and single-leg drop landings from a 30.5 cm platform (SLDL). Another goal was to investigate bilateral asymmetries in the SEBT anterior (Ant), posteromedial (PostMed) and posterolateral (PostLat) excursion directions, in both the correlations to each other and the correlations to the four functional movement tasks listed above. **METHODS:** Twenty recreationally active men (n=9) and women (n=11) (mean ± SD age: 21.9 ± 2.6 yrs; height 171 ± 8.8 cm; mass 67.2 ± 1.9 kg) performed three measured trials of each excursion direction of the SEBT, five 20 second quiet standing trials, five unloaded (body weight) squats, five CMJ and five SLDL on each side. Leg length measurements, GRFv data and SEBT scores for each leg were collected. Asymmetry was calculated by subtracting the % load on the preferred kicking leg (KL), or during the SEBT the percent of the bilaterally summed score on the KL, from that of the non-preferred kicking leg (NKL). Results were analyzed using Pearson's correlation and paired t-tests. Eleven subjects were reassessed for repeatability measures.

RESULTS: Significant correlations ($p<0.05$) were found between asymmetries in several of the parameters measured in the LEFA tasks. Standing and average GRFv during CMJ significantly correlated to each other (r= 0.458); average GRFv during squats significantly correlated with standing GRFv (r= -0.452); both maximum and average GRFv during the squat significantly correlated with average and maximum GRFv during CMJ (r= -0.571 to -0.768). Average GRFv to peak in the SLDL significantly related to the squat (r= -0.494 to -0.500) and peak GRFv during the SLDL significantly related to CMJ average GRFv (r= -0.470). Further significance was identified among asymmetries in several SEBT excursion directions, particularly between the Ant versus PostMed (r= 0.406 to 0.564), and Ant versus PostLat (r= 0.470 to 0.570). There was a wide range of significant correlations in regards to combinations of these scores in the SEBT (r= 0.470 to 0.973). And finally, correlations were found to exist between several of the LEFA tasks and SEBT excursion directions. These included squats versus PostMed and Ant (r= 0.489 to 0.593 and r= 0.315 to 0.514, respectively), CMJ versus all excursion directions (r= -0.379 to -0.649) and the SLDL slope to peak, average GRFv to peak and average GRFv to 300ms, versus Ant (r= -0.402 to -0.609). LEFA tasks and SEBT asymmetries were generally found to be highly repeatability (α= 0.758 to 0.992 and α= 0.752 to 0.976, respectively), but with generally much lower and a wider range of repeatability shown in the absolute measures of asymmetry (LEFA: α= 0.212 to 0.791 and SEBT: α= 0.133 to 0.802). **CONCLUSION**: While most measures were highly repeatable, because the correlations between tests were of only mild to moderate strength, it is unlikely that any one test studied here could be used to accurately predict performance on any of the other tests, at least in a relatively healthy young population. Therefore, multiple tests may be necessary with specific attention on those that most closely replicate the movement patterns and specific performance needs of the individual.

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CHAPTER I

INTRODUCTION

Functional asymmetries, as discussed here and throughout the thesis, are side-to-side differences in kinetics and/or kinematics during task performance. Kinetics include variables such as ground reaction forces and joint moments while kinematics include variables such as body position and motion. While functional asymmetries during otherwise symmetric tasks might be expected in injured or physically disabled individuals, low levels of functional asymmetries have been found to be commonplace in healthy populations as well. Tasks in which this has been demonstrated include cycling (Daly & Cavanagh, 1976; Sanderson, 1990; Smak, Neptune & Hull, 1999), double-leg landing (Schot, Bates & Dufek ,1994), hang power clean (Lake, Lauder & Smith, 2010), lifting (Maines & Reiser, 2006), running (Vagenas & Hoshizaki,1992; Wong, Chamari, Chaouachi, Mao, Wisløff, & Hong, 2007), sit-to-stand (Lundin et al., 1995), loaded squatting (Flanagan & Salem, 2007; Hogdes, Patrick, & Reiser, 2011; Lake, Lauder & Smith, 2011; Newton, Gerber, Nimphius, Shim, Doan, et al., 2006), quiet standing (Blaszczyck, Prince, Raiche, Hebert, 2000; Rougier & Genthon, 2007), walking (Herzog, Nigg, Read & Olsson, 1989), and various jumping and hopping tasks (Ball, Stock, & Scurr, 2010; Barber-Westin, Galloway, Noyes, Corbett & Walsh, 2005; Hickey, Quatman, Myer, Ford, Brosky, & Hewett, 2009; Miyaguchi & Demura, 2010; Lawson, Stephens, Devoe & Reiser, 2006; Newton et al. 2006; Reiser, Paulson, & Maines, 2003;

Schilz, Lehance, Maquet, Bury, Crielaard, & Crosier, 2009; Stephens, Lawson, Devoe & Reiser 2007; Wong et al. 2007).

Functionally performing without asymmetry has been suggested to lead to improved sport-related performance (Manning & Pickup, 1998; Cavanagh, Pollock & Lands, 1977), while functionally performing with asymmetry has been linked to injury. More specifically, functional asymmetries have been used as a predictor of injury or re-injury (Herring, 1993; Paterno, Schmitt, Ford, Rauh, Myers, et al., 2010; Shambaugh, Klein, Herbert, 1991) and in some circumstances may help to identify a deficit related to past or present injury (Childs, Piva, Erhard & Hicks, 2003; Neitzel, Kernozek & Davies, 2002, Paterno, Ford, Myer, Heyl, & Hewett, 2007; Rocheford, Devoe & Reiser, 2006; Salem, Salinas, & Harding, 2003; Schiltz et al., 2009).

Although asymmetries of the lower extremities have been identified through a variety of means, lower extremity functional asymmetries (LEFA) have been shown to be related to a few specific sources (i.e. variables which may directly cause someone to function asymmetrically). These include side-to-side differences in strength (Hewett, Stroupe, Nance, & Noyes, 1996; Newton et al. 2006; Schiltz et al., 2009), anthropometry (Blustein & D'Amico, 1985; Shambaugh et al., 1991), and neural control (Simon & Ferris, 2007; Dorge, Andersen, Sorensen, Simonsen, 2002). Although it has also been suggested that side-to-side differences in flexibility contribute to functional asymmetries, (Knapik, Bauman, Jones, Harris, & Vaughan, 1991) this relationship is less clear.

These various sources of functional asymmetry may have an origin point in a few possible places including incomplete recovery from injury (Neitzel et al., 2002; Paterno et al., 2007; Rocheford et al., 2006; Salem et al., 2003), repetitive asymmetrical task performance (Schiltz et al., 2009; Riganas, Vrabas, Papaevangelou, Mandroukas, 2010), the way the fetus sits in the womb (Blustein & D'Amico, 1985), laterality of neural development (Gabbard & Hart, 1996; Myaguchi & Demura 2010) and fluctuating asymmetries, which are small deviations from bilateral symmetry as a result of random interactions with the environment (Trivers, Manning, Thornhill, Singh & Mcguire, 1999).

One of the more common ways to assess LEFA is by measuring the bilateral differences in ground reaction forces under the feet, the most common of which is the assessment of ground reaction forces in the vertical direction (GRFv). GRFv provide an overall assessment of loading of the limb and have been used to assess injury or re-injury risk (Herring, 1993; Paterno et al., 2010; Shambaugh et al., 1991) as well as identify injury related deficits (Childs et al., 2003; Neitzel et al., 2002; Paterno et al., 2007; Rocheford et al. 2006; Salem et al. 2003; Schiltz et al., 2009).

Unfortunately, the equipment to accurately and reliably measure GRFv is typically expensive and lacks portability for widespread use. Therefore, additional options to assess LEFA are desirable. A test which has been used in screening for LEFA, that is relatively inexpensive and portable, is the Star Excursion Balance Test (SEBT). The SEBT requires multiple reaches (a.k.a. excursions) with one foot in a star-like pattern while standing and maintaining balance on the other (Gray, 1995). This test is relatively easy to administer and has been used to identify lower-extremity asymmetry in relation to chronic ankle instability (Hertel, Braham, Hale & Olmsted-Kramer, 2006; Hertel, 2008; Hubbard, Kramer, Denegar & Hertel, 2007A; Hubbard, Kramer, Denegar & Hertel, 2007b; Olmsted, Carcia, Hertel, Shultz, 2002), ankle sprains (Chaiwanichsiri, Lorprayoon, Noomanoch, 2005), anterior cruciate ligament deficiency (Herrington, Hatcher, Hatcher, & McNicholas, 2009) and general lower extremity injury risk (Plisky et. al, 2006). It has also been used as a measure of unilateral balance and neuromuscular control (Bressel, Yonker, Kras & Heath, 2007; Cote et al., 2005; Chaiwanichsiri et al., 2005; English & Howe, 2007; Filipa, Byrnes, Paterno, Myer, Hewett, 2010; Leavey, 2010; Rasool & George, 2007; Thorpe & Ebersole, 2008).

While the SEBT appears to be a promising replacement for GRFv measures, it is not clear if they are measuring similar attributes. Task specific factors have been shown to affect functional asymmetry, to include level of intensity (Ball et al., 2010; Carpes, Rossato, Faria & Mota, 2007; Rocheford et al., 2006; Sanderson, 1990), speed of movement (Daly et al., 1976; Sanderson, 1990; Smak et al., 1999), and level of fatigue (Hodges et al., 2011). Furthermore, the form of muscle contraction involved (e.g. concentric versus eccentric or isometric) may also effect asymmetry expression, as take-off /accelerational movements have been found to differ in asymmetry level compared to landing/decelerational movements (Wong et al., 2007). Other factors that haven't been examined may also play a role in the level of asymmetry expressed. Different balance requirements have not been examined with regards to functional asymmetry, such as single versus double-leg tasks or double-leg tasks with varying levels of stability. In-phase relative to out-of-phase activities have also not been examined. Respective examples would include that of a barbell squat (balance required) compared to a leg press or Smith machine (relatively little balance required); or that of a double-leg jump (in-phase, both legs used simultaneously) compared to cycling (out-of-phase, one leg used at a time). And finally technical requirements of a movement are also theorized to affect functional asymmetry.

Overall, there is a general lack of understanding regarding factors that affect the expression of LEFA during task performance. It is not well understood if or why LEFA in one task are expressed similarly in other tasks, if these asymmetries are detectable or similarly expressed with the SEBT, or if the asymmetries expressed within the different excursions of the SEBT are correlated with each other. Therefore, the goal of this investigation was to explore the relationships between GRFv asymmetries identified in commonly studied functional lower-extremity tasks of various speeds and effort levels (standing, squat, counter-movement jump (CMJ), and single-leg drop landings (SLDL). Other goals are to explore the relationship between LEFA in the aforementioned tasks with asymmetries identified in the SEBT, as well as the asymmetries within the different excursions of the SEBT compared to each other. The results of this study will serve to increase our understanding of the relationships between asymmetry in functional tasks, performance, and future methods that may be suitably used to identify injury risk.

Statement of Problem

Problem: The relationship of various LEFA identified using GRFv are not well understood, with little research currently existing relating these to each other.

Also, with the SEBT gaining popularity as part of functional movement assessment; a more clear understanding should be developed as to how asymmetries detected with this test relate to other LEFA; and furthermore how asymmetries detected with one excursion direction relate to asymmetries in the other directions.

Therefore, the purpose of this study was to examine the relationship between LEFA during four common tasks measured using GRFv, examine the SEBT in relations to these four tasks, and examine the relationship between asymmetries in different SEBT excursions.

Hypotheses

LEFA measured in one functional task will correlate to LEFA measured in other functional tasks, with a higher degree of asymmetry on one task relating to a higher degree of asymmetry in all other tests. Furthermore, asymmetries measured in all excursions of the SEBT will correlate with each other as well as all functional tasks with a higher degree of asymmetry in one excursion relating to a higher degree of asymmetry in all functional tasks and all other excursions.

CHAPTER II

LITERATURE REVIEW

Bilateral asymmetries are any side-to-side differences in the body. In the following review, the focus is functional asymmetry and is considered a difference in the body's kinetics or kinematics which significantly affects the way the body moves or performs during otherwise symmetric activities of daily living or sport. Kinetics include variables such as ground reaction forces and joint moments while kinematics include variables such as body position and motion. The sources of these functional asymmetries are most often said to relate to side-to-side differences in anatomic/anthropometric variables, strength, flexibility, or neural control differences; all of which may originate in a variety of ways. The term "strength" will be used to encompass muscular force production capabilities such as maximal force production, power, and ability to repeatedly generate force (endurance). The goal of this literature review is to discuss the evidence for LEFA in relation to its possible sources, origins, effects on performance and injury risk, and how different LEFA may relate to each other. Furthermore, the SEBT will be examined as a possible assessment tool regarding LEFA. Consideration will also be given to the relationship between this and other methods of assessing LEFA.

Existence of LEFA

While LEFA might be expected in an injured or physically disabled population, there is strong evidence that LEFA commonly exists, and may even be the norm in healthy people performing seemingly symmetric tasks. However, it is common in the field of rehabilitation and muscle testing to assume that one lower extremity is representative of the other. Based on this, measurements taken from one side should allow the contralateral side's kinetics and kinematics to be predicted in healthy limbs. Under this assumption, the contralateral limb is often used as a reference point for an injured limb during rehabilitation (Barber, Noyes, Mangine, McCloskey &Hartman, 1990; Ernst, Saliba, Diduch, Hurwitz & Ball, 2000; Petschnig, Baron & Albrecht, 1998). If LEFA exist in healthy individuals, this assumption may be questionable. It may also explain why rehabilitation may be considered successful when the injured limb has healed to within a certain percent of the healthy limb rather than matching it exactly.

In this review, the definition of asymmetry is any measurable deviation from perfect symmetry. Groups are considered asymmetric if differences in measurements are statistically different from side-to-side. Despite what is statistically significant, it is worth mentioning that some sources suggest that there may be a cut-off under which functional asymmetry is biologically/clinically significant. This cut-off is often set at a 15% bilateral difference, however, to my knowledge, only a relative few studies which have used functional testing to quantify asymmetry, exist to support the use of this specific number (Barber et. al., 1990; Noyes, Barber & Mangine, 1991). Both of these papers concentrated primarily on the study of functional limitations related to anterior cruciate ligament injury. Because of only a few sources seeming to exist supporting this number, and the relative lack of scope encompassed, it is possible that this 15% cut-off is arbitrary in some cases. Therefore, it may require adjustment based on what measure is being discussed. Friberg (1982) suggested that with anatomic asymmetries small differences may be negligible to one population while being significant to another. This may also be the case with LEFA, where an asymmetry may not relate to injury and performance in one particular task, sport or population, but might relate much more significantly to another. At this time it is unknown if there is one particular cut-off which can or should be used regarding LEFA, if this cut-off may change from one situation to the other or if individuals should just strive to be as symmetric as possible in all functional tasks.

Further confounding this issue is the fact that there are quite a few possible ways to quantify asymmetry. Aside from simply comparing asymmetries in absolute terms, another simple method is to compare each side as a percentage of the whole (Stephens et al., 2007; Hodges et al., 2011). For example someone one might be said to bear 48% on of their weight on one foot and 52% on the other, which might be reported as a 4% difference in weight-bearing (|48-52%|). This method may leave some confusion if misinterpreted, as it does not actually mean that the GRFv measured under one foot is necessarily 4% larger than the GRFv measured under another foot. For instance, someone weighing 75 N, in this case would load 36 N on one limb and 39 N on the other (the second limb actually having ~8.3% more load the first). Interpretation of the results of this method need to be careful.

The Symmetry Index (SI), as discussed by Sadeghi, Allard, Prince and Labelle (2000) is another way to quantify asymmetry. This is commonly quantified by the equation below. A score of 0 would equal perfect symmetry with asymmetry being quantified as numbers between 1 and -1.

$$SI = \frac{(X_{right} - X_{left})}{0.5*(X_{right} + X_{left})} \times 100\%$$

The disadvantage of this equation, however, is that asymmetries are reported against their average value. Therefore, if a large asymmetry is present, then the average value doesn't correctly reflect performance of either limb. Another symmetry index, shown below, attempts to address this shortcoming by using the maximum value as reference in the denominator (Vagenas & Hoshizaki, 1992).

$$SIa = \frac{(X_{right} - X_{left})}{Max(X_{right}, X_{left})} \times 100$$

This index also has limitations however, if one limb had an abnormally high value for the measure recorded. None of the proposed methods to quantify asymmetry are without limitation and must be considered when assessing the relevance of the asymmetry. Since several methods exists to assess asymmetries it can be difficult to compare one study to another at times.

It has been suggested for decades that LEFA existed in common tasks. Daly et al. (1976) showed that LEFA exist within a population of 20 male recreational cyclists. Within this study, they found that LEFA varied greatly on a day-to-day basis. Generally though, it has been found that LEFA are highly repeatable from day-to-day (Schot et al., 1994; Hodges et al., 2011), with LEFA in cycling seeming to be an exception to this. Sanderson (1990) and Smak and Hull (1999) also both showed functional asymmetries to be both common place in cyclists and variable in nature, with Sanderson studying a group of 45 cyclists of different levels, and Smak and Hull studying 11 competitive male cyclists.

In 1989 Herzog et al. showed that normal human gait was asymmetric in a number of components calculated from ground reaction forces and stance times. They reported that 0 of the 62 subjects studied exhibited perfect gait symmetry in all of the variables. In subsequent studies, a large range of different movement tasks have been examined, which also demonstrated LEFA to be a common occurrence in task performance. Vagenas et al. (1992) and Wong et al. (2007) both showed running to be asymmetrical in the majority of subjects. Vagenas et al. (1992) showed asymmetry to exist in 29 male distance runners, evaluating several kinematic parameters during touchdown and the entire phase of foot support during running. Wong et al. (2007) showed asymmetry to exist in plantar pressure during steady-state running in 15 male university soccer players.

Aside from asymmetries in walking, running and cycling, the existence of LEFA has been shown in a number of other tasks as well. Blaszczyck et al. (2000) and Rougier et al. (2009) both showed that quiet standing is commonly performed asymmetrically. Other tasks shown to exhibit LEFA include double-leg landing (Schot et al., 1994), hang power clean (Lake et al., 2010), lifting from the ground (Maines & Reiser, 2006), loaded squatting (Flanagan et al., 2007; Hodges et al., 2011; Lake et al., 2011; Newton et al., 2006) and various jumping and hopping tasks (Ball et al., 2010; Barber-Westin et al., 2005; Hickey et al., 2009; Miyaguchi, 2010; Lawson et al., 2006; Newton et al. 2006; Reiser et al. 2003; Schiltz et al. 2009; Stephens et al., 2007; Wong et al. 2007). Because of this, it is well supported that LEFA exist in a normal otherwise healthy population and can be demonstrated in a variety of ways.

Sources and Origins of LEFA

It is important to understand what sources (i.e. variables which directly cause an individual to function asymmetrically) actually cause LEFA and how these sources may originate. With knowledge of the underlying lineage from initial cause to eventual effect, the ability to intervene to avoid detrimental asymmetries may be much more achievable. The most commonly suggested sources (i.e. variables which directly cause LEFA) include side-to-side differences in anthropometry, strength, flexibility and neural control. Each source may have multiple potential origins (i.e. initial occurrences of variables eventually leading to one or more of the sources of LEFA). Also worth mentioning is the idea of fluctuating asymmetries, which are deviations from perfect symmetry that change over time due to random interactions with the environment (Trivers et al., 1999). These fluctuating asymmetries may be the cause of many of the LEFA that are observed. However, other origins also potentially exist, and in some cases may fit under the realm of these “random” environmental interactions.

Anthropometric Asymmetries

The majority of the population is not anatomically symmetrical in regards to the lower extremities, with differences in limb length being the most commonly observed anatomic asymmetry leading to LEFA. Blustein and D’Amico (1985) suggest that the population as a whole has on average a 1.1 cm limb length inequality (LLI), with the left limb typically being shorter than the right. Similarly, a review by Knutson (2005) concluded that, on average, people have a 0.52 cm LLI, 90% of the general population having some LLI, and the left leg is anatomically longer in 53 to 75% of the population. At this time, I am uncertain as to why one paper found the left leg to generally be longer, while the other found the opposite.

According to McCaw and Bates (1991), LLI can be broken into 3 categories; mild (<3cm), moderate ($\geq$ 3 but $\leq$ 6 cm) or severe (>6 cm). However, it appears that anatomic LLI is not clinically significant at a magnitude <2 cm (Knutson, 2005A). Despite this, White, Gilchrist and Wilk (2004) showed that a LLI greater than 1 cm resulted in asymmetric loading based on values calculated from GRFv. Furthermore, a study by Friberg (1982) examined 371 Finnish army conscripts and an additional 102 parachutists where a significant relationship between the magnitude of LLI and the incidence of stress fractures was found. The relationship was shown to be even stronger in the group of parachutists, who were at the time engaged in a 330 day heavy training period. Friberg (1982) concluded that a relatively small LLI, which in most may not be clinically significant, may have a greater relevance to prolonged and repetitive stresses (i.e. a small leg length discrepancy may only be significant under certain circumstances). LLI has also been suggested to relate to performance (Delacerda & McCrory, 1981) as well as injury by others (Knutson, 2005; Kujala, Friberg, Aalto, Kvist & Osterman, 1987).

Multiple possible origins also exist for these differences in anthropometry. A review by Blustein and D'Amico (1985) suggests that the way that the fetus sits in the womb may have an effect. Because, according to them, most subjects have a shorter left leg, it has been suggested that the common in utero position, may subject the left leg to different stresses than the right leg during fetal development. A paper by Dunn (1976) states that the left side of the human fetus is commonly pressed against the hard vertebrae of the mother while the right side is not. Additionally, 67% of third trimester fetuses have the left leg crossed over the right leg, subjecting the left hip, knee and epiphyseal growth plates to different stresses than the contralateral side.

After birth, repetitive asymmetric task performance over the course of one's life has also been suggested to have an anatomic effect. Singh (1970) showed that the majority of people put a greater strain on the left lower extremity in walking and weight bearing and that bone weight differed between legs. This research showed that lower extremity bone development was asymmetrical and suggested that by measuring the weight of the femur alone, one can indicate which lower extremity has or had the greater amount of use, or which was the preferred limb.

Neural Control or Learned Movement Patterns

Differences in neural control and how the body may learn to perform a task is also a potential source of functional asymmetry. It is possible that asymmetries may partially stem from the way the body learns to perform a certain task, thus potentially causing LEFA to exist even if other underlying differences have been equalized. Bilateral asymmetries in neural control have possible origins in both the laterality of neural development and in repetitive asymmetric task performance. These two origins are often intertwined and may be inseparable. As the term is used here, the laterality of neural development relates to the tendency of individuals to develop preferred sides of the body for certain tasks. One usually develops a leg for precision oriented tasks such as kicking a ball, while the other leg generally becomes a more stable, potentially stronger stance leg

(Myaguchi & Demura, 2010; Gabbard & Hart, 1996). The precision oriented limb which is usually the preferred kicking leg (KL) is frequently termed the “dominant” leg, while the contralateral limb, the non-preferred kicking leg (NKL) is frequently termed the non-dominant limb. However it is important to note that leg dominance is often defined differently based on the author and publication, not always staying with KL and NKL to define dominance.

Another potential origin for LEFA is the repetitive performance of a task in an asymmetric manner. There are some repetitive tasks which may have little to do with limb preference. For example, repetitiveness caused by entering and exiting a car from the driver’s seat (e.g. such as in police work) could potentially develop a difference in development of one leg or side of the back. However, this would have more to do with car manufacturing and traffic laws and less to do one’s preferred side. Many other tasks do strongly relate to which side of the body is preferred. Kicking primarily with the right leg for example, may be initiated from neural laterality, and may lead to asymmetric development of that limb. This would support learned neural patterns that develop one side differently than the other. Furthermore, it is frequently unclear whether asymmetrical training caused an asymmetrical function or whether the asymmetrical training was primarily a result of preexisting asymmetry or the laterality of neural development. Although limb dominance relates to the development of LEFA, and LEFA may lead to injury, it is thought that limb dominance alone is not a reliable way to predict injury. This means that one cannot tell which limb will be injured or how it will be injured based only on knowledge of which is the preferred side during a functional task (Matava, Freehill, Grutzner, & Shannon, 2002).

This potential neural development difference or possible repetitive asymmetric training has been demonstrated by McLean and Tumilty (1993) which showed left to right asymmetries in soccer kicking. The study used 12 elite junior soccer players, measuring a variety of factors on kicking mechanics. The group showed better velocity (79 km/h vs. 66 km/h) and accuracy (66.6% accuracy compared to 33.3%) in a "drive kick" with the right leg (preferred kicking leg), but no differences in performance of a chip shot. This difference may however, have a stronger relationship to strength, which will be discussed later.

A later study by Dorge et al. (2002) also studied soccer kick mechanics and demonstrated differences between the preferred and non-preferred leg in ball velocity in the soccer kick using a population of skilled soccer players (n=7). They showed that the linear speed of the foot was greater with the preferred leg, and that ball collision mechanics were such that there was a higher coefficient of restitution with the preferred kicking foot. However, it was shown that there was no significant difference between muscle moments or rate of force development between legs, making the difference in kicking performance likely due to a better inter-segmental motion pattern from one side to the other. This suggests a neural or coordination difference from preferred side to non-preferred side, instead of a potential muscular strength or power difference.

Ball and Scurr (2009) showed how repetitive asymmetric task performance may occur in a seemingly symmetric task like a drop jump. Subjects were tested using a drop jump of 0.4 meter height, and found that there was no significant difference in duration of foot contact and peak resultant force between legs. However, there was a significant side-to-side differences in activation of the triceps surae muscles, which tended to equalize after 40ms into the landing/propulsion phase. They also showed that there were differences in when foot contact occurred and stressed that although slight, this difference in loading may relate to further development of asymmetry. It is admitted by the author however, that the way that subjects stepped off the platform to engage in the drop jump, may have been the determining factor in difference in when each foot contacted. Nonetheless, this may state the importance of how asymmetry may develop in a task that initially appears symmetric. It also states the possible long term importance of taking smaller factors into account, such as which leg steps first in a task, which may make for asymmetrical training. Ball et al. (2010) also reported on drop jumps and showed that at drop heights of 20cm and 40cm foot contact time differed from left to right sides, but at a height of 60cm this was no longer the case. The authors suggest that the subject had more time to equalize the feet so that ground contact time would be the same, regardless of which foot stepped from the platform first. However, it is also possible that intensity of effort may play a role in the expression LEFA in this case.

In addition, a study by Lawson et al. (2006) looked at the bilateral differences in step-close jumps in a group of 24 recreationally competitive volleyball players. They found a number of variables to be different in the lead leg compared to the trail leg of the step-close jump, which might typically be used in sport-specific jumping tasks. The bilateral differences included minimum hip and ankle angle, average GRFv, maximum and average hip moments, maximum and average knee moments, and average ankle moment and maximum power. Because of the asymmetrical training stimulus involved in the step-close jump, the authors suggested that training should involve alternating between which foot makes contact or steps first, in order to reduce unwanted asymmetry.

Since both lead leg conditions were not examined, the bilateral difference in this study may be due to foot preference, repetitive asymmetrical training related to volleyball competition, or both.

Simon & Ferris (2008) further demonstrated the role of neural control in functional asymmetry, with a study in which subjects completed maximal isometric leg presses on a leg press machine. Each subject underwent a pre-test where isometric maximal voluntary contractions were performed and kept in the study only if they demonstrated at least a 10% side-to-side asymmetry in force production. Following the pre-test the subjects which weren't excluded performed isometric repetitions at various force levels where they were asked to match a force produced by one leg, with the other leg. Instead of matching the amount of force between legs, the subjects more often matched the percentage of maximal voluntary contraction from one leg to the other, even at submaximal levels. This suggests that production of force asymmetry during a leg press tasks appears to be related more to neural factors and not to the mechanical force producing capabilities of the muscles. However, it is worth noting that force production differences greater than 10% are not the majority, so it is unclear if this relationship exists with those that are more symmetric.

Muscular Force Production (includes Strength, Power and Endurance)

Another potential source of LEFA is bilateral differences in strength, in both magnitude (strength) and rate (power) of force production. Furthermore, the ability to repeatedly generate force (endurance or fatigability) may also be a factor. It is important to note however, that muscular strength, power and endurance asymmetries are often difficult to entirely differentiate from neural control asymmetries, being that neural function, along with structure and cross-sectional area of the muscle, is one of the contributing factors to muscular force production.

There are several studies which have looked at lower extremity asymmetries in strength; however most have been performed without comparing them directly to functional differences. Asymmetry in strength between sides has been shown to be a possible indicator of injuries including ankle injury (Baumhauer, Alosa, Renstrom, Trevino & Beynnon, 1995), hamstring muscle strains (Croisier, Forthomme, Namurois, Vanderthommem & Crielaard, 2002; Croisier, Reveillon, Ferret, Cotte, Genty et al., 2003; Yamamoto, 1993), iliotibial band syndrome (Fredericson, Cookingham, Chaudhari, Dowdell, Oestreicher & Sahrmann, 2000), adductor muscle strains (Tyler, Nicholas, Campbell & McHugh, 2001), general knee joint injury (Grace, Sweetser, Nelson, Ydens & Skipper, 1984), and general lower extremity injuries (Knapik et al., 1991). It is usually assumed that these side-to-side strength differences also might cause a difference in function (i.e. creating LEFA), which is what then leads to the associated injuries. However, it is difficult to tell how these differences in strength affect the function of the body to increase injury risk, and what role they have in creating LEFA. Only a few studies have looked at how asymmetries in muscular force development change the performance of functional tasks. And even in these few examples, it is often unclear as to what factors were actually causing the changes in function.

Newton et al. (2006) examined 14 Division I softball players to study the relationship between various unilateral and bilateral closed chain tests and isokinetic dynamometry (knee flexion and knee extension both at $60°s^{-1}$ and $240°s^{-1}$). They found that significant relationships existed in asymmetries between squat peak force and isokinetic knee flexion average peak torque at 60°s^{-1} (r=0.674); as well as squat average force and isokinetic knee flexion average peak torque at 60°s^{-1} (r=0.618). Isokinetic knee extension trended toward a relationship with asymmetry in the squat, but failed to gain significance. Another significant relationship was isokinetic knee flexion at 240°s^{-1} and two legged countermovement jump (r=0.768) with isokinetic knee extension at the same speed having a slightly weaker relationship which did not gain significance.

Schiltz et al. (2009) studied a population of 15 professional basketball players, 10 junior basketball players and 20 healthy men, in relation to lower extremity strength asymmetries in different training levels. Tests used included a single-leg drop jump, 10 second repeated 1 legged hop and isokinetic strength measures (knee flexion and knee extension at 60ºs^{-1} and 240 ºs^{-1}; knee flexors eccentric at 30 ºs^{-1} and 120 ºs^{-1}). Interestingly, the professionals had a significant bilateral difference of 12±7.9% in comparison to no significant difference in junior players (-1.4±7.5%) and healthy controls (-4.1±11.6) in the single-leg drop jump test ($p<0.0001$). The professional group also had a 10 second repeated 1 legged hop asymmetry of 10.5±12.4% compared to 3.4±7.1% of junior players and 3.2±15.6% of healthy controls. Although the hop test did not gain significance (p=0.24), all isokinetic strength measures also showed a higher bilateral difference in professional players than the other 2 groups. Only the knee flexion at 60ºs^{-1} and eccentric knee flexion at 30ºs^{-1} showed significance (p=0.04 and p=0.03, relatively), with the knee extension at 60ºs^{-1} trending toward significance (p=0.06). Scores for professional players, junior players and healthy controls, respectively, were 8.2±11.3%, 7.4±11.3%, -2.6±14.9% (knee flexion at 60ºs^{-1}); 8.9±8.8%, -4.3±12.0%, 1.8±13.3% (eccentric knee flexion at 30ºs^{-1}), and 11.3±17.4%, 3.6±8.8%, and -0.2±10.8% (knee extension at 60ºs^{-1}). The professional players were more asymmetric in all measures (both functional and isokinetic), however these measures were not directly tested for correlation. Therefore, it is not clear based on this study what the specific relationship between strength and functional asymmetry might be.

Hewett et al. (1996) examined a population of 11 female high school volleyball players and 9 healthy males in a study involving plyometric training and impact forces. They used a 6-week jump and landing training program (2 hours, 3 days/week) with an emphasis on proper posture, soft landing, and avoiding excessive side-to-side movement, which included 15 exercises of different types and intensity. After this a basic stretching and resistance training program (1 set of 12-15 repetitions) was performed. Pre-test and post-test were performed regarding knee flexion to knee extension peak torque ratio, measured with a dynamometer (both isometric and isokinetic at 360°s^{-1}). It was found that knee flexion isokinetic peak torque and knee flexion to knee extension peak torque ratio all increased more in the non-dominant side (both variables increasing 26%) than on the dominant side (both variables increasing 13%), with bilateral differences becoming less pronounced through training. However, isokinetic average power of the knee flexors increased 44% on the dominant side and 21% on the non-dominant side, with bilateral differences becoming, in contrast, more pronounced through training. This study does not make direct measures of how bilateral differences in functional tasks relate to bilateral differences in dynamometry, but would suggest that something in the functional training intervention was having an effect on bilateral asymmetry in regards to specific muscle testing. With many confounders existing in this study, it is not clear what was truly causing the changes in asymmetry measured. The intervention involved multiple types of strength training and flexibility training, as well as an emphasis on posture and mitigating excess side-to-side movement during jump performance. Therefore one might suggest that strength has a strong role here, but it is left unclear as to whether bilateral asymmetries in strength are truly related to LEFA.

A study by Jacobs, Uhl, Seeley, Sterling, & Goodrich (2005) is important to note, as it brings up a concept regarding the difference between strength and endurance measures in asymmetry testing. A dynamometer was used in order to measure both peak torque and fatigability of the hip abductors. Fatigability was measured using a submaximal contraction (requiring the subject to maintain a 50% maximal voluntary contraction for 30 seconds) while measuring the electromyographic power spectrum for the gluteus medius. It was found that in these measures, asymmetry in strength and asymmetry in fatigability were independent, with the peak torque and muscle fatigability not being significantly correlated (r= -0.07, p=0.53). Hip abduction peak torque of the (KL) was significantly larger than that of the (NKL), but leg fatigability between limbs was not significantly different. This suggests that differentiating between muscle strength and endurance measures may be important when discussing asymmetry. This may have implications in regards to fatigue's effect on LEFA. This measure may help better predict functional asymmetry within or between sets of an exercise, or over the course of the day.

Functional asymmetries in strength may have origins in the laterality of neural development and asymmetric task performance. It is not clear why some groups of athletes, as discussed above, had various levels of strength asymmetry. It is certainly possible and potentially even likely that these strength asymmetries relate to repetitive asymmetric movements performed in their sport. However, it is difficult to make this conclusion based on the information presented.

This difference in leg preference or in repetitive asymmetric task performance might be inferred through a study like Rahnama, Lees and Bambaecichi (2005) which found significant side-to-side strength differences between the KL and NKL in soccer players. This study showed that the hamstring eccentric strength to quadriceps concentric strength ratio was significantly different from side-to-side, and that the knee flexors of the KL tended to be weaker than the NKL. Also they found, that of the 41 elite soccer players studied, 68% had a 10% or greater imbalance on one or both muscle groups (i.e. quadriceps and/or hamstring strength).

McLean et al. (1993), as discussed above, also showed left to right asymmetries in soccer kicking. The 12 elite junior soccer players being examined were measured for isokinetic knee extension and knee flexion strength at 3 different speeds. The group showed significant strength dominance at all dynamometer speeds on the right leg (along with the better velocity and accuracy mentioned above in the “drive kick” with the right leg). However, at an elite level of play in soccer, it would generally be the intent to be skilled with both feet, bringing into question how repetitive asymmetric task performance relates to these differences in strength, power or endurance.

Flexibility

Flexibility is another category of sources which might be suggested to cause functional asymmetry. Although there are several studies relating side-to-side differences in flexibility to injury, to my knowledge, there are no studies correlating flexibility with LEFA.

Of the studies that measured lower extremity flexibility asymmetry in relation to injury, Agre, and Baxter (1987) found that subjects with a side-to-side hip flexion range of motion difference of 6 degrees were more prone to knee and lower back injury than those that didn't show this difference. Cibulka and Threlkeld-Watkins (2005) in a case study showed that a patient with unilateral patellofemoral syndrome and pronounced asymmetries in hip external rotation and hip internal rotation range of motion, reduced symptoms through a basic stretching and strengthening program which reduced bilateral asymmetry. Knapik et al. (1991) found that if the right hip extensors had greater than a 15% higher flexibility than the left, a subject was 2.6 times more prone to lower extremity injury, and 1.7 times more prone to these same injuries if this 15% higher flexibility occurred on the left side. Soderman, Alfredson, Pietila & Werner (2001) showed that bilateral asymmetries in both ankle dorsiflexion and hamstring flexibility significantly related to lower extremity overuse injuries.

However, because none of the existing literature made a direct comparison from flexibility asymmetries to LEFA, it is not clear how one relates to the other. Therefore, it is impossible at this time to make sound conclusions about flexibility as a source of functional asymmetry. Currently it may just be considered a suspect in the underlying sources of LEFA. Furthermore, it is not clear where side-to-side differences in flexibility originate. It is likely that these bilateral differences in flexibility, like those of strength, may relate to repetitive asymmetric training, previous or current injury, or anthropometric differences. However, to my knowledge there is no direct research into this subject.

Injury as an Origin of Functional Asymmetry

Past or current injury state may be an origin for any of the possible functional LEFA sources. This section will cover how injury status has been associated with functional asymmetry, but it is important to note that the lineage has not been directly established from LEFA expression, to specific source (muscular force production capabilities, flexibility, neural control), to injury as an origin. Thus based on the studies presented below, it is difficult to put injury status as an origin point into a specific category of sources. Furthermore, it is also possible that injury may cause repetitive asymmetrical task performance, as an injured subject favors one side of the body due to pain or loss of function. That being said, injuries have been shown to have a relationship to LEFA, even if it is unclear how direct that relationship is. A strong body of evidence relates LEFA to Anterior Cruciate Ligament (ACL) injury, with some evidence supporting the association with other types of injuries as well.

A study by Neitzel et al. (2002) studied a post-ACL reconstruction population, showing that during several squat conditions (unloaded and loaded to different levels and at 3 different knee angles) the post reconstruction group asymmetrically loaded the uninjured leg to a greater extent than healthy controls. This increased magnitude of asymmetry lasted about 12-15 months post-surgery at which point asymmetry generally returned to levels comparable to controls. Paterno et al. (2007) showed that these asymmetries may exist for even longer in landing and takeoff. Paterno et al. (2007) examined a group of post-ACL reconstruction women which were on average 27±13 months post-surgery. Those that had undergone surgery demonstrated increased GRFv and loading rate on the non-surgically repaired leg when compared to the post-surgical limb and when compared to the limbs of non-ACL injured controls.

ACL deficient subjects were also shown to express LEFA differently from healthy controls during walking in a study by Ferber, Osternig, Woollacott, Wasielewsk & Lee (2003). ACL deficient subjects demonstrated asymmetrical knee joint moment and power patterns, while being symmetrical at the hip joint in these same measures. This was shown prior to and for 3 months following reconstructive surgery, whereas controls demonstrated symmetrical knee and asymmetrical hip in these same parameters. This suggests that certain asymmetries (i.e. asymmetries at some joints or in some areas) may be normal or acceptable, whereas other asymmetries indicate a functional deficiency.

This idea seems to be supported by Salem et al. (2003) in a small 8 subject study using submaximal squats in testing asymmetry in post ACL reconstruction subjects. This study showed that the uninjured limb tended to equally distribute muscular effort between the knee and the hip extensors, whereas the injured limb tended to show increased muscular effort at the hip and reduced effort at the knee. This again suggests that injury may not just change the magnitude of an asymmetry, but also that it may cause asymmetry to be expressed in different ways. Salem et al. (2003) also looked at asymmetry in post ACL reconstruction (post-surgery 30$\pm$12 weeks) subjects in a small 8 subject study using submaximal squats. They found that peak knee extensor moment was 25.5% greater in the non-injured limb in comparison to the ACL reconstructed limb.

Including other types of unilateral injury, Rocheford et al. (2006) examined a group of firefighters who previously had various types of unilateral injury to either the upper or lower body. Using isometric lifting and quiet standing, they showed that the overall magnitude of asymmetry was no different from a previous unilaterally injured group to controls. However, there was a small but significant difference between groups in how asymmetry was demonstrated. The previous unilateral injury subjects were significantly more asymmetric while standing compared to lifting (while the controls were not) and control subjects produced significantly greater forces under their non-kicking limb while lifting, while previous unilateral injury subjects did not. However, both differences were small being on the order of 1-2%.

Schiltz et al. (2009) showed that professional basketball players with diagnosable previous knee injuries were significantly more asymmetric (even after being cleared for return to sport) than controls which included pro-basketball players, recreational basketball players and non-basketball healthy males. These asymmetries were of greater magnitude in knee flexor and extensor concentric peak torque and two unilateral jumping tasks. They were above 10% difference in isokinetic knee flexor and extensor tests and above 15% difference in single-leg hopping tasks (both considered a clinically significant amount of asymmetry). This difference was not shown in the other non-previous knee injury subjects.

LEFA has also been shown to relate to injury involving the lower back as shown in Childs et al. (2003). This study concluded that subjects with low back pain were more asymmetric in regards to side-to-side weight bearing, being more than double that found in healthy control subjects. This study however did not normalize to age, with the low back pain subjects being on average 7.9 years older than the controls, therefore it is unknown if the observed weight-bearing asymmetry is the effect of age, or actually related to the observed back pain.

Relationship between LEFA and Future Injury

As reviewed above, several studies relate general lower extremity asymmetry to injury risk or LEFA to past injury. Although somewhat limited, there have also been a few studies which relate LEFA to future injury risk.

Herring et al. (1993) examined 13 male and 13 female collegiate competitive cross country runners and had three “limb dominance” tests including a ball kicking accuracy test, balance test and 1-leg hopping test. Each test was ranked based on how one limb performed compared to the other. Although, those who were identified as having a limb dominance asymmetry in any one of the tests had an injury rate of 60% (compared to 35.7% in who were not significantly asymmetrical), the findings were not able to gain statistical significance. The authors suggest that having a small sample size is likely the reason for not obtaining significance.

Shambaugh et al. (1991) studied a population of 45 recreational basketball players, measuring a variety of lower extremity anatomical measures, standing weight-bearing asymmetry, and injury data collected over a 4 month playing season. They found that using weight-bearing asymmetry, left or right Q-angle and any one of the other variables tested, a logistic regression equation could correctly predict injury with 85% or higher accuracy. Injury prediction however was not specific, and their methods couldn’t determine to what part of the body the injury would occur.

Paterno et al. (2010) also used a double-leg drop jump to predict second ACL injuries (in either leg) after initial reconstruction and return to sport. The population included 56 individuals who participated in cutting and pivoting sports. A variety of motion capture data was examined, and it was found that side-to-side differences in sagittal plane knee moment at initial contact were significantly different between those who obtained a second ACL injury over the next year, and those that did not. The second injury group demonstrated a 4.1 fold greater asymmetry in internal knee extensor moment at initial contact when compared with those who did not suffer additional ACL injury. Post hoc analysis found that the internal knee extensor moment of the uninvolved limb immediately upon contact in the second ACL injury group was significantly lower than the involved limb, and both limbs in the non-second-injury group. Participants who demonstrated asymmetry in this variable were over 3 times as likely to incur a second ACL injury.

Relationship between LEFA and Performance

Performance is another measure in which asymmetry has been suggested to relate, but currently the research involving this relationship is relatively small in scope. Several studies have been performed regarding asymmetry in a generalized sense in relation to performance in running and other sports. For instance, Manning and Pickup (1997) looked at symmetry and performance in middle distance runners. The study examined symmetry in ear, nostril width, wrist width and 2nd to 5th digit length. Symmetric individuals were determined to have better run performance times than the asymmetric individuals with the best performance predictors being symmetry in nostril width and ear length. However, this study tells nothing of how these asymmetries actually cause a difference in performance, possibly suggesting that these measures may somehow correlate with other more meaningful attributes.

Tomkinson, Popovic, and Martin (2003) studied basketball and soccer players, both at the elite and sub-elite level of play, with the hypothesis that asymmetries would vary between sports, and that players at a higher level of competition may exhibit higher symmetry. Asymmetries studied were a variety of anthropometric measures, involving 9 skinfolds, 8 body segment girths and 11 different bone lengths. It was found that no significant differences existed between anthropometric symmetry between the two levels of play or between each sport. This calls into question the role of anthropometric asymmetry in sport and level of play.

Cavanagh et al. (1977) examined a group of 22 runners classified into elite runners (n=14) and good runners (n=8), based on race performance times. They used a variety of kinematic and kinetic variables to measure side-to-side differences in the subject population. It was found that symmetry in the average rise in center of gravity per stride from one leg to the other, tended to be higher in elite runners and more asymmetrical in good runners.

A study by Yoshioka, Nagano, Hay, & Fukashiro (2010) used a computer simulation model examining jumping performance with either a zero or 10% overall strength asymmetry from one limb to the other. They showed minimal differences in jump height between the two situations, with the stronger leg compensating for the weak. The authors do state that a bilateral strength asymmetry greater than 20% may have a significance impact on jump height.

Correlations in Task-to-Task Expression of LEFA

It has been established that LEFAs can be used as predictors of injury, identifiers of deficits related to past injury and potentially to relate to how one may perform in some activities. However, as shown above, LEFA can be measured in a large variety of different ways. One thing that is unclear is how these functional movements relate to each other. It is useful to understand the relationship of these commonly studied functional tasks to each other, in order to have a broader understanding of the implications of LEFA when it is identified. Differences in muscle activation, joint angles, balance requirements, effort levels and speeds of movement are just some possible differences from one task to another. Therefore one functional task may or may not strongly relate to another in regards to asymmetry.

One variable that might affect LEFA is intensity. As discussed above, Ball et al. 2010 used drop jumps of various height (20cm, 40cm, and 60 cm) and found that at 60 cm there was no longer an asymmetry in time of ground contact and triceps surae activation, which was found at the lower heights. However, as stated above, it is possible that this is related to asymmetry in lower drop heights being affected by which limb stepped from the platform first. Carpes et al. (2007) examined 6 sub-elite competitive cyclists and found that an increase on crank torque output and exercise intensity elicited a reduction in pedaling asymmetry. However, Sanderson (1990) studied both power output and cadence changes in 45 cyclists with a variety of experience. They found that work asymmetry increased with increases in cadence at lower power output, but at high power output asymmetry first decreased and then increased with changes in cadence. Also mentioned above regarding intensity was Rocheford et al. (2006). As stated above, the previous unilateral injury subjects were significantly more asymmetric while standing compared to lifting (while the controls were not) and control subjects produced significantly greater forces under their non-kicking limb while lifting, while previous unilateral injury subjects did not. Although this might relate a lower intensity task (standing) to a higher intensity task (lifting) it is difficult to draw conclusions from this study regarding intensity's effect on LEFA.

Lake et al. (2010) and Lake et al. (2011) used the hang power clean and weighted back squat, respectively, and noted that progressive increases in loading during these exercises didn't seem to affect left to right side differences. Also, Lake et al. (2010), using the hang power clean suggests that the technical requirements of the hang power clean may have caused their study population to appear more symmetric than similar populations studied using the back squat. However, because this was not directly studied in their examination, Lake et al. (2010) does admit that more research is needed to clarify this.

Another possible variable includes speed of movement. Aside from Sanderson (1990) which is mentioned above, Daly et al. (1976) also showed that pedal speeds changed asymmetries in cycling, with no clear directional trend being apparent. Smak et al. (1999) also concluded that pedaling asymmetry was highly variable among subjects when considering pedaling rate and that individual subjects may exhibit asymmetries differently. Other than cycling, little has been done regarding LEFA and the effects of speed of movement. Gilliam, Sady, Freedson and Villanacci (1979) measured high school football players in isokinetic flexion and extension at both 30º/sec and 180º/sec, and found that the right to left flexion ratio was 102% at the slower speed and 103% at the faster speed. The right to left extension ratio was 105% and 103% at slow and fast speeds, respectively. However, these were not found to be significantly different and this study used isokinetic testing instead of functional tests, making it uncertain as to how these findings correlate to LEFA.

Some other variables have also had a mild amount of research regarding the effects on asymmetry. Level of fatigue in LEFA was examined by Hodges et al. (2011) using GRFv collected during weighted squats. They found that although no difference in asymmetry occurred with fatigue when the entire subject pool was examined together, average asymmetry dropped from the beginning to the end of the set in those that were above a 1.7% level of asymmetry. Also, Wong et al. (2007) notes that in the 4 functional movements studied, subjects tended to put higher plantar pressure in the KL during take-off and the NKL during landing, which might suggest a relationship between asymmetry and type of muscle contraction (concentric versus eccentric).

There are also potential factors which might affect the functional expression of asymmetry, which haven't yet been examined. Balance requirements have not been examined with regards to LEFA, such as single versus double-leg tasks or double-leg tasks with varying levels of stability. In-phase (i.e. both legs used simultaneously) relative to out-of-phase (i.e. legs alternating between use) activities have also not been examined.

Although it might be assumed that asymmetry in one functional task will likely relate to asymmetry in another functional task, only a small number of studies have attempted to correlate functional asymmetries with each other. One of the few studies to directly correlate asymmetries from one functional task to another was Newton et al.

(2006). They studied squatting with 80% of 1 repetition maximum, bilateral CMJ, unilateral CMJ, and a 5 hop test involving a maximal distance single-leg hop followed by consecutive vertical hops. The only significant correlation found between these functional tasks was that the squat peak force asymmetry and bilateral CMJ peak force had a moderately high correlation (r=0.734). All other asymmetries in functional tasks showed no significance, usually having a very low or even slightly negative correlation. Interestingly, the peak forces in the bilateral and unilateral countermovement jumps had a r=-0.616 correlation, but not being quite enough to gain significance.

Stephens et al. (2007) also looked at asymmetry in single-leg CMJ and double-leg CMJ in comparison to each other. They examined 13 men and 12 women with competitive volleyball experience. All subjects had one leg that they could jump significantly higher with, and asymmetries were found in maximum GRFv and ankle joint power during the single-leg CMJ in men. No significant differences in the women were found for the single-leg CMJ. During the double-leg CMJ the only asymmetries found were in the average GRFv during propulsion. Through analysis Stephens et al. (2007) determined that there was no evidence that the difference existing in the single-leg CMJ also existed in the double-leg CMJ. These findings would agree with the previous findings of Newton et al. (2006) in finding no significant relationship between asymmetry in these two tasks.

Rocheford et al. (2006) used quiet standing and isometric lifting to explore asymmetries in 49 firefighters, as mentioned above. They found that about 64% of the subjects had greater loads on the same side while standing and static lifting, and that those who had a previous unilateral injury were more asymmetric while standing when compared to lifting, while the control group was not. However, a direct correlation was not discussed between asymmetry in the two tasks, and it is not clear how this study relates to the general population or those in an uninjured population. Also, it is admitted by the authors that the setup of the lifting apparatus didn't allow a high degree of asymmetry and thus may have affected expression of the magnitude of asymmetry.

Based on this evidence, the relationship between many of the commonly used LEFA screening methods is relatively unknown and deserves further investigation. With further understanding of this correlation, it may be possible to refine screening methods in order to make broader statements regarding LEFA implications toward injury or performance.

Screening for LEFA

One of the more common variables that has been used to identify LEFA is measurement of side-to-side differences in GRFv. This has been used to identify asymmetries in tasks discussed above such as standing (Blaszczyck et al., 2000; Rougier et al., 2007), squatting (Flanagan et al., 2007; Hodges et al., 2011; Newton et al., 2006), jumping (Hickey et al., 2009; Lawson et al., 2006; Newton et al., 2006; Stephens, , Lawson, & Reiser, 2005; Stephens et al., 2007; Wong et al., 2007), and landing (Schot et al., 1994). And, although slightly different apparatus were used to measure force at the foot due to non-ground based movement, similar methods have also been used to identify LEFA during cycling (Sanderson, 1990; Smak et al., 1999)

Although GRFv have been used successfully in a number of studies to identify LEFA, there are some limitations in measuring only GRFv. Although functional asymmetries may be identified, it is not clear through GRFv data collection alone where the specific location of the asymmetry is and how this asymmetry leads to altered joint loading and/or motion. Furthermore, restricting ground reaction force data to the vertical direction alone poses more limitations. While the vertical component is typically the greatest in magnitude of the directional force components, it may not capture all asymmetries being expressed. For instance, Maines and Reiser (2005) did study ground reaction forces in the anterior/posterior direction as well as the medial/lateral direction, finding that 7.1% and 96.4%, respectively, of 28 subjects studied were asymmetrical over the course of a lift, in this case involving lifting a milk crate from the floor. This alone however, does not express the specific sources of asymmetry, but does potentially allow further insight into expression of LEFA.

Another consideration is that if repetitions of an exercise are analyzed as a whole repetition, taking an average GRFv, it may not capture when within the movement an asymmetry is expressed. For instance, one may be weight bearing heavily to one side at one point in a movement and heavily to the other side at a different point, but on average it may appear that the movement is relatively symmetrical. This was another variable examined in Maines and Reiser (2005) where the lift was broken into phases and analyzed for asymmetry as a whole repetition and in individual phases. They found that more subjects were asymmetric in the vertical and medial/lateral direction over the entire lift rather than in any particular phase, which they suggest means that people tend to shift back and forth over the course of a repetition.

Additionally, other variables such as muscle activation, joint moments, or joint angles may be asymmetric from one side to the other, without creating a ground reaction force differential. Therefore, it should always be taken into consideration when using GRFv or any ground reaction forces alone, that some asymmetries may not be captured even when highly noticeable by other means. However, GRFv is still useful in serving as a gross indicator of the presence of LEFA, and have been used in many cases.

Other Tests that Screen for Functional Asymmetry

Aside from using GRFv or any of the various methods discussed in the review above, functional asymmetry screening tests that have been shown to be valid and reliable are relatively limited in number. Furthermore, many of these tests often concentrate on differentiating between injured and uninjured lower extremities, or tracking an individual's readiness for return to sport. Examples of these include the triple jump test, stairs hopple test, and the side jump test described by Risberg and Ekeland (1994) for assessing function of ACL injured knees post-surgery.

However, although tests are available for analyzing function for post-injury rehabilitation progress, there are much less in the way of tests which may evaluate a subject not only post-injury, but also potentially evaluate an individual's risk for future injury and serve as a possible indicator of performance. One test that does claim to screen for injury risk (Myer, Brent, Ford & Hewett, 2011) and post-injury rehabilitation progress (Myer, Paterno, Ford, Quatman & Hewett, 2006) is the tuck jump assessment. This involves performance of a repeated tuck jump maneuver in which criteria for performance and symmetry are evaluated for movement pattern trends which may relate to increased injury or re-injury risk. However, as of yet, this assessment tool is still under development and in need of further validation.

Although there may be a limited number of options, many of which are relatively new in development, one test that has had a comparatively robust amount of research is the SEBT. As discussed below, the SEBT has been shown to fit the criteria of being reliable, screening for injury risk, differentiating between injured and non-injured lower extremities, and being a measure of dynamic balance. Because of its proven potential for assessing lower extremity asymmetry, it stands as a screening tool that might be able to serve similar function to other methods, such as using GRFv or motion capture collection. If this is shown to be the case, it may even allow replacement of more expensive or less convenient means, while still being effective in assessment of LEFA.

The Star Excursion Balance Test (SEBT)

Background and Development

The SEBT was introduced in a publication by Gary Gray in 1995 as a possible tool to assess dynamic postural control and a screen for balance decrements. The SEBT can be used as a measure of overall dynamic balance, as well as being able to assess and compare side-to-side differences. This test originally used strips of tape placed on the floor at 45 degrees to each other, creating eight directional reaches (Figure 2.1). These excursion directions, moving clockwise around the star, have been termed Anterior (Ant), Anterolateral (AntLat), Lateral (Lat), Posterolateral (PostLat), Posterior (Post), Posteromedial (PostMed), Medial (Med), and Anteromedial (AntMed). The SEBT is scored by attempting to make light contact as far as possible onto each measuring tape, while maintaining a unipedal stance and not allowing the stance foot to move from the established footprint, for the entire trial. Small variations to this, such as a maintaining hands on hips position or not allowing the heel to rise from the ground, have been described. Plisky, Gorman, Butler, Kiesel, Underwood and Elkins (2009) reported on 19 different publications using the SEBT and different variations of the SEBT, presenting in a table methods used in each study. Based on this table, it is apparent that many different versions of the SEBT exist, and Plisky et al. (2009) emphasized the need to further standardize this test in order to be more widely used and accepted as a screening tool.

Several studies have suggested that a redundancy exists in the eight directional reach protocol, and thus a reduction in the number of directional reaches may be appropriate. It was found by Hertel et al. (2006) that the AntMed, Med and PostMed excursions were best able to differentiate between ankles with chronic ankle instability (CAI) and those without, and suggested that the PostMed direction best represented the functional demands of the SEBT. Support for reducing the number of excursion directions was also presented by Robinson and Gribble (2008b), who found that significant functional factors (primarily hip and knee flexion) accounted for the majority of difference in reach distances, having significant overlap between each direction.

Many studies have followed up on the original suggestion of reducing the number of individual reach directions and several subsequent studies reduced this number to just three directional reaches. The three directional version has become prominent (Figure 2.2), the most common combination of which is the use of the Ant, PostMed, and PostLat directions (Hubbard et al., 2007a; Hubbard et al., 2007b; Plisky et al., 2006; Plisky et al. 2009). Although not entirely clear as to how these three directions were decided upon, this common 3-directional Y-shaped layout has been suggested to be traced back to the results of Hertel et al. (2006).

Originally, only three trials were attempted in each excursion direction (Gray, 1995). However, based on a study by Hertel, Miller and Denegar (2000), a more common method of 6 practice trials in each direction followed by 3 recorded trials in each direction has become popular. Hertel et al. (2000) used a series of 1 warm-up plus 12 measured trials in each of the eight excursion directions on 16 healthy young subjects and found that measured trials 6-9 generally showed the highest excursion scores. It was therefore suggested that 6 practice trials be conducted before recording data in order to reduce the potential learning curve. However, a more recent study by Robinson et al. (2008a) suggests that an even further reduction from 6 practice trials down to 4 may improve efficiency of testing without compromising the results of the test. However, the 6 practice and 3 measured structure, at this time, would still be considered the standard.

When using the 6 practice and 3 measured attempts protocol, the SEBT has been shown to have moderate to good intratester reliability, ICC= 0.67-0.97, (Hertel et al., 2000; Kinzey & Armstrong, 1998). Between session reliability was also reported to be good with ICC = 0.84-0.96 (Munro & Herrington, 2010; Plisky et al., 2006), with Munro and Herrington concluding that changes in scores (normalized to leg length) of at least 6-8% are needed to feel confident that a real change in SEBT performance has occurred from an intervention.

Plisky et al. (2009) reported very good scores for intratester reliability (ICC= 0.85 to 0.89) and for intertester reliability (ICC= 0.97 to 1.0) using a contraption specially designed for use in the common 3 directional SEBT instead of the usual method employing a tape-measure on the ground. This now commercially available set-up has been termed the “Y Balance-Test.”

On the other hand, intertester reliability was reported in a wider range by Hertel et al. (2000). This study took place over two days with the correlation coefficients drastically improved from day 1 (ICC= 0.58 to 0.84 in all directions except Lateral which scored ICC= 0.35 to 0.53) to day 2 (ICC= 0.81 to 0.93 in all directions). The authors of this study state that they feel that performance of the subjects performing the test tended to become steadier due to a learning curve from day to day, while consistency of measuring methods also may have improved from day one to day two by the scorers.

Additionally, there has been significant variation in the analysis of the collected data. The average of the excursions, the maximal excursion in each direction and the average of the 3 greatest excursions in each direction have all been used for analysis. Furthermore, composite scores (a sum of all the directional reaches on one side added together) have also been used. At this time, there doesn't appear to be a consensus on which method is most accurate or most repeatable, with no study as of yet looking to specifically answer this question. Plisky et al. (2009) showed that of 19 publications using variations of the SEBT, 4 reported on the maximal trial, and 2 reported average of the greatest 3 trials, with the rest (and the majority) reporting based on the average of 3 trials.

One standardization that has come to be more common is due to that fact that taller or longer limbed individuals tend to score higher, because the SEBT requires participants to reach as far as possible along a tape measure. Gribble and Hertel (2003) discovered that height and leg length did significantly correlate with scores on the SEBT ($p<0.05$) in six of the eight reach directions, with $r = 0.32 - 0.44$ between height and reach distance, and $r = 0.32 - 0.48$ between leg length and reach distance. Therefore, when comparing between individuals or across groups it has become increasingly standard to normalize scores based on height or more often leg length.

The SEBT as a Measure of Balance or Neuromuscular Control

In its original intent, the SEBT has been used in several studies as a measure of dynamic balance and neuromuscular control. Rasool and George (2007), with a population of 30 healthy athletes (16 training, 14 controls), demonstrated that a 4-week, 5 day per week exercise routine of progressive difficulty single-leg balance exercises, demonstrated significant improvement after 2 and 4 weeks on the SEBT in all directions. The smallest improvement occurred in the Ant direction and the largest improvement in the AntLat direction. Note, however, that there was no measure taken of strength, muscle activation or flexibility changes, and it is therefore ambiguous as to specifically why improvement occurred. Furthermore, side-to-side differences in SEBT scores were not discussed.

Filipa et al. (2010) also suggested a relationship between neuromuscular control and performance on the SEBT, using the Ant, PostMed and PostLat directions. Young female athletes participated in an 8-week, twice per week training program which used a variety of core and balance exercises, progressed in phases over the course of the study. The training group displayed significant improvement on the SEBT in the PostLat and PostMed directions, and significantly improved composite scores on both sides in comparison to the control group. According to the authors the exercises selected were related to studies that have shown these interventions to relate to reductions in lower extremity risk factors, none of which emulated the SEBT. This study showed a significant improvement of composite and PostLat scores on both sides and significant improvement in the PostMed excursion in the left limb. Although described as a neuromuscular training program, no direct measurement of strength, muscle activation or flexibility was taken, again leaving the direct sources of the improvements ambiguous. One is also left to wonder why the left limb excursions (stance on right foot) in this study seemed to improve more than the right limb excursions (stance on left foot).

Leavey, Sandrey, and Dahmer (2010) also used the SEBT as a measure of dynamic balance in a study which involved a 6-week proprioceptive training program. This program progressed each week to more proprioceptive demanding exercises, using a variety of eyes open and eyes closed exercises, on the floor, tilt board and wobble boards. It was shown that all 3 posteriorly directed excursions (Post, PostMed and PostLat) improved in relation to the control, along with the AntMed direction showing the largest improvements among groups. The gains, shown through this intervention were likely, although not certain, relating to better neural control and/or improvements in strength. This study did not report legs separately and conclusions regarding detected asymmetries cannot be drawn from this study.

Components Relating to Performance on the SEBT

In addition to the original intent of the SEBT to assess dynamic balance (Gray, 1995), and the notion that taller/longer limbed individuals should be able to reach further, there are several other factors which may potentially be involved in how one performs/scores in the SEBT. It is then likely that side-to-side differences in these factors may determine the amount of symmetry in bilateral scores on the SEBT.

However, few studies have reported on these attributes in direct relation to asymmetric performance on the SEBT. Sources which have been related to performance on the SEBT, notably falling under similar categories as those which may contribute to LEFA, include anthropometric measures other than overall height and leg length (Gribble and Hertel, 2003), flexibility (Gribble and Hertel, 2003; Hoch, Staton, McKeon, 2011), and strength (Earl & Hertel, 2001; Hubbard et al., 2007b; Leavey et al. 2010; Thorpe & Ebersole, 2008).

Other than height and leg length, foot type is one other body dimension that has been tested in relation to SEBT performance. Gribble and Hertel (2003) used a classification of foot type, classifying feet into 1 of 3 categories (pes planus, pes rectus, or pes cavus). However this study did not find significant correlation between foot type and performance on the SEBT. The same study also measured passive range of motion in the hip (internal rotation and external rotation) and ankle (dorsiflexion), which also were not found to be significantly correlated with SEBT scores. In this particular case, internal rotation and external rotation were measured in a prone position with the hip at zero degrees of extension, which itself may not be a specific measurement to the active range of motion, hip flexed environment of large portions of the SEBT. Also, maintaining heel contact with the ground during each trial in this study was not mentioned as a criterion for completion, and therefore possibly made the need for adequate dorsiflexion range of motion unnecessary for superior performance.

On the other hand, Hoch et al. (2011) contradicted some of the findings regarding range of motion of the Gribble and Hertel (2003) study. Hoch et al. (2011) showed that the Ant direction of the SEBT was significantly correlated with a measure of ankle dorsiflexion range of motion, the weight bearing lunge test (r=0.53), with no significant correlation between this test and the PostMed and PostLat reach trials. This indicates that 28% of the variance in the Ant reach can be explained by the weight bearing lunge test. Hoch et al. then suggests that this portion of the SEBT may be a good clinical test to use to assess restrictions in dorsiflexion range of motion in regards to dynamic balance.

Further studies have attempted to establish a link between scores on the SEBT and muscle strength or activation. In an attempt to identify muscle activation patterns during the SEBT, Earle & Hertel (2001) used electromyographic data collected from the vastus medialis oblique, vastus lateralis, medial hamstring, biceps femoris, anterior tibialis and the gastrocnemius on the stance leg. They found that the quadriceps and hamstring muscles produced a co-contraction during all eight reaches of the SEBT, with the quadriceps being most active in the three anteriorly directed reaches; hamstrings most active in the Post, PostLat and Lat directions; and the anterior tibialis most active in the three posteriorly directed reaches. They conclude that the muscle activation in the lower extremity during the SEBT is directionally dependent and therefore each direction may be indicative of slightly different strength or muscle activation related deficits. It might also be the case that a variation in strength or level of activation from one side to the other may be a source of bilateral asymmetry demonstrated in the SEBT, but this has not directly been tested.

Later, Hubbard et al. (2007b) tested three directional reaches (Ant, PostMed and PostLat) in relation to isometric strength at the hips (abduction and extension) and isometric strength at the ankles (dorsiflexion, plantarflexion, inversion and eversion). They found significant correlation between isometric hip abductor strength and isometric hip extensor strength, both in the PostMed reach direction (r=0.51 and 0.48, respectively), as well as the PostLat reach (r=0.49 and 0.49, respectively) with no significance in correlation between any of the other variables.

Evidence for hip abductor strength being an important indicator for performance on the SEBT was later somewhat supported by research from Leavey et al. (2010). They used a 6-week, 3 times per week, approximately 20 minute long gluteus medius strengthening program on 48 healthy female college students. The program involved six exercises which were typical of rehabilitation programs focusing on the hip abductors and the gluteus medius. These exercises were progressed every 2 weeks through increases in volume and intensity. Difference between training groups and controls were not statistically significant in composite scores, but did show a significant improvement in the posteriorly directed excursions, as well as the most improvement in the laterally directed excursions. Furthermore, when combined with the proprioceptive training discussed above, this gluteus medius training program showed even greater improvements in the posteriorly directed excursions, as well as the Ant and Med excursion directions. However, when measuring isometric hip abduction strength gains, they found it to have a very low correlation with functional improvements on the SEBT. It is possible however, the isometric hip abduction measurement used, did not specifically capture the type of strength gains attributed to improved performance in the SEBT. Furthermore, the functional improvements may not have been related to strength, but instead another variable such as flexibility or neural control; and as stated above each leg was not reported separately for this study.

Examination into the relationship between strength and the SEBT was also performed by Thorpe and Ebersole (2008). They used the SEBT Ant, Med, and Post excursions to test two groups of individuals divided between soccer (n=12) and non-soccer (n=11) players. SEBT performance was correlated with isokinetic (90 deg. /sec.) strength measures of ankle dorsiflexion, ankle plantarflexion, hip extension and hip flexion, all in the supine position; as well as seated knee extension and knee flexion. Results showed that in both the soccer and non-soccer populations, SEBT performance was very similar on both legs; with the more physically trained soccer population scoring significantly higher on both sides and in all 3 directions tested. However, the authors found no significant relationships between the strength measures used and performance in the majority of the directional reaches. Ankle plantarflexion and ankle dorsiflexion strength had a moderate correlation (r=0.62, and 0.66, respectively) to the Post excursion in non-soccer players. Hip extension strength showed a correlation with the Post excursion (r=0.66) in non-soccer players and the Med excursion (r= -0.58) in soccer players. Interpretation of these results remains ambiguous, as it seems to suggest that being stronger in some movements helps in a non-soccer trained population, but may not help in a soccer population, with a surprising negative correlation, in the soccer population in the one measure that did show significance in regards to strength. This might indicate that the soccer players obtained overall higher scores while relying on a factor other than strength. Again, it is possible that the strength measures used were not specific to SEBT performance due to the slower and sometimes eccentric muscle actions necessary for SEBT performance. Also, symmetry reported between legs in the SEBT and measures of strength, lends weak support to symmetry in one measure relating to symmetry in the other measure.

Robinson and Gribble (2008a) measured all 8 reach directions and used a step-wise regression model to show that differences in hip flexion and knee flexion angles separately and in combination accounted for 62% to 95% of the variance in reach distances (normalized to leg length). This might support the idea that the ability to reach and maintain optimal knee flexion and hip flexion angles may be the primary reason for larger or smaller excursion distances in the SEBT. This conclusion is supported by work by Gribble, Hertel, Denegar, and Buckley (2004) which showed that legs suffering from chronic ankle instability (CAI) demonstrated lower scores on the SEBT when used as the stance leg as well as less knee flexion and hip flexion compared to the uninjured limb and control limbs. Therefore, a difference between legs in the ability to reach and maintain these angles may be a primary cause of asymmetries on the SEBT. However, no study to date has specifically studied this potential side-to-side difference. Because of this, it is not clear what causes one limb to be able to reach and maintain optimal hip and knee angles during the SEBT while another limb cannot. Again, strength, flexibility, some other skill or a combination thereof, may be the determining factor.

It is important to note that studies thus far have not attempted to specifically examine sources relating to asymmetric performance on the SEBT. Although it might seem logical that side-to-side differences in these variables discussed above would likely cause asymmetric performance, one can't confidently determine that bilateral differences in these variables would necessarily cause asymmetric performance. Below, the link between injury and asymmetry in the SEBT is discussed, establishing that a relationship very likely exists, but further study is necessary before being able to make conclusions regarding what specifically is causing these side-to-side differences, and possibly how to become more symmetric at this test.

SEBT Link to Injury

The SEBT has been linked to injury in a few different ways. The SEBT has been an important factor in studying CAI. It has also been used, to a lesser extent, in examining ACL deficiency and general lower extremity injury risk. A series of studies (discussed below) have shown the SEBT to be effective in the evaluation of CAI. More specifically, it has been shown that when using a CAI identified ankle as the stance leg during the SEBT significantly smaller reach distances were obtained, as compared to a non-CAI leg. This has been shown in a variety of different reach directions. This reach deficit is supported by Gribble et al. (2004) showing reach deficits in the Ant, Med, and Post excursions; Hubbard et al. (2007a) with deficits in Ant & PostMed excursions; and Olmsted et al. (2002) in all eight directions. Hertel et al. (2006) showed reach deficits in CAI stance leg ankles in the AntMed, Med and PostMed, with the PostMed direction to be most predictive of CAI.

Instead of a screening tool, Chaiwanichsiri et al. (2005) used the SEBT as a training protocol for athletes with grade 2 ankle sprains. The training groups performed the SEBT 3 times per week for 4 weeks on both feet (injured and uninjured sides) in addition to a traditional physical therapy treatment, while the control group just received the physical therapy treatment. Prospectively, a decreased rate of injury was shown in the experimental group, although not found to be statistically significant, presumably due to the low number of injuries in the follow-up period. Interestingly, this may suggest that the SEBT may not just identify injury, but getting better at the SEBT may actually prevent injury.

Another study by Herrington et al. (2008) compared all 8 reach directions of the SEBT of ACL deficient knees (injured between 5 months and 2 years prior) with uninjured knees in the same subjects and a control population. They found significant decrements in excursion distance in seven out of eight of the reach directions when balancing on the injured leg as compared to the uninjured side. It is not clear, based on the evidence presented, if this bilateral difference was caused by the ACL injury or if it contributed to the event which caused injury. However, in this case, the SEBT does seem to be able to differentiate between ACL deficient and healthy knees. However, bilateral asymmetries in the control population were not discussed in relation to the asymmetries observed in the ACL deficient population. Therefore, it is not apparent in this study to what degree asymmetry plays a part within a healthy population.

And finally, a large prospective study by Plisky et al. (2006) showed a relationship between the SEBT and lower extremity injury in general. This study used the SEBT on a group of 235 high school basketball players, and then monitored this group for lower extremity injury during the following basketball season. It was found that right side excursion composite reach distances under a base level (normalized to leg length) and bilateral differences in Ant reach distance (of $\geq$4 cm) predicted a higher risk of lower extremity injury. A decreased normalized composite right reach distance indicated a 3 times higher likelihood of lower extremity injury in all players, and a 6.5 times higher likelihood of lower extremity injury in female athletes. Interestingly, this same relationship was not found for left side (right stance leg) composite excursion scores. Furthermore, Ant side-to-side differences equal to or greater than 4 cm indicated an increased likelihood of injury in all subjects by 2.7 times and increased likelihood of injury in boys by 3 times.

Relationship between Asymmetries in SEBT Excursions and LEFA

Based on the information presented above, the underlying reasons for performance differences on the SEBT (both absolute scores and side-to-side differences), and those of LEFA, show a large potential area of overlap. Both the SEBT and LEFA have been related to injury prediction, injury identification and various measures of performance. Sources causing side-to-side differences in both potentially relate to underlying strength, flexibility, neural and anatomical measures and origins in previous injury, anthropometry and neural laterality also seem to overlap. However, even though there seems to be strong grounds to suggest a relationship, very little direct research has been done relating the SEBT to LEFA. Furthermore, the relationship between one excursion direction on the SEBT compared to another also deserves more attention, as different excursions possibly screen for different things. There have almost no studies which seek a link to asymmetries in these seemingly overlapping areas.

A study by Bressel et al. (2007) compared three groups of athletes from different sports to each other in regards to measures of static balance and all eight directions of the SEBT. From this test it was shown that scores on the static balance tests and the SEBT were not predictive of each other, although the tendency, on average, was to have the same side better at both tests. However, whether that side was identified as the dominant or non-dominant side varied between sports, and the degree of asymmetry between tests also varied between sports. However, this study did not directly discuss the relationship between asymmetries on the static balance tests and asymmetries in the SEBT.

Another study performed by Hubbard et al. (2007b) also looked at static single-leg balance in comparison to the SEBT using the Ant, PostMed and PostLat excursions in subjects with CAI. However, no significant relationship was found between measures of single-leg static balance and any directional reaches measured in the SEBT. Again, the relationship between side-to-side asymmetries in each test was not discussed. In this case, with no correlations being shown, it might be suggested that asymmetries seen in static balance tests are unlikely to represent those seen in the SEBT.

The potential overlap between asymmetries in the SEBT and functional tasks seems to be large, suggesting asymmetry to be related to the same underlying factors in both, but little has been done to examine this relationship. The SEBT may be measuring very similar variables as measurements taken by more expensive, less convenient means currently used to screen for LEFA. If asymmetries in the SEBT demonstrate a high correlation to asymmetries measured by other popular laboratory equipment (i.e. force platforms, motion capture, etc.) then the SEBT may serve as an alternative option to other methods of identifying LEFA. However, the minimal research performed to date relating the SEBT with LEFA suggests that a strong relationship may not exist, but only measures specific to static and dynamic balance have been compared. Might other various tasks, such as standing, jumping, squatting, landing, etc. yet to be compared, have a stronger relationship? Based on this, it is clear that more research is needed in this area in order to determine the true relationship, and answer the question as to whether the SEBT and LEFA are related, and if one might be used to predict the other.

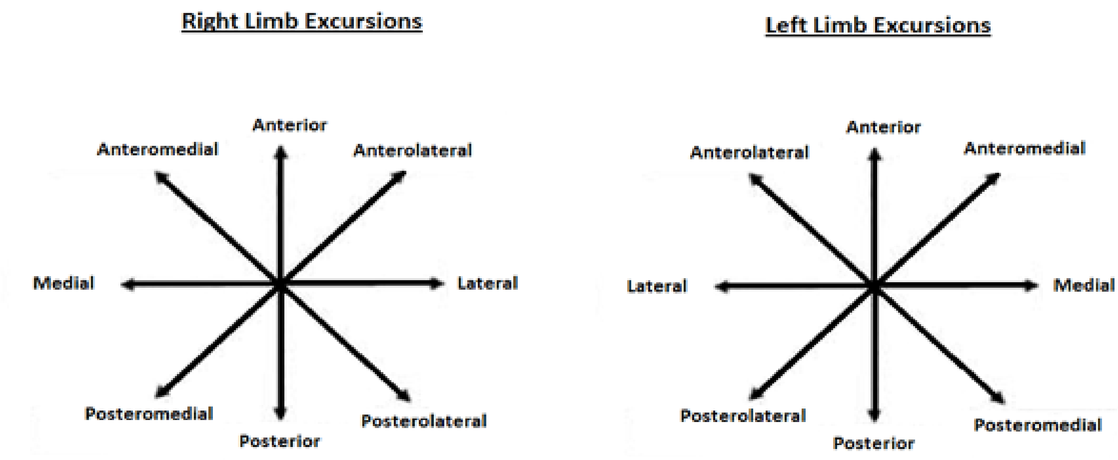


Figure 2.1: Eight-directional SEBT. Right Limb Excursions involve a left foot stance while reaching with the right leg; vice-versa for left limb excursions. The distal aspect of great toe is placed on the intersect of lines while facing the anterior direction.

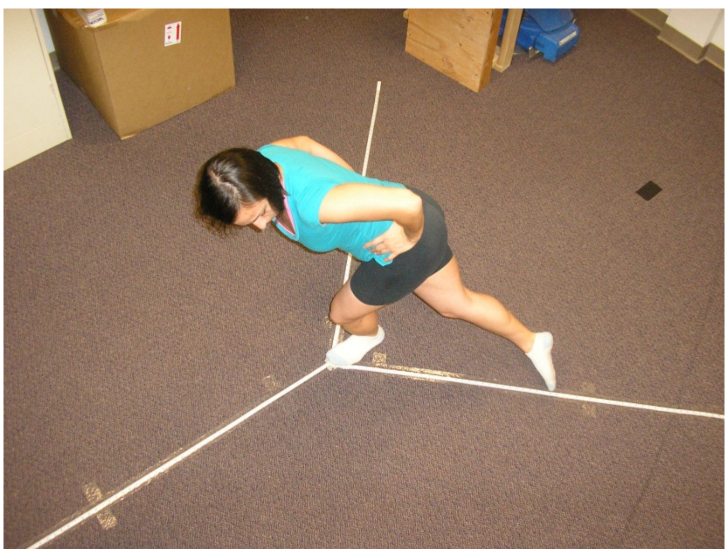


Figure 2.2: Demonstration of common 3-directional Y-shaped SEBT, with only Ant, PostLat and PostMed directions used; right limb PostMed excursion shown.

CHAPTER III

METHODS AND PROCEDURES

Experimental Approach to the Problem

To accomplish the goals of this investigation, a cross-sectional research design was used and approved by the Colorado State University Institutional Review Board (Appendix A). Subjects provided written informed consent (Appendix B) and visited the lab for one data collection lasting approximately two hours. The lab visit included a warm-up, followed by anthropometric measurements, learning and performance of the SEBT, nine active range of motion (AROM) measurements of the lower extremities on each side, and four functional movements while GRFv were measured under each foot. Functional movements included quiet standing, body weight squats, CMJ, and SLDL on each leg from a 30.5cm elevated platform. A subset of 11 subjects returned for a repeatability assessment conducted within 31 days of the first visit. Measurements were taken by a single researcher for all tests.

Subjects

Twenty non-obese (BMI < 30 kg/m^2), healthy individuals aged 19-30 years recruited from the Colorado State University student population volunteered to participate. The men (n=9) and women (n= 11) examined were identified as recreationally active individuals that had been involved in activities which required jumping and squatting type movements at least once a week for the past eight weeks (i.e.

resistance training, basketball, racquetball, etc.). Exclusion criteria included self-reported pain, injury, or soreness to the lower back or lower extremities at the time of the visit. Any injuries must have healed with a return to regular activity at least four weeks prior to participation. Those with a history of back or lower extremity pain, major previous surgery, bone, joint, or muscular disorder, history of neurological/orthopedic dysfunction, or pain that would limit the ability to perform functional tasks correctly, were excluded. Any subjects with a known reason to perform these activities asymmetrically for anthropometric reasons were also excluded (e.g. known limb-length discrepancy, bilateral corrective devices, braces, etc.). Finally, women who were pregnant at the time of investigation were excluded.

Procedures

Prior to participation, subjects were contacted over the phone or in person to complete a brief health and activity questionnaire, verifying eligibility (Appendix C). All subjects made one visit to the laboratory with a subset of subjects returning a second time for a repeatability assessment. Subjects were instructed to abstain from heavy exercise of the lower limbs and back for 48 hours before the visit, and to limit exercise to normal daily activities for the lower body the day before and day of testing. Caffeine consumption was limited to normal daily intake and no other ergogenic aids were allowed for consumption during the prior 24 hours leading up to the visit.

Upon arrival to the lab, final eligibility of subjects was determined by reviewing their health and activity questionnaire. If not already obtained, the subjects provided written University-approved informed consent before physical activity (Appendix B).

Subjects were given orientation of the laboratory followed by measurement of body weight and height without shoes. A warm-up of no less than five minutes was required for all subjects, which was completed on a stationary cycle ergometer. Stretching was not allowed at any point during the study in order to avoid confounding factors which might be caused by stretching one side more vigorously than the other. Following the warm-up, functional leg-length asymmetry and anatomical leg-length measurements were taken with the subject in the supine position on an elevated examination table.

The functional leg length asymmetry was performed as directed by Hinson and Brown (1998); starting supine with shoes on, the subject bent the knees placing the feet directly next to each other, with the researcher lining up the feet so that the toes were flush with each other. The subject then lifted the pelvis off of the table ~6-10" before relaxing and setting it back down. The researcher extended the subject's legs, and applied equal pressure to the soles of the feet, directing the pressure longitudinally toward the subject's hips. Visual approximation was then taken as the difference in how far one sole extended off the edge of the table compared to the other. The anatomical leg length measurement was consistent with the directions by Evans (1994). In the relaxed supine position each leg was measured with an inextensible tape from the palpated anterior superior iliac spine (ASIS) to the medial malleolus of the ankle. The left side was always measured first. Functional and anatomical measurements were taken twice with the average used for analysis.

The subject then removed their shoes and performed the SEBT as described in Plisky et al. (2006). Briefly, the SEBT is a dynamic balance test, in which a subject stands on one foot reaching as far as possible with the contralateral foot in three specified excursion directions. The excursions included a reach to the front (Ant), a reach diagonally back and to the medial side of the reaching leg (PostMed), and a reach diagonally back and to the lateral side of the reach leg (PostLat) (Figure 2.1 and 2.2).

The distal aspect of the subject's great toe was put in the center of the measuring surface (i.e. junction of the star), and each trial was a maximal effort reach in each direction. The subject performed six correct practice trials on each foot for each of the three excursions, with the researcher correcting improper technique. Criteria for a correct trial were that the heel of the plant foot stayed in contact with the ground, the hands remained on the hips at all times, the subject lightly brushed the measuring tape at the furthest point possible without planting weight onto the reaching foot, and the subject recovered to a single-leg standing position for at least two seconds. After these six trials, the subject performed three more correct trials in which data was recorded. The researcher visually identified the furthest point reached on a tape measure and recorded this score. Trials were repeated if the subject didn't meet the criteria for a correct trial. A fourth or fifth trial was granted if performance during the last trial appeared to be significantly further than the previous (e.g. if the third trial was significantly higher than the second), so that a score that was truly representative of the subjects maximum capability was obtained.

Nine AROM measurements were then performed either in a seated of lying position (six on each hip joint and three on each ankle joint), lasting approximately 45 minutes, which were not included as part of this thesis. After this, functional movements were performed wearing shoes consistent with physical activity (i.e. tennis, running, cross-training, etc.). Ground reaction forces were sampled at 1000 Hz with two commercial force-measuring platforms (model 4060-10, Bertec Corp., Columbus, OH) mounted side-by-side and flush to the surrounding floor. The force platforms were verified to measure within 0.1% of each other within the range of measures of the study (excluding high magnitude instantaneous peak forces during SLDL which could not be replicated adequately for evaluation of the platforms).

Five trials of 20 seconds of quiet standing were first obtained with approximately 1-2 minutes rest between trials. Subjects stood with eyes open, looking straight ahead, hands relaxed and at the sides with feet approximately hip width apart. The subjects were instructed to stand as naturally as possible, not leaning to one side or the other, with minimal movement (Figure 3.1).

Second, six to seven body weight squats were performed (with the first five useable repetitions being analyzed during later analysis). Each foot was again approximately shoulder width apart and squats were performed with approximately one second down and one second up tempo, with clear pauses in between dictated verbally by the researcher. During squatting, subjects remained looking straight ahead, dropping down to approximately thighs parallel to the ground position, maintaining a hands-on-hips position. Subjects were given a brief practice in order to obtain correct tempo and form before data was collected. Trials were discarded if the GRFv was not stable at the initiation of the movement or did not stabilize quickly at the end (Figure 3.3).

Third, the subject performed CMJ's after familiarization with the movement through brief practice. Six to seven maximal effort CMJ's were performed with the feet approximately shoulder width apart (again, the first five useable trials were analyzed). Emphasis was put on jumping as high as possible, with no instruction given regarding particular landing technique and without using a landing or overhead target. Subjects looked forward and maintained their hands on the hips. Tempo and countermovement depth were not dictated, as to allow subjects to jump as naturally as possible. Again, clear pauses between each repetition were dictated verbally by the researcher. A distinct and stable pause before the initiation of the countermovement was needed to be acceptable for inclusion (Figure 3.5).

Finally, SLDL from a 30.5cm platform were performed on each foot. Subjects were given an equal number of practice trials on each foot, until they felt comfortable with their ability to perform the movement. The SLDL was performed while maintaining a hands on hips position, and by stepping forward smoothly off of the front of the platform and sticking the landing on the lead leg with the contralateral leg neither touching the ground nor the platform. Five SLDL on each foot were alternated right side, then left side, using the same force platform each time. Other than landing similarly on each side, landing technique was not dictated by the researcher in order to encourage subjects to land as naturally as possible (Figure 3.7).

In order to verify the day-to-day repeatability of the experimental design and measurements, eleven subjects returned to the lab a second time. A minimum of 48 hours between visits was required, with no more than 31 days separating the two visits. The same criteria were enforced for subject eligibility (i.e., pain, injury, and soreness free) with the same instructions for the 48 hours leading up to the visit.

Data Processing and Analyses

The SEBT was analyzed using the average of the last three trials for each reach direction for each lower extremity, as well as the average of the total of the three reach directions. Also analyzed, was the maximum value measured for each direction, as well as a total of the maximums for each lower extremity. In order to control for the effect of limb length between subjects, SEBT values were normalized to percent of average limb length (average of right and left sides). The normalized KL SEBT value was subtracted from that of the NKL in order to quantify the presence of asymmetry (% NKL-KL).

For the functional movement analysis, GRFv for the standing, squat, and CMJ trials were low-pass filtered at 15 Hz (4^{th} order recursive Butterworth) to remove any high-frequency noise. In order to maintain the high-frequency peak of the GRFv during landing, the SLDL forces were not filtered.

For the standing trials, the average GRFv of each foot during each of the 20 second trials was normalized to a percentage of the average total GRFv, i.e. the sum of left and right sides (Figure3.2). In this way, a score of 50% on each side would represent a trial where on average the GRFv were split perfectly even between feet. The 5 trials were then averaged to obtain a representative score for each leg. Similar to the SEBT, the normalized preferred KL value was subtracted from the NKL value to quantify functional asymmetry (% NKL-KL).

For squatting (Figure 3.3) and CMJ (Figure 3.6) trials the start of a repetition was defined as the time when the total GRFv (sum of right and left sides) dropped below bodyweight. The end of a squat repetition occurred when the total GRFv returned to body weight after completing the up phase, whereas the end of the CMJ repetition was defined as the point at which the total GRFv reached zero (i.e. the toes left the ground). Average and maximum GRFv for each foot were measured for each repetition. The average GRFv on each foot was calculated as a percentage of the total GRFv over the entire repetition. The maximum GRFv was calculated as the highest force observed for each leg, as a percentage of the instantaneous total. Asymmetry measures were then created as above by subtracting the KL side value from the NKL side value (%NKL-KL).

For the SLDL trials, the start of a repetition was defined as the time at which GRFv exceeded zero when first contact with the ground was made (Figure 3.8). For each repetition the following were analyzed: peak instantaneous GRFv, time to GRFv peak (amount of time from repetition start to peak instantaneous GRFv), slope (GRFv peak divided by time at GRFv peak), GRFv average to peak (average GRFv from beginning of the repetition to the peak GRFv), impulse to peak (GRFv average to peak multiplied by time to GRFv peak), and GRFv average over the first 300 ms of the landing. The SLDL were also then analyzed in a similar manner as listed above, where an average was found on both sides over the course of the 5 repetition, for each variable measured. Percent of bilateral total was then calculated for each side with asymmetry calculated by subtracting KL form NKL (%NKL-KL).

Statistical Analyses

Means and standard deviations for anthropometric and GRFv data were compiled in addition to performing paired t-tests on all NKL versus KL values for anatomical leg length, each individual and combination of excursions of the SEBT and each functional movement parameter, in order to determine the existence of significant bilateral differences. Also, Pearson's r correlations were performed comparing asymmetries (%

NKL-KL) in each individual and combination of excursions in the SEBT, each parameter of the functional movements, and anatomical leg-length asymmetries both within and between different test types. Finally, intraclass correlations (Chronbach's Alpha) were used to establish inter-session repeatability of all measures reported. Statistical analysis was conducted in PASW version 19.0 (SPSS, Inc., Chicago, IL) with significance set at $p<0.05$.

Figure 3.1 Example body position during a quiet standing trial.

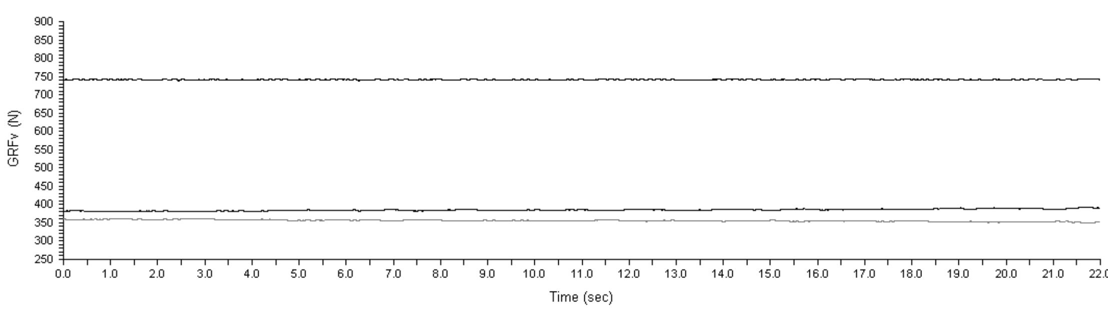


Figure 3.2: Exemplar total GRFv (top line), left GRFv (black bottom line), and right GRFv (grey bottom line) for a quiet standing trial. The inner 20 seconds of the 22 seconds recorded was utilized in the analysis.

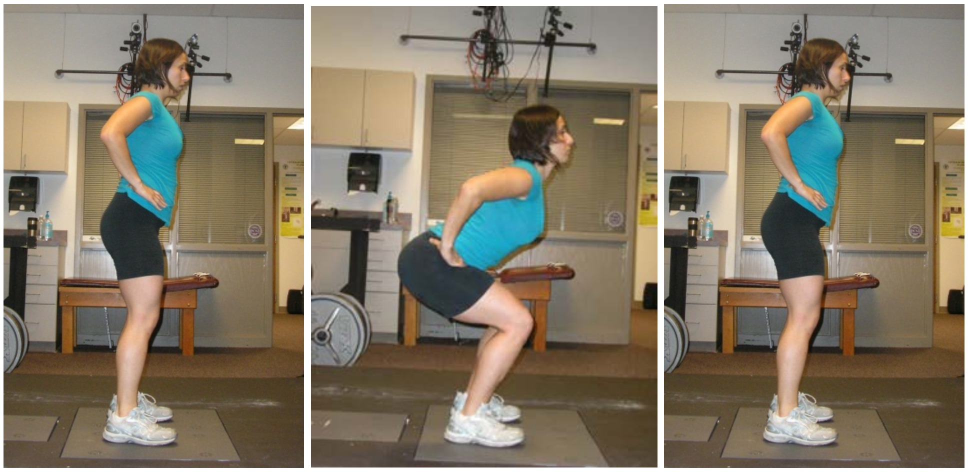
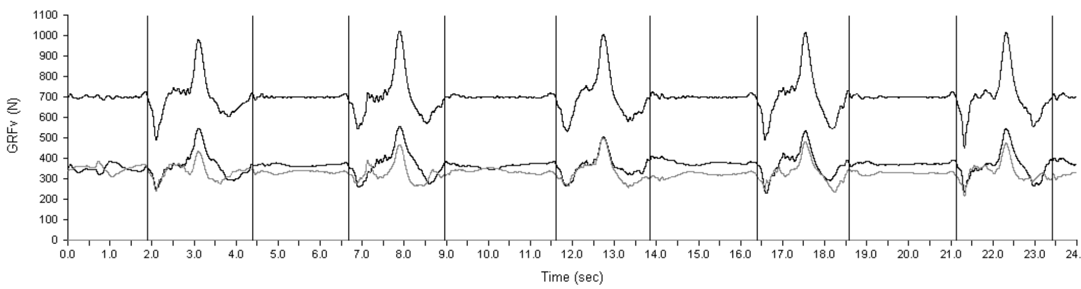


Figure 3.3: Example of starting position (left), bottom of squat (middle) and ending position (right) of a single squat repetition.

A



B

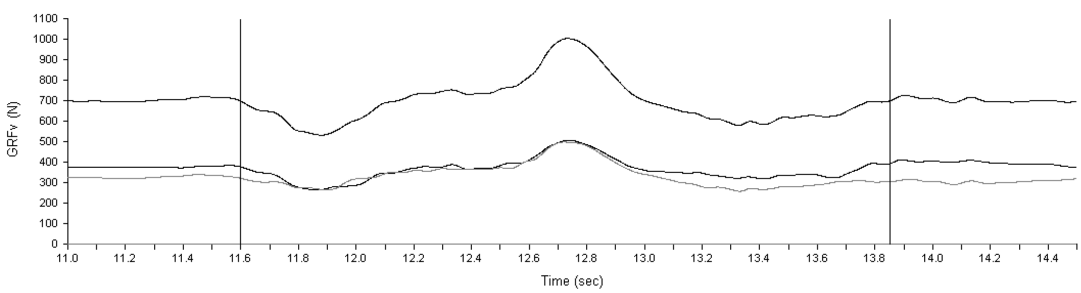
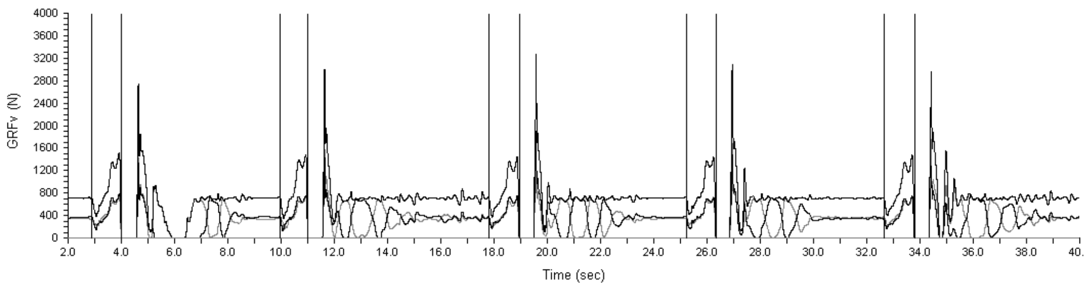


Figure 3.4: (A) Exemplar GRFv for a five body weight squat trial. (B) Exemplar GRFv for one repetition of a body weight squat. Total GRFv (top black line), left foot GRFv (bottom black line), and right foot GRFv (grey bottom line). Vertical lines identify the beginning and end of one repetition.

Figure 3.5: Example of start (left), reversal of direction (middle) and just after takeoff (left) of a single CMJ repetition.

A



B

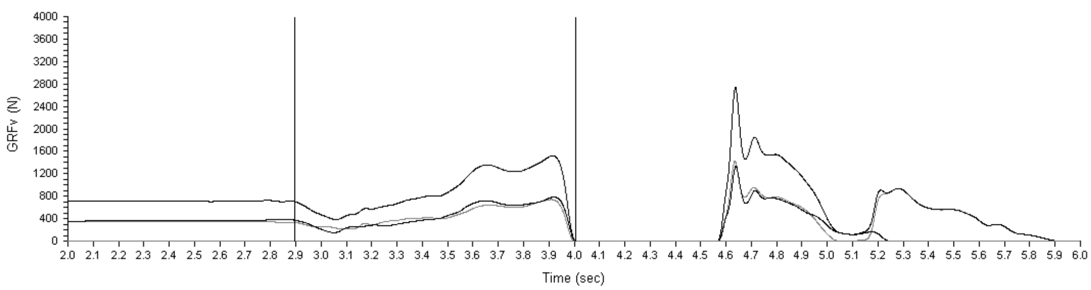


Figure 3.6: (A) Exemplar GRFv for a five CMJ trial. (B) Exemplar GRFv for a single CMJ. Total GRFv (top line), left foot GRFv (black bottom line), and right foot GRFv (grey bottom line); vertical lines identify the beginning and end of one repetition.

Figure 3.7: Example of a single SLDL right lower extremity trial, stepping from platform (left) and landing (right).

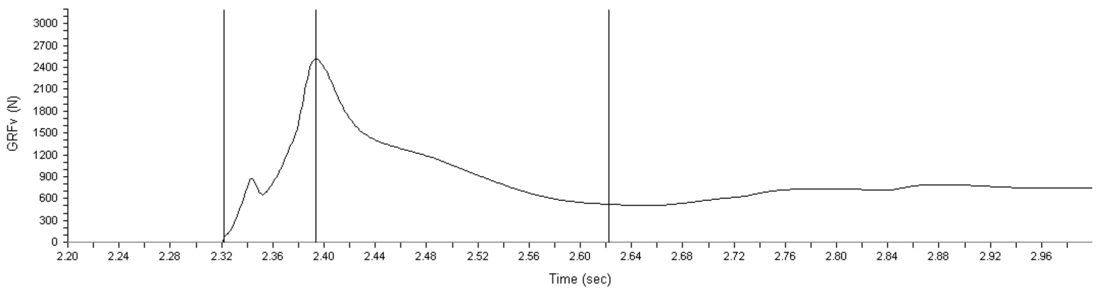


Figure 3.8: Exemplar GRFv for a SLDL. Vertical lines identify the beginning, peak GRFv, and 300ms after the beginning of the repetition.

CHAPTER IV

RESULTS

Twenty recreationally active subjects, eleven women and nine men, completed the study, with 18 indicating the right foot as their preferred kicking side and two indicating the left foot (Table 4.1). Of the 20 subjects, 11 (six women and five men) returned for a second visit within 31 days with an average days between visits of 19.0±9.5 to assess repeatability of the measurements taken. Though small in magnitude, the NKL, in anatomic terms, was on average significantly longer than the KL ($p < 0.001$). General subject characteristics tended to be highly repeatable from day to day ($\alpha \geq 0.747$), except for absolute functional leg length difference ($\alpha = 0.444$).

All tests were performed by all subjects, however due to technical error, the data collected for the SLDL on two male subjects was deemed unusable, reducing the number of subjects to 18 for the SLDL only. Though small levels of asymmetry were present based on the absolute NKL-KL, none of the functional movements analyzed (Table 4.2 and Table 4.3) were shown to have significant between leg differences when compared as NKL to KL ($p \geq 0.141$). On average the %NKL-KL differences were between +/-3% except for Time to Peak and Slope to Peak in the SLDL. In this case one of the subjects landed quite stiffly on one leg compared to the other which pushed the average and standard deviation higher than the other variables. This also carried over to the Abs. NKL-KL averages and standard deviations for these two variables. While this person was a statistical outlier in these variables compared to the others, his technique was consistent and there was no reason to believe the values were erroneous. Therefore, his data was included in all the analyses. Bilateral differences in LEFA GRFv data (% NKL – KL) showed high repeatability in standing ($\alpha \geq 0.926$) and CMJ ($\alpha \geq 0.959$), with more moderate repeatability in squatting ($\alpha = 0.595$ to 0.827) and in most SLDL data ($\alpha = 0.570$ to 0.910). However, repeatability of absolute bilateral differences in impulse to peak measurements during SLDL were low ($\alpha = 0.212$).

Several significant correlations between tasks in LEFA measurements existed (Table 4.4). Bilateral asymmetries in standing average GRFv significantly correlated with bilateral asymmetries in average GRFv during CMJ and inversely with bilateral asymmetries in average GRFv during squats ($p \leq 0.045$). Bilateral asymmetries in average and maximum GRFv during squats significantly correlated inversely with average GRFv during CMJ as well as maximum GRFv during CMJ ($p \leq 0.008$). Bilateral asymmetries in average GRFv to peak in SLDL significantly correlated inversely with bilateral asymmetries in average and maximum GRFv during squats ($p \leq 0.034$). Bilateral asymmetries in peak GRFv in SLDL significantly correlated with bilateral asymmetries in CMJ average GRFv ($p=0.049$), with a trend toward significance in correlation with average force to peak ($p=0.058$). No correlations were found between anatomic leg length asymmetries and any LEFA measurements.

Though small differences were noted when viewed as absolute side-to-side differences, none of the SEBT measures were shown to have significant between leg differences ($p>0.05$ for all NKL vs. KL comparisons) when reported as a three trial average or a single trial maximum (Table 4.5). Individual leg scores and bilateral differences in SEBT scores showed good repeatability ($\alpha \geq 0.751$ and $\alpha \geq 0.752$, respectively), with absolute between leg differences having a broader range in repeatability (α= 0.036 to 0.802).

Significant correlations existed among most bilateral side-to-side differences (% NKL-KL) in SEBT scores (Table 4.6), with exceptions that PostMed and PostLat excursions didn't correlate significantly with each other ($p \geq 0.291$). Furthermore, those which used these in different combinations (i.e. Ant+PostMed vs. Ant+PostLat, also did not significantly correlate with each other ($p \geq 0.063$). Bilateral anatomic leg length differences showed no significant correlations with any of the individual or combinations of excursions ($p \geq 0.156$ except for average PostLat excursion where $p=0.054$). While the correlations were positive between SEBT scores, the non-significant correlation of the SEBT scores within anatomical leg length difference, exhibited an inverse relationship.

Several significant correlations were found between asymmetries in SEBT measurements and LEFA measurements (Table 4.7). Significant correlations existed between asymmetries in squat average GRFv and several asymmetries in excursion scores (average and maximum PostMed, Ant + PostMed, PostLat + PostMed, and Composite scores) ($p \leq 0.045$). Significant correlations also existed between squat maximum GRFv and several excursion scores (average Ant as well as average and maximum scores in PostMed, Ant + PostMed, PostLat + PostMed, and Composite) ($p \leq 0.037$). There was also a trend toward significance in correlation betwen squat maximum GRFv and maximum Ant + PostLat scores ($p= 0.052$).

Significant inverse relationships existed between asymmetries in CMJ average GRFv and asymmetries in excursion scores in all excursion directions and combinations of excursion scores ($p \leq 0.037$). Similarly significant negative correlations existed between asymmetries in CMJ maximum GRFv and asymmetries in excursion scores in all excursion directions and combinations of excursion directions except the PostMed direction ($p \leq 0.025$).

Some significant correlations existed between asymmetries in SLDL and asymmetries in excursion scores ($p \leq 0.050$). Slope to Peak asymmetries showed a significant inverse relationship with asymmetries in maximum Ant excursions ($p=0.045$) and maximum Ant + PostLat excursions ($p= 0.050$). Average GRFv to time at peak asymmetries showed a significant inverse relationship with excursion scores in average and maximum Ant, average and maximum Ant + PostLat, average Ant + PostMed , and average composite scores. Asymmetries in average GRFv for the first 300ms also significantly inversely correlated with excursion scores in average Ant and average Ant + PostLat ($p \leq 0.010$).

Table 4.1: General Subject Characteristics

	Mean	SD	α
Age (yrs.)	21.9	2.6	-
Height (m)	1.71	0.09	1.000
Mass (kg)	67.2	1.9	0.998
BMI (kg/m^2)	22.9	1.9	0.997
Anatomic Leg Length NKL (cm)	92.2	5.7	0.997
Anatomic Leg Length KL (cm)	91.4**	5.8	0.997
Anat. Difference NKL-KL (cm)	0.9	1.1	0.865
Absolute Anat. Diff (cm)	1.1	0.8	0.747
Bilateral Avg. Leg Length (cm)	91.8	5.8	0.998
Functional NKL-KL Diff. (cm)	0.0	0.4	0.765
Absolute Functional NKL-KL Diff (cm)	0.3	0.3	0.444

α= Cronbach's Alpha, KL= Preferred Kicking Leg, NKL= Non-Kicking Leg, SD= Standard Deviation, **($p<0.01$) between NKL and KL

Table 4.2: GRFv Standing, Squats & CMJ (Scores Reported as % of Bilateral Total)

		Average			Maximum		
		Mean	SD	α	Mean	SD	α
Standing					-	-	-
	NKL	50.0%	2.9	0.975	-	-	-
	KL	50.0%	2.9	0.975	-	-	-
	NKL-KL	0.1%	5.8	0.975	-	-	-
	Abs NKL-KL	4.6%	3.4	0.926	-	-	-
Squat							
	NKL	50.8%	2.4	0.776	51.1%	2.8	0.906
	KL	49.2%	2.4	0.776	50.4%	2.5	0.906
	NKL-KL	1.6%	4.9	0.776	0.7%	5.2	0.827
	Abs NKL-KL	4.6%	2.1	0.784	4.5%	2.5	0.595
CMJ							
	NKL	49.7%	2.7	0.992	50.3%	2.1	0.972
	KL	50.3%	2.7	0.992	49.9%	2.4	0.972
	NKL-KL	-0.5%	5.3	0.992	0.4%	4.5	0.963
	Abs NKL-KL	4.1%	3.3	0.989	3.4%	2.9	0.959

NKL= Non-Kicking Leg, KL= Kicking Leg, SD=Standard Deviation, α= Cronbach's Alpha, Abs=Absolute, GRFv= Vertical Ground Reaction Forces, CMJ= Counter-Movement Jumps

Table 4.3: GRFv SLDL (Scores reported as % of bilateral total)

		Mean	SD	α
Peak GRFv				
	NKL	50.6%	1.5	0.758
	KL	49.4%	1.5	0.758
	NKL-KL	1.1%	3.0	0.758
	Abs. NKL-KL	2.5%	2.0	0.585
Time-to-Peak				
	NKL	48.6%	4.4	0.975
	KL	51.4%	4.4	0.975
	NKL-KL	-2.8%	8.3	0.856
	Abs. NKL-KL	4.9%	7.1	0.575
Slope to Peak				
	NKL	47.8%	5.3	0.936
	KL	52.2%	5.3	0.936
	NKL-KL	4.4%	24.6	0.835
	Abs. NKL-KL	6.9%	9.0	0.665
Avg. GRFv to Peak				
	NKL	50.1%	2.5	0.769
	KL	49.9%	2.5	0.769
	NKL-KL	0.2%	5.0	0.769
	Abs. NKL-KL	3.4%	3.5	0.671
Impulse to Peak				
	NKL	48.6%	4.0	0.776
	KL	51.4%	4.0	0.776
	NKL-KL	-2.9%	8.1	0.776
	Abs. NKL-KL	6.2%	5.8	0.212
Avg. GRFv to 300ms				
	NKL	49.8%	0.6	0.891
	KL	50.2%	0.6	0.891
	NKL-KL	-0.4%	1.2	0.910
	Abs. NKL-KL	0.9%	0.8	0.791

NKL= Non-Kicking Leg, KL= Kicking Leg, SD=Standard Deviation,
α= Cronbach's Alpha, Abs.=Absolute, SLDL= Single Leg Drop Landings
GRFv= Vertical Ground Reaction Forces

Table 4.4: Between Tasks LEFA (GRFv) Correlations

		Standing	Squat		CMJ		SLDL						Anatomic
		Avg	Avg	Max	Avg	Max	Peak	time @ Peak	Slope to Peak	Avg. to Peak	Imp. to Peak	GRFv to 300ms	LLI
Standing	Avg	1.000	-0.452*	-0.380	0.458*	0.352	-0.322	0.231	-0.226	0.198	0.347	-0.011	-0.188
Squat	Avg		1.000	0.925**	-0.768**	-0.601**	0.373	-0.251	0.017	-0.500*	-0.407	-0.155	0.011
	Max			1.000	-0.714**	-0.571**	0.273	-0.102	-0.141	-0.494*	-0.230	-0.282	0.059
CMJ	Avg				1.000	0.915**	-0.470*	0.307	-0.124	0.421	0.448	0.262	0.172
	Max					1.000	-0.403	0.208	-0.047	0.455	0.374	0.179	0.358
SLDL	Peak						1.000	-0.312	0.207	-0.369	-0.428	0.117	-0.042
	Time @ peak							1.000	-0.861**	-0.216	0.932**	-0.269	0.039
	Slope to Peak								1.000	0.567*	-0.729**	0.414	-0.147
	Avg to Peak									1.000	0.107	0.299	0.079
	Impulse to Peak										1.000	-0.215	0.162
	GRFv @ 300ms											1.000	-0.267

Avg= Average, Max= Maximum, CMJ=Countermovement Jump, SLDL= Single Leg Drop Landing, LLI= Leg Length Inequality, ms= milliseconds, GRFv= Vertical Ground Reaction Forces
*(p<0.05) , **(p<0.01)

Table 4.5: SEBT Scores (Scores reported as % of Leg length)

	3 Trial Average			Single Trial Maximum		
	Mean	SD	α	Mean	SD	α
Ant						
NKL	66.1	4.1	0.895	67.5	3.7	0.763
KL	66.7	4.7	0.976	68.0	4.7	0.959
NKL-KL	-0.5	2.9	0.908	-0.4	3.0	0.803
Abs. NKL-KL	2.2	1.9	0.682	2.4	2.1	0.036
PostLat						
NKL	103.9	4.3	0.808	105.6	4.0	0.751
KL	104.1	4.2	0.923	106.2	4.4	0.835
NKL-KL	-0.2	2.9	0.876	-0.6	2.7	0.752
Abs. NKL-KL	2.5	1.8	0.486	2.4	1.7	0.621
PostMed						
NKL	101.0	5.3	0.912	102.8	4.9	0.895
KL	101.8	5.1	0.907	104.1	5.2	0.901
NKL-KL	-0.8	4.2	0.920	-1.3	4.4	0.914
Abs. NKL-KL	3.8	2.4	0.722	4.0	2.8	0.727
Ant+PostLat						
NKL	170.0	7.6	0.851	173.2	7.1	0.816
KL	170.8	8.2	0.961	174.2	8.1	0.919
NKL-KL	-0.8	5.3	0.887	-1.0	5.3	0.809
Abs. NKL-KL	4.2	3.2	0.133	4.2	3.2	0.260
Ant+PostMed						
NKL	167.1	7.9	0.906	170.3	7.3	0.842
KL	168.5	9.1	0.968	172.1	9.0	0.963
NKL-KL	-1.4	6.4	0.930	-1.8	6.9	0.904
Abs. NKL-KL	5.3	3.7	0.802	6.0	3.7	0.780
PostLat+PostMed						
NKL	204.9	8.8	0.862	208.4	8.1	0.851
KL	205.9	8.5	0.916	210.3	8.5	0.885
NKL-KL	-1.1	6.1	0.900	-1.9	6.0	0.894
Abs. NKL-KL	5.2	3.2	0.584	4.9	3.7	0.680
Composite						
NKL	270.9	11.5	0.870	274.9	11.5	0.855
KL	272.6	12.5	0.951	276.0	12.6	0.939
NKL-KL	-1.7	7.7	0.911	-1.1	8.3	0.803
Abs. NKL-KL	6.7	4.8	0.696	6.6	5.7	0.380

NKL= Non-Kicking Leg, KL= Kicking Leg, Abs.= Absolute, Ant= Anterior,
PostLat=Posterolateral, , PostMed= Posteromedial, Avg= Average, Max= Maximum
SD= Standard Deviation, α= cronbach's alpha

Table 4.6:. Correlations (r) between SEBT Average Bilateral Differences (NKL-KL)

		Ant		PostLat		PostMed		Ant + PostLat		Ant + PostMed		PostLat + PostMed		Composite		Anatomic
		Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Max	LLI
Ant	Avg	1.000	0.897**	0.550*	0.570**	0.483*	0.406	0.870**	0.863**	0.790**	0.693**	0.640**	0.600**	0.821**	0.828**	-0.220
	Max		1.000	0.556*	0.470*	0.564**	0.495*	0.818**	0.869**	0.800**	0.801**	0.703**	0.621**	0.830**	0.793**	-0.284
PostLat	Avg			1.000	0.918**	0.249	0.188	0.890**	0.852**	0.422	0.386	0.698**	0.599**	0.722**	0.613**	-0.437
	Max				1.000	0.237	0.176	0.853**	0.846**	0.423	0.337	0.647**	0.628**	0.690**	0.650**	-0.272
PostMed	Avg					1.000	0.959**	0.411	0.474*	0.919**	0.920**	0.867**	0.874**	0.800**	0.783**	-0.136
	Max						1.000	0.333	0.398	0.855**	0.917**	0.806**	0.876**	0.728**	0.742**	-0.124
Ant+PostLat	Avg							1.000	0.973**	0.680**	0.606**	0.761**	0.681**	0.874**	0.814**	-0.378
	Max								1.000	0.722**	0.674**	0.788**	0.729**	0.890**	0.845**	-0.324
Ant+PostMed	Avg									1.000	0.957**	0.896**	0.883**	0.931**	0.922**	-0.195
	Max										1.000	0.878**	0.889**	0.884**	0.876**	-0.216
PostLat+PostMed	Avg											1.000	0.954**	0.963**	0.894**	-0.325
	Max												1.000	0.913**	0.905**	-0.231
Composite	Avg													1.000	0.949**	-0.320
	Max														1.000	-0.265

KL= Preferred Kicking Leg, NKL= Non-Kicking Leg, Ant= Anterior, PostLat=Posterolateral, PostMed= Posteromedial, Avg= Average, Max= Maximum, LLI=Leg Length Inequality, *(p<0.05) , **(p<0.01)

Table 4.7: SEBT Correlations with LEFA (GRFv)

		Ant		PostLat		PostMed		Ant + PostLat		Ant + PostMed		PostLat + Postmed		Composite	
		Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Max
Standing	Avg	-0.265	-0.318	0.034	-0.088	-0.241	-0.314	-0.125	-0.242	-0.288	-0.363	-0.161	-0.291	-0.210	-0.315
Squat	Avg	0.391	0.315	0.089	0.277	0.593**	0.537*	0.266	0.346	0.591**	0.515*	0.484*	0.560*	0.484*	0.570**
	Max	0.514*	0.380	0.167	0.373	0.577**	0.489*	0.379	0.440	0.636**	0.512*	0.512*	0.569**	0.556*	0.605**
CMJ	Avg	-0.537*	-0.470*	-0.484*	-0.600**	-0.506*	-0.473*	-0.579**	-0.621**	-0.597**	-0.542*	-0.622**	-0.668**	-0.649**	-0.696**
	Max	-0.559*	-0.519*	-0.550*	-0.649**	-0.405	-0.379	-0.629**	-0.678**	-0.536*	-0.500*	-0.582**	-0.617**	-0.630**	-0.680**
SLDL	Peak	-0.004	-0.002	0.039	0.029	0.255	0.279	0.021	0.016	0.181	0.203	0.220	0.242	0.170	0.167
	time @ peak	0.233	0.353	0.356	0.262	0.111	0.047	0.336	0.356	0.186	0.195	0.283	0.179	0.285	0.170
	Slope to Peak	-0.402	-0.484*	-0.359	-0.328	-0.132	-0.029	-0.427	-0.469*	-0.278	-0.240	-0.301	-0.199	-0.361	-0.258
	Avg to Peak	-0.597**	-0.651**	-0.267	-0.279	-0.281	-0.220	-0.476*	-0.533*	-0.473*	-0.456	-0.366	-0.328	-0.474*	-0.460
	Impulse to Peak	0.023	0.103	0.255	0.179	0.027	-0.033	0.164	0.165	0.030	0.023	0.162	0.070	0.127	0.008
	GRFv to 300ms	-0.609**	-0.455	-0.254	-0.319	0.009	0.076	0.476*	-0.447	-0.271	-0.151	-0.133	-0.110	-0.311	-0.219

Avg= Average, Max= Maximum, CMJ=Countermovement Jump, SLDL= Single Leg Drop Landing, ms= milliseconds, SEBT= Star Excursion Balance Test, LEFA= Lower Extremity Functional Asymmetries, GRFv= Vertical Ground Reaction Forces, *(p<0.05) , **(p<0.01)

CHAPTER V

DISCUSSION

The main goal of this investigation was to explore the relationships between GRFv LEFA in four different tasks and those observed during performance of the SEBT in a group of healthy, recreationally trained men and women. Secondarily, relationships were examined within the tasks as well as within the SEBT. The secondary hypothesis examining relationships within the functional tasks was partially supported as several significant correlations between tasks were found. However, most correlations between tasks were moderate to low. Surprisingly, some significant correlations were negative (e.g. squatting compared to both CMJ and quiet standing). The secondary hypothesis examining relationships within the SEBT directional scores was also partially supported. There were several significant correlations between side-to-side differences in excursion directions and combinations of directions. However, the significant correlations which did exist between the individual excursions were low to moderate.

The main hypothesis was similarly supported by the findings that asymmetry on the SEBT also significantly correlated with many of the variables regarding asymmetry in GRFv during the functional tasks studied. Again, although there were significant correlations between the SEBT with squatting and CMJ, these correlations ($r \leq |0.680|$) are not strong enough to make an accurate prediction of asymmetries measured between tests. Additionally, the SEBT did not significantly correlate with LEFA found in standing and in the majority of variables measured in SLDL. With respect to several variables of the SLDL, the Ant excursion of the SEBT did have significant relationships, although they again were of limited strength ($r \leq |0.651|$).

Limb-length Inequalities within the Population:

Consistent with Blustein and D'Amico (1985), on average the population studied had an average absolute leg-length inequality of approximately 1.1 cm. Also, Knutson (2005) found that the left leg is anatomically longer in 53 to 75% of the population, consistent with our findings that 80% of the subjects (16 out of 20) had the left leg anatomically longer. None of the subjects measured had what would be considered a large anatomic leg-length difference, the upper limit of which was 2.5cm in one subject, which under classifications by McCaw and Bates, (1991), is still considered mild. Even though anatomic leg length differences were shown to be statistically significant in this population, when these asymmetries were correlated with asymmetries in functional movement GRFv and SEBT scores, there were no significant correlations found. Therefore, it is not anticipated that this minimal difference played a role in the results and that it was appropriate to normalize the SEBT reach distances by the average of the two leg lengths. The small inequalities observed in the functional leg-length difference measure further supports the notion that the subjects where highly symmetric with respect to their lower extremity structure

Comparison of Symmetry in Functional Tasks

While there were also no significant differences between the NKL and KL in the functional tasks, in absolute terms our population exhibited average GRFv asymmetries which ranged between 3-5% in the standing, squatting and CMJ measurements. This could be considered a measurable but not clinically significant level of asymmetry and is comparable to other studies finding low levels of asymmetry to be common in otherwise healthy populations.

Blaszwyk et al. (2000) with a similarly aged group (23.9±4.8 years), reported quiet standing asymmetry as a ratio of the more highly loaded leg compared to the contralateral side. They reported a ratio of 1.08±0.05, which is slightly less, but similar to our symmetry findings which calculate out to a ratio of ~1.1. Hodges et al. (2011) also observed a very similar population of young recreationally active college-aged students, using loaded squats. They reported an absolute average GRFv asymmetry of ~4% bilateral difference. Stephens et al. (2007) examined a similarly aged group of adults using CMJ as a test for LEFA, reporting an average dominant to non-dominant (not in absolute terms) asymmetry of ~2%.

SLDL measures in our study tended to have a wider range of absolute asymmetry depending on the variable measured (1-12%). However, the peak GRFv and average GRFv (from landing to peak) were on the order of 3%, both within a similar range of asymmetry as the other functional tasks. To our knowledge, there are no sources in the literature which report LEFA in this specific functional task, which is surprising considering the injury risks associated with landing on a single leg (Boden, Dean, Feagin, & Garrett, 2000; Olsen, Myklebust, Engebretsen & Bahr, 2004).

We found that most of our LEFA measures were shown to have good day to day repeatability which agreed with other sources dealing with LEFA repeatability (Hodges et al., 2011; Schot et al., 1994). However, maximum absolute instantaneous asymmetry in the squat and most of the SLDL absolute asymmetry measures only had mild to moderate repeatability ranging between α=0.50 - 0.70, with impulse to peak being around α=0.20. Because of the nature of absolute values, the repeatability of these variables when looked at in absolute terms made for a much reduced range over which measures could be reported. Therefore, many asymmetry measures, although strong, were reduced to much weaker repeatability when looked at in absolute terms. Like the SEBT measures mentioned below, the absolute LEFA measures showed similar weak repeatability. Due to the relatively low level of asymmetry in my subject pool, it is likely that given a much more asymmetric population, repeatability would be considerably stronger.

LEFA Correlations between Tasks

LEFA in squatting and CMJ were shown to have a moderate, but negative, correlation (r= -0.571 to -0.768). This is in contrast to Newton et al. (2006) which found a correlation between these tasks to be positive (r= 0.734). However, Newton et al. (2006) used squats of 80% of 1 repetition maximum, instead of the unloaded (bodyweight only) squats used in our study. One possible reason for the large difference may have had to do with the difference in intensity of CMJ and body-weight squats, since intensity level has been shown to have an effect on levels of asymmetry (Carpes et al. 2007, Sanderson, 1990; Smak et al., 1999). The level of intensity or effort of an 80% of 1 repetition maximum squat may be more similar to maximal effort CMJ, than that of bodyweight squats.

However, if the level of intensity was the factor which caused this change in LEFA, it would be logical that quiet standing would be even lower on the intensity spectrum than body-weight squats, justifying the rationale that quiet standing would correlate more highly to the squats than to the CMJ. This however was not the case, the standing task also correlated negatively to the squats and positively to the CMJ (although both correlations were only mildly to moderately strong). Carpes et al. (2007) noted in cyclists, that increase in exercise intensity elicited a reduction in pedaling asymmetry, and Sanderson (1990) and Smak et al. (1999) both found that intensity and changes in pedal speed significantly affected LEFA within a subject, but there was no clear pattern as to how changes occurred. This may relate to what we observed in that intensity seemed to change asymmetry, but not in a distinct linear or even consistent way.

It is unclear at this time if intensity was the actual cause of the difference seen here in comparison to the study by Newton et al., or if level of intensity or effort actually has an effect on LEFA during these tasks. Other factors that may be playing a role in the different asymmetry relationships between tasks could be differences in speed of motion or range of motion; or in the case of the SLDL, a difference in a unilateral task compared to bilateral tasks, all of which, to my knowledge, have no research existing on how these factors affect LEFA.

SEBT Scores Compared to Other Populations

Plisky et al. (2006) measured SEBT performance using the maximum reach in each direction and a composite of the three directions, all normalized to leg length and averaged between legs. They reported averages of the maximum scores to be Ant= 83.9±7.1, PostMed= 113.4±9.7, PostLat= 106.4±10.8, and Composite= 100.9±8.4 (Composite reported as the 3 excursion directions summed and divided by 3). Subjects examined in our population scored less than those reported by Plisky et al. (2006), mainly in the Ant excursion where our values were ~80% of theirs. This is possibly due to differences in age, activity level or ratio of men to women that existed between our population and their high school basketball player population, however, it is uncertain as to how these variables effect SEBT scores, if at all.

Leavey et al. (2010) studied a group more closely related to ours, and reported data instead based on the average of three trials, also normalized to leg length. This group consisted of healthy college students divided randomly into 4 groups. However, in this study they did not maintain a hands on hips position. They only tested the KL as the stance leg (i.e. they did not do a bilateral test). Again, our scores were similar to theirs, except for reduced reach distances in the anterior direction.

In both cases, although PostLat and PostMed scores seem to be very similar, it is uncertain as to the cause of the large disparity in Ant excursion scores from these studies compared to ours. We speculate that the criteria that we used may have made the Ant excursion in particular harder to perform a high score. We mandated that the heel of the stance foot not lift from the ground, the hands remain on the hips, and that the toe of the reach leg needed to lightly brush the measuring tape in order for it to be counted. We have anecdotally found that if any of these criteria are relaxed, it noticeably improves the Ant excursion scores, but only has a minor effect on the other directions.

Most of our SEBT scores showed good day-to-day repeatability in line with those of other studies using the SEBT (Munro et al., 2010; Plisky et al., 2006). However, some of the absolute side-to-side differences did see low repeatability in the individual excursions, such as Ant maximum and PostLat average and maximum, which then affected scores of repeatability in some of the absolute combination scores (i.e. Ant+PostLat, PostLat+PostMed and Composite scores). As stated above, the nature of absolute values made repeatability in this case appear to not be very high. An example of this is a measure such as Ant excursion scores, which averaged a difference of ~2cm from side to side. Excursions were only measured to the 0.5cm, beyond which accuracy was very difficult, causing even a day-to-day difference of 1cm to make the repeatability of measures seem very weak. However as stated above, it is likely that given a much more asymmetric population, this repeatability would be much stronger, given the wider range over which scores might occur.

Comparison of Symmetry in the SEBT

Average absolute asymmetries in the individual SEBT excursions, reported as a percentage of leg length, in the population that we studied ranged from just over 2% (Ant) to just under 4% (PostMed) with the Composite score averaging slightly under 7%. However, although the SEBT has been used in several studies which compare injured to uninjured legs, there is currently no study, to our knowledge, that reports scores in bilateral asymmetry using healthy uninjured subjects. Although Plisky et al. (2006) did use the SEBT to study asymmetry in their healthy subject population, average score totals were not reported. Instead the reported values are of the number of subjects over or under 4cm bilateral difference in each of the individual excursions, or 12cm for the composite score. This score doesn't take into account leg length, and as mentioned above, this population also varied somewhat considerably from ours. However, when using these criteria our population does appear to be a bit more symmetric than the Plisky et al. population. They showed that 40%, 53%, 57%, and 35% of scores were above the designated threshold (Ant, PostMed, PostLat, and Composite, respectively); compared to our scores of 20%, 20%, 40% and 15%. However, as stated above, the Ant and composite scores may have been significantly affected by the difference in criteria used especially during the Ant excursions, possibly allowing for significantly higher scores. With overall higher scores, it is more likely to be able to see a larger absolute difference.

Overall, based on the low levels of leg length asymmetry as well as the SEBT scores of our subjects, which were similar to other populations, we expect our results to be highly generalizable to the healthy, young adult population. This is further supported by the fact that there were no significant differences as a group between the NKL and KL in any of the excursion directions. This finding also suggests that limb dominance does not play a major role in SEBT scores.

Correlations between Asymmetry in SEBT measures

There has previously been some sources which discuss and compare excursion directions to each other (Hertel et al., 2006; Robinson et al., 2008a), but none which have compared asymmetries in excursion directions. Therefore, a novel component of this study is the comparison of asymmetries within the SEBT excursions. As might be expected, we found that there are significant correlations between the asymmetries in the three excursion directions studied, as well as the Composite and various combination scores. The Ant asymmetry scores significantly correlated to both the PostMed and PostLat excursions, however the PostMed and PostLat excursion asymmetries did not significantly correlate to each other. This is a possible indicator that these two excursions might have disparate underlying sources which cause an asymmetry in one score, while not significantly affecting the other. Although the stance leg appears to be doing a very similar task in both movements, the reaching leg is performing in nearly opposite directions. Because the main differences lie in one reach being lateral and the other medial, it might stand to reason that flexibility and/or strength in the muscles which work primarily in the frontal plane (i.e. hip abductors and adductors, ankle everters and inverters, or lateral spinal flexors) are the main factor which influences these two reaches. For instance, strength or flexibility in the adductors may influence the PostLat excursion more, while qualities of the abductors may influence the PostMed excursion. Hertel et al. (2006) showed that the 3 medially directed excursions were indicative of reach deficits in CAI stance leg ankles, with the PostMed excursion being most predictive of CAI. Therefore, it is likely that one or more of the underlying causes of CAI may also be attributed to differences in the PostMed and PostLat performance, but without further research, it is impossible to know definitively.

Asymmetries in SEBT compared to Functional Tasks

Comparable to the various functional tasks mentioned above, there were also many correlations between scores on the SEBT and LEFA during some of the tasks studied.   Many of the observations can be summed up into a few statements. The SEBT seemed to correlate most closely (although inversely) to the CMJ, although the correlations were only of mild to moderate strength ($r \leq |0.680|$). Standing did not correlate significantly to any of the SEBT measures. Side-to-side differences in the PostLat excursion scores did not significantly correlate with asymmetries in any of the functional tasks other than the CMJ. And, there were several significant correlations relating asymmetry in the SEBT to LEFA in the functional tasks, but these varied.

Based on the principle of specificity, it would make sense that the SEBT would not relate highly to standing, in that there are dissimilar requirements of flexibility, neural control or strength in the SEBT compared to that of standing. This suggests that sources contributing to asymmetry in these tasks might be different. However, if this were entirely the case, then standing would be expected to also not relate well to squatting and CMJ which both significantly correlate to standing and the SEBT in some measures. Therefore, at this time, it is uncertain as to why the SEBT seems to correlate clearly with squatting and CMJ, while correlating very weakly with standing.

Furthermore, many measures of the SLDL did not correlate significantly with the SEBT. It's notable, that of the 3 individual excursion directions, only the Ant excursions significantly related with the SLDL asymmetries. Therefore, it may be interesting to consider which aspects of the Ant excursion and SLDL are similar to each other but disparate to the other excursions and functional tasks. Hoch et al. (2011) did note that a significant correlation existed between dorsiflexion range of motion and performance in the Ant excursion direction (r=0.53) which didn't exist in the other two excursions, and Earle and Hertel (2003) found that the quadriceps was most active in the anteriorly directed excursions when measured via electromyography. Conversely Hubbard et al. (2007b) noted a significant correlation between hip abductor and extensor strength with performance in the PostMed and PostLat excursion scores (but not in the Ant excursions). Based on this, it might stand to reason that asymmetries in the SLDL, like the Ant excursion direction, may rely more on flexibility of the ankle plantarflexors and strong activation of the quadriceps, whereas asymmetry in the PostMed and PostLat excursions may rely more heavily on hip extensor and/or hip abductor strength. However, further research is required to clarify these relationships between asymmetric performance and the underlying sources.

Limitations of this study and its design

Limitations of the present study include a relatively small sample size and a homogenous population of college age, recreationally active subjects, with no previous major lower-extremity injuries. This potentially limits the generalizability of the findings. Also, injury history was self-reported, leaving opportunity for recall bias. Furthermore, because the study population was relatively symmetric, (none of which being over the 15% clinically significant level of asymmetry) and subjects with any sort of physical disability, past or present injury were excluded, results that may occur in more highly asymmetric people may have not been detected. These small levels of asymmetry could have limited many of the correlations from being significant, as clustering around the origin was common. Also, our relatively young and slim subject pool may make results less generalizable to an older and/or more overweight population.

Another detail which should be noted is that only a relatively small number of functional tasks were examined. Therefore, these results may not be generalizable to LEFA which may occur in other tasks such as walking, cycling, lifting, single-leg jumps, etc. The manner in which the functional tasks were performed also doesn't necessarily replicate how they may be performed in an everyday setting. The subjects were given direction on how to perform each functional task, all of which were performed in a non-fatigued state, thus potentially limiting the cross-over which may exists in sport or everyday settings. However, subjects were allowed as much freedom as possible without compromising the ability to compare one subject to another. For example, minimal directions were provided on SLDL technique as long as the same technique was used on both sides. Some subjects landed softly while others used a rapid deceleration upon ground contact.

Additional kinematics and/or muscle activation data during the functional tasks or during the SEBT may have allowed for further understanding of the sources of LEFA. In this case, only GRFv were used during functional tasks, and a measuring tape with visual identification of excursion scores was used on the SEBT. These methods do not necessarily pick up all existing LEFA and also make it difficult to tell what the source of the differences in measurements was (either in GRFv or in SEBT scores). For instance, assessment of joint moments or muscle activation might have allowed for better understanding of what joints or muscles contribute to asymmetric weight bearing in performing any of the given tasks. Lake et al. 2011, studying functional asymmetries in the power hang clean, stated that the asymmetries seen in GRFv are not seen in bar end power asymmetries. They assert that the body must compensate in some way to avoid the quite considerable ground kinetic asymmetries affecting the symmetry of the bar, supporting the idea that GRFv doesn't tell the whole story in some situations. However, in order for a test be useful for screening purposes, it must be simple to administer and easy to produce results. Additionally, due to the many degrees of freedom within the body to compensate, statistically finding a consistent source may be difficult, even in a very homogenous population (Lawson et al., 2006).

Another limitation is that repetitions were analyzed as a whole, without regard to individual parts of the movement. It is possible that differences in flexibility, muscle activation, etc. might affect one part of the movement differently than another part. For example there were several occurrences in our data during the squat and CMJ that a repetition showed a higher GRFv on one side during part of the squat or jump, but then shifted to the opposite side during a different phase in the movement, potentially allowing these noticeable asymmetries to average out. This might have changed our measures of asymmetry if the movements were analyzed in different phases. The underlying source of this is unlikely to be elucidated from GRFv data collection alone, but might be explained by a muscle's variation in function at different ranges of motion. For instance, a muscle like the gastrocnemius might have a stronger effect on symmetry as the knee is straighter, but less so as the knee bends and the gastrocnemius becomes slack, making the muscle's activation or flexibility less/more of a factor as the joint angles change. Therefore, a bilateral asymmetry in this example may show much less/more prominently in certain ranges of motion. A similar example could be that of the gluteus maximus, which as angle at the hip changes during a squat or CMJ, may become more/less active. Or as the angle of hip flexion decreases (and the muscle becomes more taught), a side-to-side difference in flexibility may present itself, while at a different point in the range of motion, there may not be enough tension on the muscle in order to observe a bilateral difference. However, in order to accurately create appropriate phases additional kinematic data may be necessary.

It is also important to acknowledge that we have analyzed subjects based on KL and NKL, however this is not the only way to determine leg dominance, but is possibly a more realistic representation than just classifying as left or right limbs alone. Limb dominance may be determined in a variety of other ways. Examples include choosing dominance based on which lower extremity bears a heavier load during a movement, which leg one performs better with in various single leg tasks, or which leg is preferred when performing a step-up type motion. However, we do think that it is reasonable to divide legs into KL and NKL as this has become a common method of determining limb dominance and also seems to be a natural development in having a leg that is better for stance and balance, and one that is better for fine motor functions (Myaguchi & Demura 2010; Gabbard & Hart, 1996).

Also, the method which we used to quantify asymmetry, i.e. ($GRFv_{NKL}$/($GRFv_{NKL}$+ $GRFv_{KL}$)*100), is only one of many methods which can be used. However, we do feel that this is a reasonable and straightforward method, with probably no more or less drawbacks than other current methods (discussed in more detail in the literature review). The usefulness of this calculation allowed us to easily compare LEFA and asymmetry in the SEBT, with asymmetry scores in percentage terms that, in my opinion, were more easily conceptualized than other common systems such as asymmetry indexes. It is also not anticipated that other means to quantify asymmetry levels would have an effect on the correlations when comparing tasks, since favoring of a given limb would not be altered by the algorithm just the number representing the level of asymmetry.

Summary, Conclusions and Practical Applications

Due to only mild to moderate correlations between tests, it is unlikely that any of the functional movement measurements used here or the measurements taken from the SEBT could independently be used to accurately predict LEFA on any of the other tests used in this study, at least in a relatively healthy population, without major levels of asymmetry. Furthermore, results of this study suggest that one should not assume that all LEFA are created equal or that bilateral asymmetries commonly measured via muscular strength, flexibility, LLI or neural control necessarily affect LEFA in all movements. The variation in LEFA from one movement to the other helps explain why an asymmetry might pose a strong potential injury risk for one sport or population, but might not in a sport or population not utilizing the same movement patterns. Effort should be put toward better understanding the sources of LEFA, understanding how a source might affect one functional task differently than another, and where the underlying areas of overlap exist.

Furthermore, coaches, trainers, and medical practitioners who might use these methods to screen for LEFA would likely be best to ensure that the tasks chosen are as specific as possible to the sport or activity in which the person is most likely to express functional asymmetries. A combination of screening methods which most accurately represent the demands of the sport or activity will likely be the most efficient and effective screening method. For instance, basketball players might need screening tools such as the CMJ and SLDL, as well as those which might incorporate single-leg jumps, cutting or running. Conversely, a standing or weighted squat test will likely not give an accurate assessment of injury risk or performance decrements to this same population. Similarly, a coach for a sport requiring fewer movement patterns, such as cycling or running, for the sake of time efficiency might be better off avoiding other LEFA screening methods outside of the single task required by their sport.

Future Research

With further research into establishing the sources of LEFA and how these sources might affect various functional asymmetries differently, one might be able to establish more accurate LEFA screening methods for individual activities. Details other than GRFv might also be useful to collect, such as joint moments, muscle activation, or joint range of motion data in order to better establish the specifics of why LEFA occur and also how they may potentially relate to adverse effects.

Also, understanding of how different variables affect LEFA such as exercise intensity, balance, motion complexity, fatigue, etc., would further help predict the correlations between movement patterns without the need to study a wide variety of movement patterns in a wide variety of environments. If the understanding of the individual variables was better it might then be possible to predict how changing a certain movement or task might change LEFA, without the necessity of testing a plethora of different movement patterns. This same concept would also apply to understanding to what extent LEFA may be affected by age, sex, obesity or a host of other possible population specific variables, which might help us understand the consequences of LEFA to specific populations or individuals.

Finally, further tests other than the SEBT might be developed and/or studied in trying to establish methods which more accurately predict a wider variety of LEFA. Based on the results of this study, it is unlikely that the SEBT alone will reliably predict LEFA in most cases.

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APPENDICES

APPENDIX A

Human Subjects Approval

Research Integrity & Compliance Review Office
Office of the Vice President for Research
321 General Services Building - Campus Delivery 2011
Fort Collins, CO
TEL: (970) 491-1553
FAX: (970) 491-2293

NOTICE OF APPROVAL FOR HUMAN RESEARCH

DATE:	October 13, 2010
TO:	Reiser, Raoul, Health & Exercise Science
	Israel, Richard, Health & Exercise Science
FROM:	Barker, Janell, CSU IRB 1
PROTOCOL TITLE:	Relationship between Functional Screening and Functional Asymmetries
FUNDING SOURCE:	NONE
PROTOCOL NUMBER:	10-2193H
APPROVAL PERIOD:	Approval Date: October 08, 2010 Expiration Date: September 16, 2011

The CSU Institutional Review Board (IRB) for the protection of human subjects has reviewed the protocol entitled: Relationship between Functional Screening and Functional Asymmetries. The project has been approved for the procedures and subjects described in the protocol. This protocol must be reviewed for renewal on a yearly basis for as long as the research remains active. Should the protocol not be renewed before expiration, all activities must cease until the protocol has been re-reviewed.

If approval did not accompany a proposal when it was submitted to a sponsor, it is the PI's responsibility to provide the sponsor with the approval notice.

This approval is issued under Colorado State University's Federal Wide Assurance 00000647 with the Office for Human Research Protections (OHRP). If you have any questions regarding your obligations under CSU's Assurance, please do not hesitate to contact us.

Please direct any questions about the IRB's actions on this project to:

Janell Barker, Senior IRB Coordinator - (970) 491-1655 Janell.Barker@Research.Colostate.edu
Evelyn Swiss, IRB Coordinator - (970) 491-1381 Evelyn.Swiss@Research.Colostate.edu

Barker, Janell

Barker, Janell

Colorado State University
Knowledge to Go Places

Research Integrity & Compliance Review Office
Office of the Vice President for Research
321 General Services Building - Campus Delivery 2011
Fort Collins, CO
TEL: (970) 491-1553
FAX: (970) 491-2293

Includes:
Approval is for a maximum of 30 participants ages 18-30 using the approved consent form to obtain consent.

Approval Period:	October 08, 2010 through September 16, 2011
Review Type:	FULLBOARD
IRB Number:	00000202

APPENDIX B

Consent Form

Consent to Participate in a Research Study

Colorado State University

TITLE OF STUDY: Relationship between Functional Screening and Functional Asymmetries

PRINCIPAL INVESTIGATOR: Raoul F. Reiser, II

Contact Information: 970-491-7980, RFReiser@CAHS.Colostate.edu

WHY AM I BEING INVITED TO TAKE PART IN THIS RESEARCH? *You are being asked to volunteer for this research because you are a relatively fit healthy adult between the ages of 18-30 years with no current injuries (pain and soreness free for the last month). You must be free of any current or chronic low-back pain, leg pain, or orthopedic problems. You must be regularly (at least once a week) participating in activities that require jumping and squatting. You must be willing to perform jumping, squatting and standing tasks as well as balance and range of motion tests for the lower extremities.*

WHO IS DOING THE STUDY? *This research is being performed by Raoul F. Reiser II, Ph.D. of the Health and Exercise Science Department. Trained graduate students, undergraduate students, research associates, or research assistants are assisting with the research.*

WHAT IS THE PURPOSE OF THIS STUDY? *It is well documented that asymmetries exist in the lower extremity (i.e., one leg is naturally favored over the other), and that these asymmetries may influence performance and injury risk. However, it is not well understood which screening methodologies may be predictive of such asymmetries, and how various movements in which these asymmetries exist relate to each other. The goal of this investigation is to clarify the relationship between screening methods and asymmetric force production of the lower extremities.*

WHERE IS THE STUDY GOING TO TAKE PLACE AND HOW LONG WILL IT LAST? *This research project will take place in the Clinical Biomechanics Laboratory located on the 2nd floor of Moby Arena (B wing) on the CSU main campus. Your involvement will last roughly 1-1.5 hours. If you decide to return for a repeat visit, to help us determine the reliability of our measures, your involvement will double (2-3 hours total for both visits). However, a second visit is not required.*

WHAT WILL I BE ASKED TO DO? *If you agree to participate we will test the active range of motion (the range of motion which you can achieve through activation of muscles surrounding the joint alone) of the hip and ankle of each leg. You will also perform a common balance test known as the Star Excursion Balance Test. This test will have you in a standing position to start followed by examination of how far you can place a foot in front, behind, and to your side. After this you will conduct a short series of standing, unresisted squatting, maximal effort vertical jumping and single leg landing trials stepping down from a small box.*

While performing all tasks, the forces under your feet will be measured. There are no needles or other devices that will break the skin. We will lead you through a warm-up procedure, have you practice the task at submaximal levels of effort, spot you during the jumps and squats, and give you rest between tasks.

ARE THERE REASONS WHY I SHOULD NOT TAKE PART IN THIS STUDY? *You should not volunteer for this study if you do not meet the criteria outlined above. Additionally, if you have any preexisting conditions that would lead you to believe that you are highly asymmetric (significantly favor one side over the other during otherwise symmetric tasks), you should not participate. If you are a woman, you should not participate if you are pregnant. Regardless of gender, you should also not participate if you have any reason to believe you might be injured by these activities. All physical exertions are controlled by you.*

WHAT ARE THE POSSIBLE RISKS AND DISCOMFORTS? *As with all physical activity, there is a risk for injury. The most likely risks associated with this study are muscle strains and pulls as well as muscle fatigue. That fact that you are relatively fit, are familiar with the squat and jump, and that we will spot you and give you plenty of opportunity to warm-up minimizes these risks. During standing trials we will also have a spotter beside you in the case you lose your balance. We will also have a railing nearby to grab onto. Furthermore, we suggest you not "lock" your knees when standing, as this can sometimes cause lightheadedness.*

You are also given breaks between each task to minimize risk for injury. If at any time you feel uncomfortable, pain, or are excessively tired, you should discontinue effort and tell the investigator. It is not possible to identify all potential risks in research procedures, but the researcher has taken reasonable safeguards to minimize any known and potential, but unknown, risks.

WILL I BENEFIT FROM TAKING PART IN THIS STUDY? *While this study should provide useful information on lower limb asymmetries, there are no current personal benefits to participation in this study.*

DO I HAVE TO TAKE PART IN THE STUDY? *Your participation in this research is voluntary. If you decide to participate in the study, you may withdraw your consent and stop participating at any time without penalty or loss of benefits to which you are otherwise entitled.*

WHAT WILL IT COST ME TO PARTICIPATE? *There are no costs to participate in this study.*

WHO WILL SEE THE INFORMATION THAT I GIVE? *We will keep private all research records that identify you, to the extent allowed by law.*

Your information will be combined with information from other people taking part in the study. When we write about the study to share it with other researchers, we will write about the combined information we have gathered. You will not be identified in these written materials. We may publish the results of this study; however, we will keep your name and other identifying information private.

We will make every effort to prevent anyone who is not on the research team from knowing that you gave us information, or what that information is. For example, your name will be kept separate from your research records and these two things will be stored in different places under lock and key. You should know, however, that there are some circumstances in which we may have to show your information to other people. For example, the law may require us to show your information to a court. The files containing information about you will be identified with a code, such as "FSAS01", where FSAS is short for Functional Screening and Asymmetry Subject and 01 is a subject number. Upon completion of data collection and verification of results, the list linking your name to the code will be destroyed.

CAN MY TAKING PART IN THE STUDY END EARLY? *Your participation in the study may end early if you are unable to perform the tasks as described. Your participation may also end early if you experience any pain or discomfort.*

WILL I RECEIVE ANY COMPENSATION FOR TAKING PART IN THIS STUDY? *There is no monetary compensation for your involvement in the study. However, if you are a student in an HES activity course (HES 100O, HES 100N, or HES 332F) your participation qualifies you for "extra credit". Speak with your course instructor for details.*

WHAT HAPPENS IF I AM INJURED BECAUSE OF THE RESEARCH? *The Colorado Governmental Immunity Act determines and may limit Colorado State University's legal responsibility if an injury happens because of this study. Claims against the University must be filed within 180 days of the injury.*

In light of these laws, you are encouraged to evaluate your own health and disability insurance to determine whether you are covered for any physical injuries or emotional distresses you might sustain by participating in this research, since it may be necessary for you to rely on your individual coverage for any such injuries. Some health care coverages will not cover research-related expenses. If you sustain injuries, which you believe were caused by Colorado State University or its employees, we advise you to consult an attorney.

WHAT IF I HAVE QUESTIONS? *Before you decide whether to accept this invitation to take part in the study, please ask any questions that might come to mind now. Later, if you have questions about the study, you can contact the investigator, Raoul F. Reiser II, Ph.D. at 970-491-6958. If you have any questions about your rights as a volunteer in this research, contact Janell Barker, Human Research Administrator at 970-491-1655. We will give you a copy of this consent form to take with you.*

Your signature acknowledges that you have read the information stated and willingly sign this consent form. Your signature also acknowledges that you have received, on the date signed, a copy of this document containing 3 pages.

____ _____________________
Signature of person agreeing to take part in the study Date

____
Printed name of person agreeing to take part in the study

____ _____________________
Name of person providing information to participant Date

____
Signature of Research Staff

APPENDIX C

Health and Activity Questionnaire

Relationship between Functional Screening and Functional Asymmetries

(Fall-Spring 2010-11)

Health & Activity Questionnaire Date & Time: _______________

Subject ID #___________________________ Sex: **M** or **F**

Are you between the ages of 18-30 years? __________ DOB: ____/____/____

Are you healthy (pain, soreness, and injury free)? ________________________________

Have all previous injuries healed at least 4 weeks ago? ____________________________

Women only: Are you pregnant? ____

Do you have now, or ever had, chronic low-back pain or scoliosis? ____________________

Do you have any orthopedic or arthritic problems? _______________________________

Do you have any prior injuries or conditions that would cause you to favor one side of the body while performing otherwise symmetric tasks (broken bones, torn muscles and ligaments, a leg-length differential, ACL reconstruction etc.)? ________________________________

____

Do you use any bilateral corrective devices (heel lift, brace, etc.)?____________________

Have you regularly (at least once per week) participated in a recreational activity which includes squatting and jumping within the past 8 weeks? __________________________

Describe these activities ____

____

Any current or chronic medical conditions (heart disease, diabetes, asthma, allergies, epilepsy, etc.) or medications that would prevent or interfere with maximal physical activity?__________

____

____

Please estimate your Height:________ Weight:_________ ⇨ BMI___________

Should you be identified as a good match for this project based on your answers, can we schedule a 2 hour block of time for you to come in to the lab? ____________________________

Should you be scheduled for a visit to the lab to participate in the study, will you refrain from major physical activity using the legs 48 hours prior to lab visits and refrain from excessive caffeine and all ergogenic aids on the days of the lab visit? _______________________

Should you be asked to participate in this study, do you agree to wear clothing that does not restrict motion (t-shirt, shorts, comfortable shoes, without excessive heel lift, that would be appropriate for squatting and jumping tasks)? ______________________________________