2009

Running Impulse, Functional Strength and Dynamic Balance Asymmetry in Healthy Recreational Runners

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RUNNING IMPULSE, FUNCTIONAL STRENGTH AND DYNAMIC BALANCE ASYMMETRY IN HEALTHY RECREATIONAL RUNNERS

BY

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A Thesis submitted to the
Department of Sport and Exercise Sciences
in partial fulfillment of the
requirements for the Degree of
Master of Science in
Movement Science
with a specialization in
Biomechanics

Miami Shores, Florida
2009

BARRY UNIVERSITY
MIAMI SHORES, FLORIDA

December 16, 2009

To the Dean of the School of Human Performance and Leisure Sciences:

I am submitting herewith a thesis written by Wesley Windham entitled "Running impulse, functional strength, and dynamic balance asymmetry in health recreational runners." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science with a major in Movement Science.

Dr. Kathy Ludwig, Thesis Committee Chair

We, members of the thesis committee,
have examined this thesis
and recommend its acceptance:

Accepted:

Chair of Department of Sport and Exercise Sciences

Accepted:

Dean of School of Human Performance and Leisure Sciences

Acknowledgements

I would like to thank my committee, who aided in the eventual completion of this thesis project. Over the past several years, these individuals were also greatly involved in my overall development and progress in the pursuit of my Bachelor's and Master's Degrees in the Exercise Sciences. Their advice and teaching, greatly and positively influenced the academic decisions I made.

My thesis chair, Dr. Kathy Ludwig has been extremely supportive and instrumental in the ontogenesis of this thesis project. Her strong work ethic, open-mindedness, and insightfulness are invariable and inspiring. She is a provocateur of knowledge and has always encouraged me toward a burgeoning cognizance. Her teaching occupation might as well have been her avocation and her astute comicality accorded a boisterous learning environment.

My advisor and thesis committee member, Dr. Claire Egret, whose door is always open and whose air-conditioning vent is always closed. As my advisor, Dr. Egret continuously offered help and advice, academically and professionally. Her teaching was adroit, incorporated a mélange of effective strategies, and was conveyed with panache. Her civility, kindness and professionalism, enabled a rapport to be built, during the short time that I have known her. Her knowledge of physics and biomechanics is unprecedented, she is truly a Littérateur.

My undergraduate advisor and thesis committee member, Dr. Constance Mier, who always offered great advice, I owe extensive appreciation. It was a conversation with Dr. Mier that firmly solidified my decision to come to Barry to pursue the B.S. in

Exercise Science, and subsequently the M.S. in Biomechanics Degrees. Her advice was interminably unbiased and was sincerely based on what she thought was best for me. Her support and assistance in my thesis project demonstrates her dedication and thoughtfulness as an educator and scientist.

Abstract

Studies on running mechanics have assumed that normal healthy running is a symmetrical process, yet bilateral asymmetry has been found in healthy individuals. The causes of asymmetries remain unclear, but could be the result of lateral dominance, in which the dominant limb (D) provides more propulsion and the non-dominant limb (ND) provides more support. The purpose of the study was to test the functional asymmetry hypothesis, asymmetry in functional strength and dynamic balance in healthy, recreational runners. Twenty eight (male 14, female 14) healthy runners (mean ± sd, age 27.39 ± 6.39 years; mass 67.48 ± 9.15 kg; weekly training 37.35 ± 24.51 km; running history 8.88 ± 6.99 years) volunteered to participate in the study. Participants were asked to run across a force plate at 3.5 ± 5% m/s, in which vertical (VI) and propulsive impulse (PI) were measured. The Star excursion balance test (SEBT) and Triple hop distance test (THD) were used to test dynamic balance and functional strength. A two-tailed, paired samples *t*-test was calculated to compare the mean scores between the D and ND limbs in each of the measures. No significant differences were found between D and ND limbs in any of the tests. However, an Absolute Asymmetry Index (ASI) revealed that the participants in this study exhibited some level of asymmetry in all of the measures tested. Asymmetries exist in healthy recreational runners, but they are not related to dominance. Levels of asymmetry can vary greatly between and within individuals in different tests. The asymmetries could be the result of individual compensations or individual differences in lateral dominace in varying tasks.

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Introduction

Running mechanics have been studied extensively over the past several decades to explain the causes of injury (Zifchock, Davis, & Hamill, 2006), describe the kinetics and kinematics of elite performers (Williams, Cavanagh, & Ziff, 1987) and to determine differences between males and females (Ferber, Davis, & Williams, 2003). It has been assumed that normal healthy running is a symmetrical process, thus data is collected from only one side (Ferber, et al., 2003) Asymmetry of gait is normally studied as a result of a pathological condition or injury. For instance, asymmetry of gait has been studied as a consequence of pathological conditions, such as leg length discrepancy, leg amputation, and anterior cruciate ligament (ACL) injury (Ferber, Osternig, Woollacott, Wasielewski, & Lee, 2004; Silverman, Fey, Portillo, Walden, Bosker, & Neptune, 2008; White, Gilchrist, & Wilk, 2004). On the other hand, some researchers have suggested that gait is comparable to other tasks that demonstrate laterality and is naturally asymmetrical (Sadeghi, Allard, & Duhaime, 1997). A number of studies have examined asymmetry of strength, walking, and running mechanics in able-bodied and injured persons (Niemuth, Johnson, Myers, & Thieman, 2005; Sadeghi, Allard, & Duhaime, 1997; Zifchock, Davis, Higginson, McCaw, & Royer, 2008). However, the question regarding natural asymmetry levels of running gait has not been fully answered. If asymmetry is natural and the lower extremities are responsible for different tasks, as suggested by Sadeghi, et al., (1997) then naturally there will be strength imbalances that should reflect the task demands of each leg. Subsequently, some level of asymmetry in kinetics and strength would be expected, the extent of which is unknown.

Kinetic, kinematic and electromyographic (EMG) asymmetries have been found in healthy participants during normal walking (Ferber, et al., 2004; Gundersen, Valle, Barr, Danoff, Stanhope, & Snyder-Mackler, 1989; Herzog, Nigg, Read, & Olsson, 1989; Ounpuu & Winter, 1989). Gundersen, et al., (1989) found significant limb differences within subjects, in 10 out of 12 kinematic variables that were measured while participants walked at a self-selected pace. Ounpuu and Winter (1989) found between leg differences in plantar-flexor EMG during walking in normal adults and suggested that the assumption of symmetry might not be accurate. Additionally, control subjects demonstrated asymmetrical hip moment and power patterns while walking at a comfortable, self-selected pace (Ferber, et al., 2004). Likewise, Herzog, et al., (1989) quantified symmetry/asymmetry of normal human gait in 34 kinetic gait variables and calculated a symmetry index, which varied between ±0.1 and ±711.7 percent. Apparently, normal walking of able-bodied persons reflects some level of asymmetry. Indeed, Sadeghi, Allard, & Duhaime (1997) proposed a functional asymmetry hypothesis (FAH), in that one limb is principally responsible for propulsion while the contralateral limb is largely responsible for support. They used principal component analysis (PCA) to distinguish which muscle powers and associated mechanical energies were related to the support and propulsion functions of each leg. They found altered task priorities between the left and right hips which they postulated could be related to limb dominance. Moreover, Sadeghi further distinguised altered task priorities at the ankle, knee and hip level for the right and left lower extremities (Sadeghi, 2003; Sadeghi, et al., 2002; Sadeghi, Prince, Sadeghi, & Labelle, 2000).

On the other hand, not all research is in agreement with this hypothesis (Goble, Marino, & Potvin, 2003; Seeley, Umberger, & Shapiro, 2008). Goble, Marino, and Potvin (2003) used a force plate to measure eleven gait parameters at slow, normal and fast walking velocities and determined that generally, symmetry was sustained across parameters and velocities. Interestingly, significant differences between legs were found in two parameters at the slow velocity, stance time was longer for the left leg and peak vertical force occurring during the propulsive phase was greater for the right leg. The researchers conceded that these results could be interpreted to support the functional asymmetry hypothesis. However, they indicated that as velocity increased asymmetries between legs decreased and suggested Dynamic Systems Theory as an explanation for the results. In a test of the functional asymmetry hypothesis, Seeley, Umberger, and Shapiro (2008) measured vertical and propulsive impulse during slow, preferred and fast walking speeds. They found no significant differences between legs for vertical or propulsive impulse at the slow or preferred walking speeds. Conversely, dominant limb propulsive impulse was 7% greater at the fast walking speed. Even though the studies are not completely in agreement with one another the results indicate that some level of asymmetry seems to be normal in able-bodied walking gait.

Typically, the perspective of studies that examine asymmetry in runners involve injury (Niemuth, et al., 2005; Zifchock, Davis, & Hamill, 2006; Zifchock, Davis, Higginson, McCaw, & Royer, 2008) or specific populations (Williams, Cavanagh, & Ziff, 1987). For instance, Zifchock, Davis, and Hamill (2006) compared asymmetry levels in never-injured and previously injured female runners. Suprisingly, symmetry indices of the eight kinetic variables measured were not significantly different between groups. In fact, natural levels of asymmetry were found in the never-injured group that ranged from 3.1% for peak vertical ground reaction force to 49.8% for peak lateral ground reaction force. Likewise, a comprehensive investigation of strength, structure, kinetic and kinematic parameters resulted in comparable levels of asymmetry in previously injured and non-injured runners (Zifchock, Davis, Higginson, McCaw, & Royer, 2008). Although, hip internal rotation range of motion and peak tibial acceleration were elevated in the injured side of the injured runners. Furthermore, in a large study of elite female distance runners natural levels of asymmetry were found in ground reaction force, predominantly in the mediolateral component (Williams, Cavanagh, & Ziff, 1987).

Studies have specifically analyzed asymmetry in able-bodied runners, as well (Gales & Challis, 2005; Karamanidis, Arampatzis, & Bruggemann, 2003; Zifchock & Davis, 2008). Gales and Challis, (2005) found asymmetrical ground reaction force variables in male and female runners at slow and fast running speeds. Similarly, Karamanidis, Arampatzis, and Bruggemann, (2003) found asymmetric kinematic parameters during a variety of running techniques. Additionally, Zifchock and Davis (2008) found high variability between sides in four kinetic and four kinematic parameters in testing consecutive versus non-consecutive footstrikes. Seemingly, there are natural levels of asymmetry in running mechanics and although there are some minor differences between injured and uninjured runners, the asymmetry indices are similar between groups.

Apparently, some level of kinetic and kinematic asymmetry is natural, and some level of strength imbalance would be expected. However, some researchers have speculated that strength imbalance could be implicated as a cause of injury in runners and have targeted individual muscle groups for analysis. Niemuth, et al., (2005) established a correlation between hip abductor, adductor and flexor muscle group strength imbalance and lower extremity overuse injury in runners. In the injured runners, the injured side hip abductor and flexor muscle groups were weaker and the hip adductor group was stronger. Interestingly, leg dominance had no association with injury, 53.3% occurred in the dominant side and 46.7% in the non-dominant side. In the non-injured runners, no side-to-side hip group muscle strength imbalances were found. Conversely, Jacobs, Uhl, Seeley, Sterling, and Goodrich, (2005) found that hip abductor strength was significantly larger in the dominant leg of healthy subjects with an average side-to-side strength difference of approximately 11 percent. Again, it would follow that natural assymetry in gait would coincide with natural asymmetry in strength.

Moreover, certain strength imbalances are logically expected assuming the functional asymmetry hypothesis is valid. Essentially, muscle groups that are responsible for propulsion should be stronger or more powerful in the dominant leg and muscle groups that are responsible for support should be stronger in the non-dominant leg. Intriguingly, Siqueria, Pelegrini, Fontana, and Greve (2001) found that runners exhibited significantly higher knee extensor power in the non-dominant leg and suggested it was due to the greater muscular action of the knee in the supportive leg. However, muscle groups that are involved in support are also involved in propulsion at different stages of the gait cycle (Belli, Kyrolainen, & Komi, 2002; Liu, Anderson, Pandy, & Delp, 2006; Novacheck, 1998). Consequently, it may be more appropriate to measure the coordinative strength or function of all the muscle groups in each leg in the role of a supportive or propulsive function. Indeed, researchers have used field tests to measure unilateral differences in functional strength (Hamilton, Shultz, Schmitz, & Perrin, 2008; Reid, Birmingham, Stratford, Alcock, & Giffin, 2007; Ross, Langford, & Whelan, 2002) and dynamic balance (Bressel, Yonker, Kras, & Heath, 2007; Gribble, Hertel, Denegar, & Buckley, 2004; Plisky, Rauh, Kaminski, & Underwood, 2006; Thorpe & Ebersole, 2008) in a variety of athletic populations. The advantage of field tests are that they do not require expensive equipment, can be conducted in non-laboratory environments, and provide a wholistic measure of the variable being tested.

Statement of the problem

Symmetry of running mechanics has been assumed and asymmetry is normally associated with pathological conditions and is sometimes implicated as a possible cause of injury. However, laterality is prevalent in nearly all activities and logically should demonstrate itself in running, as well. The functional asymmetry hypothesis has been proposed and tested during normal walking gait. Thus far, only a few studies have tested this hypothesis and results have been mixed. Running studies have reported or investigated asymmetry, yet none have explicitly investigated the asymmetry from this perspective. Furthermore, asymmetry in functional strength and dynamic balance that would support this hypothesis has not been tested.

Purpose of the study

The purpose of the study is to test the functional asymmetry hypothesis, asymmetry in functional strength and asymmetry in dynamic balance in healthy, recreational runners. The study will use ground reaction force (GRF) data to test for kinetic asymmetry levels and field tests to measure functional strength and dynamic balance in the lower extremities. Specifically, the methods of Seeley, Umberger, & Shapiro, (2008) will be used; the vertical impulse (VI) and propulsive impulse (PI) of each leg will be measured with the force plate and compared in the dominant (D) and non-dominant limbs (ND). The Star excursion balance test (SEBT) and the Triple hop distance test (THD) will be used to test the coordinated function of the dominant and non-dominant limb in supportive and propulsive roles.

Significance of the study

The mechanics of running have been investigated considerably, yet many questions remain. A better understanding of kinetic, functional strength, and dynamic balance asymmetry in healthy runners could aid clinicians, scientists, coaches, and trainers. The establishment of a functional asymmetry condition in healthy persons could change the way practitioners view symmetry of the lower extremities. Clinicians, coaches and trainers could use the information to develop more effective training and rehabilitation programs that work to enhance the supportive and propulsive functions of the lower extremities. Researchers would have a new perspective to consider when looking at injury and performance concerns.

Limitations

The limitations of this study are as follows:

1. Participants' motivation levels may affect performance on the tests.
2. Participants' involvement in strength training may affect performance on the tests.

Delimitations

The delimitations of this study are as follows:

1. The tests (GRF, SEBT, THD) will be conducted at the Barry University Biomechanics Laboratory.
2. GRF of the dominant and non-dominant limb will be measured in non-consecutive foot strikes.
3. Participants will be recreational, non-professional runners.
4. Participants will be running at least 15 miles per week, for the past 3 months.
5. Participants will be injury free in the lower extremities and low back at time of data collection.
6. Participants will wear their normal training shoes during the tests.

Assumptions

The study is subject to the following assumptions:

1. Participants will understand the directions given in the study.
2. Participants will perform the tests to the best of their abilities.
3. The equipment used is valid and reliable.

Research Hypotheses

1. The dominant limb will have greater propulsive impulse.
2. The non-dominant limb will have greater vertical impulse.
3. The dominant limb will perform better on the Triple hop distance test.
4. The non-dominant limb will perform better on the Star excursion balance test.

Definition of Terms

Absolute asymmetry index: Absolute difference between a test measure in the dominant and non-dominant limb, in which a value of zero indicates perfect symmetry (Karamanidis, et al., 2003).

Dominant limb: Limb used to perform voluntary tasks like kicking a ball (Sadeghi, et al., 2000).

Functional asymmetry hypothesis: One limb is principally responsible for propulsion while the contralateral limb is largely responsible for support during walking (Sadeghi, et al., 1997).

Gait symmetry: The limbs function identically during walking or running (Sadeghi, et al., 2000)

Ground reaction force: "A single equivalent force equal to the sum of a distribution of forces applied to a surface" (Robertson, Caldwell, Hamill, Kamen, & Whittlesey, 2004, p.285).

Non- dominant limb: "Limb that provides postural and stabilizing support" while dominant limb performs task (Sadeghi, et al., 2000).

Principal component analysis: Multivariate statistical approach that facilitates interpretation of data based on variance estimation, explains much of the variance in data with relatively, few principal components (Sadeghi, et al., 2000).

Propulsive impulse: Integration of the anterior-posterior GRF over the time that the force is oriented in the anterior direction(Seeley, Umberger, & Shapiro, 2008).

Star excursion balance test: A unilateral, functional joint stability task that measures dynamic postural control, lower extremity balance and neuromuscular control (Thorpe & Ebersole, 2008).

Triple hop distance test: A clinical test that is used to detect strength imbalance in the lower extremities (Hamilton, Shultz, Schmitz, & Perrin, 2008).

Vertical impulse: Integration of the veritical GRF over the stance time; used to represent support function (Seeley, Umberger, & Shapiro, 2008)

LITERATURE REVIEW

The purpose of this study is to determine if healthy, recreational runners exhibit natural levels of asymmetry in their running impulse, balance and strength. Specifically, a functional asymmetry hypothesis will be tested that suggests that the dominant limb provides more propulsion and the non-dominant limb provides more support during the stance phase of the gait cycle. Additionally, the supportive and propulsive function of the dominant and non-dominant limb will be tested with the Star excursion balance test (SEBT) and the Triple hop distance test (THD).

This chapter is divided into the following sections; (a) walking asymmetry, (b) running asymmetry, (c) functional asymmetry, (d) strength imbalance, (e) instrumentation, and (f) summary.

Walking Asymmetry

Gait asymmetry is exhibited by individuals with irregular conditions (Ferber, et. al., 2004; Silverman, et. al., 2008; White, et. al., 2004). For example, ACL deficient and ACL reconstructed groups displayed significantly greater non-injured knee positive work and knee extensor angular impulse compared to the contralateral injured limb, while walking at a comfortable self-selected pace (Ferber, et. al., 2004). Likewise, unilateral transtibial amputees demonstrated greater positive knee work, positive and negative ankle work, and propulsive impulse in the intact leg compared to the residual leg, at a variety of walking speeds (Silverman, et. al., 2008). Similarly, participants with a leg length discrepancy of greater than 1 cm exhibited asymmetric loading patterns walking at self-selected speeds (White, et. al., 2004). The shorter limb experienced larger peak weight acceptance force, weight acceptance rate and peak push-off force, while the push-off force rate was greater in the longer limb.

It would be expected that individuals with disparate anatomical or structural conditions in the lower extremities would demonstrate asymmetric loading patterns. Clearly, in these dissimilar conditions compensatory mechanisms are necessary to sustain forward ambulation. Therefore, a joint contralateral to the injured limb may bear a greater part of the load or produce a greater amount of work. These compensatory mechanisms are particularly evident when healthy controls demonstrate symmetry. In fact, healthy controls exhibited symmetrical propulsive impulse (Silverman, et. al., 2008) and symmetrical knee joint moments and powers (Ferber, et. al., 2004) in contrast to the injured participants. However, gait asymmetry can not be solely explained by a needed compensatory mechanism, as it exists in healthy individuals, as well (Ferber, et. al., 2004; Gundersen, et. al., 1989; Herzog, et. al., 1989; Ounpuu & Winter, 1989).

Interestingly, Ferber, et. al., (2004) found that healthy controls displayed asymmetrical hip joint moment and power patterns, where as the knees were symmetrical. Conversely, the ACL deficient participants displayed asymmetrical knee joint moment and power patterns, where as the hips were symmetrical. The intriguing reversal of asymmetry demonstrated in this group of participants suggests that asymmetry may be an inherent condition. Indeed, side-to-side differences have been found in healthy participants in EMG muscle activity (Ounpuu & Winter, 1989), kinetics (Ferber, et. al., 2004; Herzog, et. al., 1989), and kinematics (Gundersen, et. al., 1989), during walking.

Ounpuu and Winter (1989) found asymmetrical EMG activity in seven muscles during walking in normal adults. Herzog, et. al., (1989) quantified symmetry/asymmetry of normal human gait in 34 kinetic gait variables and calculated a symmetry index, in which a value of zero indicates that there is no difference between the right and left limbs. Gait symmetry was defined as the perfect agreement of the measured variables of the left and right leg. Most of the mean symmmetry indices were close to zero in the vertical and anterior-posterior components of the ground reaction force. However, there were substantial deviations from zero in the medial-lateral component of the ground reaction force, most prominently in the positive and negative impulse. Similarly, Gundersen, et. al., (1989) found significant differences between limbs in stance time and maximum knee extension in healthy participants. However, a within-subjects analysis revealed that the participants had significant differences in subject-X-limb interaction in10 out of 12 kinematic variables.

There were large ranges and standard deviations for many of the variables in these studies hence, pooling data could mask the level of asymmetry within participants (Gundersen, et. al., 1989; Herzog, et. al., 1989; Ounpuu & Winter, 1989). Subsequently, it appears that walking gait is not a completely symmetrical process in healthy individuals. On the other hand, the lack of uniformity across participants in the variables that are asymmetrical indicate that gait asymmetry is random and unpredictable. Accordingly, the asymmetry could be a manifestation of individual compensations that naturally occur during gait.

Running Asymmetry

The mechanics of running have been studied considerably, yet there is limited information on asymmetry due to the apparent assumption of symmetry. Consequently, extensive reviews of running mechanics do not address the issue of bilateral asymmetry (Eston, Mickleborough, & Baltzopoulos, 1995; Novacheck, 1998). However, there are studies that have reported kinetic and kinematic asymmetry in a variety of healthy running populations (Gales & Challis, 2005; Karamanidis, et. al., 2003; Williams, et. al., 1987; Zifchock & Davis, 2008; Zifchock, et. al., 2006; Zifchock, Davis, Higginson, et. al., 2008). These studies have utilized various forms of a symmetry index (SI) to quantify the level of asymmetry in runners and have reported a wide range of values. Gales and Challis (2005) found SI values in experienced runners that ranged from ~ 1.0% to ~5.0% in impact peak, active peak, and impulse of the vertical ground reaction force (VGRF). Elite female distance runners had SI values that ranged from 3.9% for peak VGRF to 28.3% for change in lateral velocity (Williams, et. al., 1987). Male and female runners exhibited SI values that ranged from 5.0% for instantaneous loading rate of the GRF to 24.3% for knee adduction angle (Zifchock & Davis, 2008). Female long distance runners had SI values that ranged from 2.95% for knee angle at touchdown to 54.68% for hip angle velocity at ground contact (Karamanidis, et. al., 2003). Zifchock, et. al., (2006) reported SI values in healthy controls that ranged from 3.1% for peak VGRF to 49.8% for peak lateral GRF. Likewise, uninjured runners exhibited SI values that ranged from 3.0% for impact peak GRF to 19.3% for hip internal rotation velocity (Zifchock, Davis, Higginson, et. al., 2008). Clearly, the evidence suggests that healthy runners exhibit some level of asymmetry in a variety of kinetic and kinematic parameters.

Interestingly, asymmetry is maintained across a variety of conditions, such as running speed, stride rate and injury status (Gales & Challis, 2005; Karamanidis, et. al., 2003; Zifchock & Davis, 2008; Zifchock, et. al., 2006; Zifchock, Davis, Higginson, et. al., 2008). There was no significant difference in SI values between control and tibial stress fracture groups in eight kinetic variables (Zifchock, et. al., 2006). Equally, Zifchock, Davis, Higginson, et. al., (2008) found no significant difference in SI values between controls and unilaterally injured runners, in measures of strength, structure, kinetics, and kinematics. Karamanidis, et. al., (2003) found that the SI values were generally maintained during nine different conditions, three stride rates at three velocities. The authors concluded that the parameter itself was responsible for the reproducibility and symmetry of the kinematic data and not the running velocity or intentional change in stride frequency. Similarly, Gales & Challis (2005) found no significant difference in SI values in VGRF variables at 3, 4, or 5 m/s measured for 700 pairs of footfalls. Moreover, Zifchock & Davis (2008) found that SI values were nearly identical, less than 1.8% different for all variables calculated from consecutive and non-consecutive footstrikes on a forceplate. Subsequently, it appears that asymmetry should be expected and may be somewhat invariant across conditions.

Asymmetry has been found in components of the VGRF, although the values tend to be relatively small. The higher asymmetry values appear to be prevalent in the mediolateral components of GRF and kinematics. For instance, peak tibial shock, impact peak of the GRF and average loading rate of the GRF asymmetry levels were 5.8, 3.0, 5.6%, respectively (Zifchock, et. al., 2008). While, hip internal rotation range of motion, average rearfoot eversion velocity, average hip adduction velocity and average knee adduction velocity SI values were 19.3, 14.8, 12.7, and 14.1%, respectively. Likewise, Zifchock, et. al., (2006) found SI values of 3.1% for peak vertical GRF, where as peak medial GRF and peak lateral GRF values were 37.5 and 49.8%, respectively. Additionally, Zifchock & Davis, (2008) found asymmetry levels of 3.0, 5.0, and 6.7% for impact peak GRF, instantaneous loading rate and peak shock, respectively. Conversely, peak rearfoot eversion, knee adduction, and hip adduction SI values were 16.2, 26.2, and 12.3%, respectively. Furthermore, Williams, et. al., (1987) reported that the majority of the asymmetry was manifested in the mediolateral component of the ground reaction force in elite female distance runners, while the smallest difference was found in the maximal vertical force. In regard to kinematics, Karamanidis, et. al., (2003) found the lower SI values, generally less than 8%, in angular displacement parameters and contact times. Higher values, genereally greater than 15% were found in angular velocity parameters and flight times. Seemingly, the assumption of symmetry during running may be incorrect due to the demonstration of asymmetry in a variety of conditions. However, it appears that the asymmetry in running is similar to walking and is expressed mainly in the mediolateral parameters. As a consequence, the asymmetry found in running could be a materialization of individual compensations that naturally occur during gait.

Functional Asymmetry

Sadeghi, et. al., (1997) postulated a functional asymmetry hypothesis (FAH) to explain the asymmetries found in healthy individuals while walking. Accordingly, most of the research concerning the FAH has been led by Sadeghi (Sadeghi, 2003; Sadeghi, et al., 2002; Sadeghi, et. al., 1997; Sadeghi, Prince, et. al., 2000). Essentially, the theory states that one limb provides more propulsion, while the contralateral limb provides more support during normal walking. Sadeghi noted that the purpose of locomotion was to support the body against gravity while producing movements that propel the body forward, which requires precise coordination between the tasks of propulsion and balance. Therefore, the FAH asserts that there is a consistent task discrepancy between the limbs.

Sadeghi used muscle powers, muscle energies, principle component analysis (PCA) and other statistical techniqes to identify these task discrepencies. Muscle power and mechanical energies were used because they represent both kinetic and kinematic parameters. Also, PCA was used to reduce and categorize the peak muscle powers and mechanical energies calculated at the hip, knee, and ankle in each plane of motion, which resulted in 48 discrete values for each limb. The values were idetified by a three component labeling system. The first letter represented the joint, followed by a number that represented the sequence of the power and energy bursts, followed by a letter that represented the plane of motion. The statistical methods enabled Sadehgi to group parameters according to their relation to the left or right, or both limbs.

The only common parameters to both limbs were H1S (hip, first burst, sagittal plane) and K3T (knee, third burst, transverse plane) bursts (Sadeghi, et. al., 1997). The right limb was characterized by four peak powers and four energy bursts, most of which were generating, occurred at the hip, in the sagittal plane, and during the push-off period. The left limb was characterized by seven peak powers and eight energy bursts, most of which occurred at the knee, involved all three planes, equally involved generation and absorption, and were spread throughout the stance phase. There was significant difference in the H3S power and energy burst in the right limb, which equated to a 20.6%

stronger pulling action of the right hip during the push-off period. There were significant differences in the H1F at heelstrike, K1F and K2S at midstance and K3S during push-off in the left limb, which all had a controlling function. The H1F burst was associated with support of the pelvis on the contralateral side. K2S was associated with restoring knee extension after its initial flexion at the end of heel-strike. K3S was an absorption burst that compensated for the hip pulling action and the ankle propulsion during push-off.

Additionally, the prioritization of the tasks of the flexors and extensors at the hip, knee and ankle were further distinguished by PCA analysis (Sadeghi, 2003; Sadeghi, et al., 2002; Sadeghi, Prince, et. al., 2000). The authors described four main functional contributions of the hip sagittal muscle powers of the flexors and extensors (Sadeghi, Prince, et. al., 2000). The first task of both hips were to support the upper body by assisting in knee control in midstance. The second task for the right hip was to propel the bodyweight forward with the flexors. The second task for the left was to transfer the bodyweight from one limb to the other with the hip flexors. The third task for the right hip was to facilitate the limb entering a new gait cycle with the hip extensors. The third task for the left was to accelerate the forward motion of the thigh prior to and shortly after toe-off and early swing with the flexors. The fourth task of the right hip was to pull the trunk over the hip during heel contact and weight acceptance. The fourth task for the left was to prepare the limb to enter a new gait cycle.

In summary, the authors determined that the second, third, and fourth tasks for the left and right hip were ordered differently, which indicated functional gait asymmetry. The first four right hip tasks were described as (1) support, (2) propulsion, (3) limb preparation, and (4) balance. The first four left hip tasks were described as (1) support,

(2) limb coordination, (3) propulsion, and (4) limb preparation. Similar findings indicated that there were different task discrepancies at the knee and ankle, as well (Sadeghi, 2003). For instance, knee moments indicated more of a support function in the left than the right. Also, during late stance, the right plantar flexors task was propulsion, while the left was support.

Sadeghi presents adequate evidence for the FAH using muscle powers and PCA, however not all research is in agreement (Goble, et. al., 2003; Seeley, et. al., 2008). Seeley, et. al., (2008) tested the FAH and used measures that are precisely related to support and propulsion of the whole body center of mass, impulses due to the vertical GRF and anterior-posterior GRF. Generally, vertical and propulsive impulses were symmetrical, although the dominant limb contributed more to propulsion when demands were high at the fast walking condition. Goble, et. al., (2003) found that GRF measures were symmetrical at normal and fast walking speeds, though there were asymmetries during the slow condition. Seemingly, asymmetries could increase or decrease with increasing velocities, depending on the population sampled.

The issue of laterality as the cause of the FAH has not been fully established. Although, Sadeghi (1997) does not specifically classify the FAH as being a task discrepancy between the dominant and non-dominant limb, essentially that is what it seems to represent. Instead, Sadeghi postulates that the different task discrepancies between limbs could be the result of laterality. In the original research all participants were determined to be right leg dominant by tests, such as the preferred leg for kicking a ball. Subsequent research by Sadeghi does not report the limb dominance of the participants, yet still characterize the right limb as propulsive and the left limb as supportive (Sadeghi, 2003; Sadeghi, Prince, et. al., 2000). On the other hand, Gundersen, et. al., (1989) reported that the asymmetries that were found during gait could not be correlated with lateral dominance. Furthermore, Kuhtz-Buschbeck, Brockmann, Gilster, Koch, & Stolze, (2008) found that arm-swing asymmetry during a variety of walking velocities was not correlated to hand dominance or asymmetrical leg movements. Moreover, Sadeghi, Allard, Prince, & Hubert, (2000) questioned if a single definition is suitable for limb dominance and argued that the basic question of foot dominance has not been settled. However, many researchers classify the dominant limb as the one used to perform dexterous tasks, such as kicking a ball (Goble, et. al., 2003; Jacobs, et. al., 2005; Sadeghi, et. al., 1997; Seeley, et. al., 2008; Siqueria, et. al., 2001; Thorpe & Ebersole, 2008).

Strength Imbalance

Bilateral lower body strength imbalance has been associated as a risk factor for injury (Nadler, Malanga, Feinberg, Prybicien, Stitik, & DePrince, 2001; Niemuth, et. al., 2005). Nadler, et. al., (2001) determined that female collegiate athletes that developed low back pain had significantly more asymmetic hip extensor strength than those that did not develop low back pain, where as there was no association with hip abductor strength. Niemuth, et al., (2005) found that injured runners were significantly weaker in the injured side hip abductors and flexors and significantly stronger in the injured side hip adductors, where as the noninjured runners had no side-to-side hip muscle strength imbalances. However, Zifchock, Davis, Higginson, et. al., (2008) found similar symmetry indexes in hip external rotation strength and hip abduction strength in injured and healthy controls.

Although, strength imbalance is found in injured participants, no cause and effect has been established and strength imbalance is found in healthy populations, as well.

Perhaps, strength imbalance is more likely related to limb dominance and/or sport specific adaptation. For instance, female, collegiate, softball players exhibited significantly greater dominant leg strength in peak and average vertical force during parallel back squat and bilateral vertical jump, peak force during unilateral vertical jump, peak torque during isokinetic flexion and extension, and distance hopped in a 5-hop test (Newton, et al., 2006). Similarly, healthy participants demonstrated significantly stronger peak torque in the dominant side hip abductors (Jacobs, et. al., 2005). Furthermore, the authors reported that 12 participants in the study had bilateral strength imbalances greater than 15% and 6 participants had imbalances greater than 20 percent.

Siqueria, et. al., (2001) tested the isokinetic, flexion and extension strength of the dominant and non-dominant limbs, and found differences that may be attributed to sport specific adaptations. Non-athlete controls exhibited significantly stronger dominant side knee flexor peak torque and total work, but symmetrical knee extensor values. Runners had significantly stronger non-dominant knee extensor average power. The authors suggested that this imbalance could be due to the demands of each limb during running. Interestingly, Rahnama, Lees, & Bambaecichi, (2005) found that the knee flexor, concentric and eccentric strength, of the non-preferred limb was significantly stronger than the preferred limb, in elite soccer players. The researchers suggested that this was due to a soccer specific adaptation that occurs during kicking. During kicking, the knee flexors in the support limb are activated for joint stabilization, bodyweight support, and to resist torque created by the contralateral limb. Conversely, the activity of the knee flexors in the kicking limb are minimized to allow the knee to extend rapidly to contact the ball. Apparently, strength imbalance can be expected in a variety of populations and could be a result of the specific demands placed on the muscular system.

Instrumentation

The Star excursion balance test (SEBT) was selected to measure the unilateral, supportive function of the lower extremities, independent of strength. The SEBT is a unilateral, non-instrumented, objective test that is used to assess lower extremity balance and neuromuscular control and is not highly correlated to isokinetic strength (Thorpe & Ebersole, 2008). It has been used to measure dynamic balance of the lower extremities in a variety of athletic populations (Bressel, Yonker, Kras, & Heath, 2007; Gribble, Hertel, Denegar, & Buckley, 2004; Plisky, Rauh, Kaminski, & Underwood, 2006; Thorpe & Ebersole, 2008). High reliability coefficient ranges of 0.82 to 0.87 for the SEBT test have been reported (Plisky, et al., 2006). Hertel, Braham, Hale, & Olmsted-Kramer (2006) reported that there was significant redundancy in the performance of the eight reach directions of the SEBT and recommended the use of three reach directions to simplify the test.

The Triple hop distance test (THD) was chosen to measure the unilateral, propulsive strength of the lower extremities, independent of balance function. Hamilton, et al., (2008) found that the THD correlated significantly with vertical jump height and isokenetic strength, but not with static balance. The THD is a unilateral, noninstrumented clinical measure that is used to detect strength imbalance in the lower extremities (Hamilton, Shultz, Schmitz, & Perrin, 2008; Reid, Birmingham, Stratford, Alcock, &

Giffin, 2007; Ross, Langford, & Whelan, 2002). Ross, et al., (2002) and Reid, et al., (2007) reported a reliablity coefficient of 0.97 and 0.88, respectively for the THD.

Summary

Lower extremity gait asymmetry has been found in kinetic, kinematic, EMG and strength variables in a variety of populations. Asymmetry is present during walking and running, in injured and uninjured participants, and across a variety of conditions. Many researchers have considered asymmetry to be a risk for injury, although no cause and effect has been established. A functional asymmetry hypothesis has been postulated and tested to explain the asymmetry found in healthy individuals while walking. Healthy runners have exhibited asymmetry, yet there is no definitive finding to explain the differences. Although, lateral dominance is thought to play a role in strength imbalance, generally it has not been correlated with biomechanical asymmetry during gait. The assumption of symmetry may be challenged, if it is shown that asymmetry exists in healthy runners. Equally, an understanding of the possible effect of lateral dominance on the rhythmical, cyclic activity of running can elucidate the cause of asymmetry.

METHODS

The purpose of the study is to test the functional asymmetry hypothesis, asymmetry in functional strength and asymmetry in dynamic balance in healthy, recreational runners. The study will use ground reaction force (GRF) data to test for running impulse asymmetry levels and field tests to measure asymmetry in strength and balance in the lower extremities. Specifically, the methods of Seeley, Umberger, and Shapiro (2008) will be used; the vertical and propulsive impulse of each leg will be measured with the force plate and compared in the dominant and non-dominant limbs. The Star excursion balance test (SEBT) and the Triple hop distance test (THD) will be used to test for asymmetry in strength and balance of the dominant and non-dominant limbs.

Participants

Participants were recruited from Barry University, local running and triathlon stores, clubs and races. The inclusion criteria for the participants were as follows; male or female, aged 18 to 45, recreational runners averaging a minimum of 15 miles per week for the past 3 months, self-reported ability to achieve the target velocity of 3.5 m/s ±5%, and absence of pain or injury to the lower extremities and low back at the time of data collection. The functional asymmetry hypothesis contends that asymmetry is an inherent human condition, thus it should exist in all populations. Accordingly, broad criteria, including large age variations and pooling of male and female data has been used by researchers that are examining asymmetries (Gundersen, Valle, Barr, Danoff, Stanhope, & Snyder-Mackler, 1989; Niemuth, Johnson, Myers, & Thieman, 2005; Zifchock & Davis, 2008; Zifchock, Davis, Higginson, McCaw, & Royer, 2008). Therefore, in accordance with similar studies, a broad inclusion criteria was used for this study. The participants were informed of potential risks and each signed an informed consent approved by the Barry University Institutional Review Board.

Instrumentation

Star excursion balance test

The SEBT has been described as a unilateral, functional joint-stability task that measures dynamic postural control, lower extremity balance and neuromuscular control (Thorpe & Ebersole, 2008). The SEBT has been used to measure dynamic balance of the lower extremities in athletic populations (Bressel, Yonker, Kras, & Heath, 2007; Plisky, Rauh, Kaminski, & Underwood, 2006; Thorpe & Ebersole, 2008). Plisky, et al., (2006) reported a reliability coefficient range of 0.82 to 0.87 for components (anterior, posteromedial, posterolateral) of the SEBT test. Thorpe and Ebersole (2008) found that strength was not highly correlated to SEBT performance. The testing grid is composed of 8 lines, each 120 cm in length that extend from a common point at 45 degree angle increments (Bressel, Yonker, Kras, & Heath, 2007). The grid was created with 4 pieces of tape and placed on the floor of the Biomechanics Laboratory.

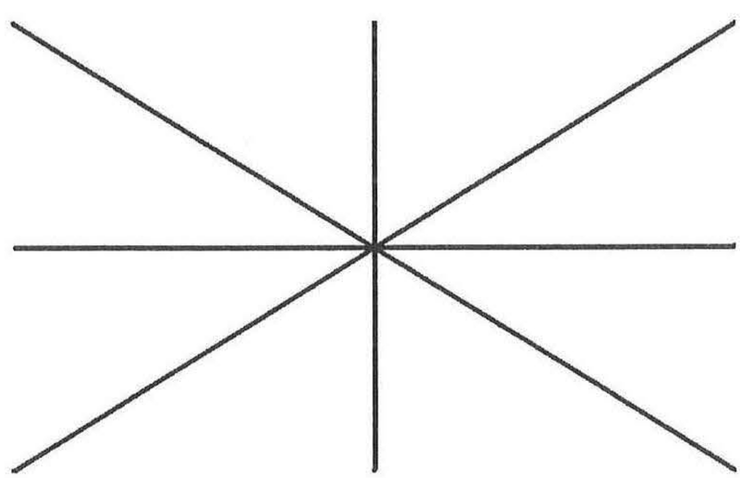

Figure 1 The layout of the star excursion balance test

Triple hop distance test

The THD is a clinical measure that is used to detect strength imbalance in the lower extremities (Hamilton, Shultz, Schmitz, & Perrin, 2008; Reid, Birmingham, Stratford, Alcock, & Giffin, 2007; Ross, Langford, & Whelan, 2002). Ross, et al., (2002) and Reid, et al., (2007) reported a reliablity coefficient of 0.97 and 0.88, respectively for the THD. Hamilton, et al., (2008) found that the THD correlated significantly with vetical jump height and isokenetic strength, but not with static balance. The testing grid is composed of a 6 m long by 15 cm wide marking on the floor (Reid, et al., 2007). The grid was created with 3 pieces of tape and placed on the floor of the Biomechanics Laboratory.

Force plate

Ground reaction force (GRF) was measured with an AMTI force plate (Advanced Mechanical Technologies, Inc., Watertown, MA) that is located in the floor of the Barry University Biomechanics Laboratory. The data was sampled at 2400Hz, streamed through a Vicon analog to digital interface unit (Centennial, CO) and processed with Vicon Nexus (Centennial, CO) software.

Procedures

Participants reported to the Barry University Biomechanics Laboratory for data collection. On arrival at the Biomechanics laboratory, the participants were informed of all the procedures. The participants were asked to fill out a brief questionaire that collected information on their weekly mileage, running and injury history, and training and racing paces (see appendix). Participants were asked to wear their normal running clothes and shoes. The entire testing procedure took approximately one hour to complete. All participants were tested in the following order (1) anthropometric measurements and leg dominance, (2) Star excursion balance test, (3) ground reaction force, (4) Triple hop distance test. The testing order was chosen according to the level of physical demand of each test, so that fatigue would not affect the subseqent test and each test provided a progressive warm-up for the next test. The starting leg of participants was counterbalanced, according to leg dominance, so that 50% of the participants started on their dominant limb and 50% started on their non-dominant limb.

Anthropometric measurements and leg dominance

Leg length was measured to normalize the scores in the SEBT (Seeley, Umberger, & Shapiro, 2008; Thorpe & Ebersole, 2008). The leg length in centimeters (cm) was measured from the anterior superior iliac spine to the medial malleolus with the participant in a supine position (Thorpe & Ebersole, 2008). The dominant limb was noted by the limb used to kick a ball (Seeley, Umberger, & Shapiro, 2008).

Star excursion balance test

The SEBT requires participants to maintain a single leg stance with the test leg and reach for maximal distance in eight directions with the other leg (Bressel, Yonker, Kras, & Heath, 2007). The toe of the reach leg must land on the tape without providing support, and the stance leg must remain in a stable position. In accordance with previous studies, only three reach directions were used in this study (Gribble, Hertel, Denegar, & Buckley, 2004; Plisky, et al., 2006; Thorpe & Ebersole, 2008). The order of the reach (anterior, posterior, lateral) was randomized and participants were allowed up to six practice attempts before three test trials. Participants started the test in a two-footed stance with the test leg aligned on the center of the grid and returned to the two-foot stance after each reach. There was a 5 second rest between each reach direction and a one minute rest between trials. Participants were asked to place their hands on their hips and to reach maximally with the contralateral leg in the test direction and lightly touch the line with the distal part of the foot. A trial was discarded if the reaching foot touched the ground for support or the stance foot moved during any part of the reach or return phase. Reach distance was marked by a piece of colored tape at the site of distal foot contact. The distance (cm) from the center of the grid to the colored tape was measured with a tape measure.

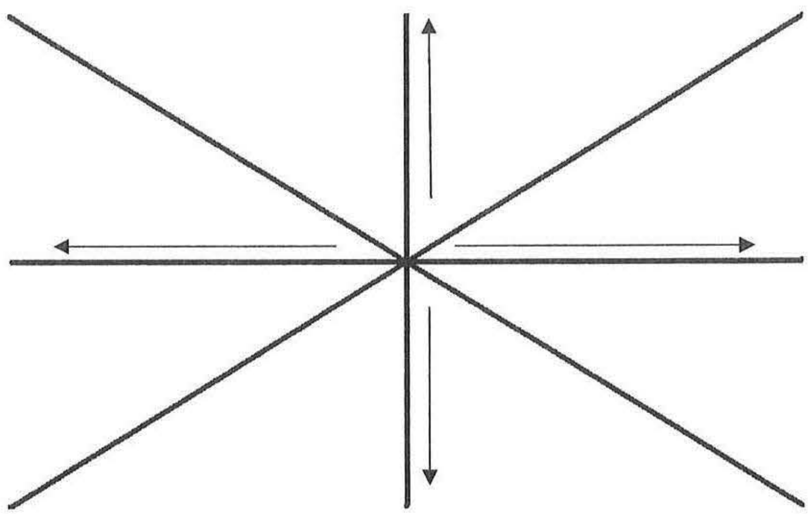

Figure 2 SEBT reach directions

Ground reaction force

A pace (3.5 m/s or 7.8 mph) similar to other studies involving runners was chosen to test the functional asymmetry hypothesis (Ferber, et al., 2003; Gales & Challis, 2005; Karamanidis, et al., 2003; Zifchock & Davis, 2008; Zifchock, et al., 2006; Zifchock, Davis, Higginson, et al., 2008). Participants warmed up on a treadmill (Life Fitness 97Ti, Schiller Park, IL) and speed was gradually increased to 7.8 mph. While the participant ran at 7.8 mph a metronome was set to coincide with their foot strike cadence.

Subsequently, the metronome was used to help the participant maintain the velocity of 3.5 m/s while running across the force plate (Ferber, et al., 2004). The actual velocity of the participants was calculated after data collection from the tracked motion of a reflective marker placed on the clothing at the sacrum using a Vicon Nexus (Centennial, CO) motion analysis system. Only the reflective light of the marker was recorded by the motion analysis system. The participants were asked to run through the lab and strike the force plate with the testing foot without breaking stride. The test was performed until three successful trials are recorded for each foot. A trial was considered successful when the velocity is within ±5% (Ferber, et al., 2004; Zifchock & Davis, 2008; Zifchock, Davis, & Hamill, 2006) of the targeted velocity (3.5 m/s), and the foot strikes the force plate during normal running stride. Zifchock and Davis (2008) found no significant difference between GRF asymmetry values collected during consecutive and nonconsecutive footstrikes, while participants ran at 3.7 m/s ±5%. Also, Gales and Challis (2005) found no significant difference in GRF symmetry index values at different running speeds. Additionally, increased GRF asymmetry values due to velocity changes have occurred at increased or decreased velocities of 10% (Goble, Marino, & Potvin, 2003) to 20% (Seeley, Umberger, & Shapiro, 2008). Therefore, a range of ±5% of the targeted velocity which has been used in similar studies was chosen for this study.

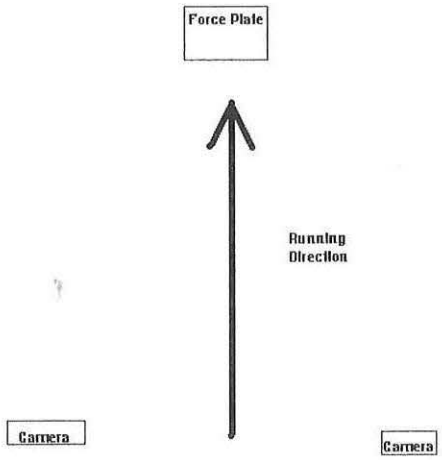

Figure 3 Layout of Biomechanics Laboratory

Triple hop distance test

The THD requires the participant to perform three maximal hops forward on the same leg (Hamilton, et al., 2008). The participants were sufficiently warmed up from the previous tests, and were allowed 1 to 3 practice trials on each leg to familiarize themselves with the protocol, followed by 3 test trials on each leg. A rest time of 1 minute was allowed between each trial. The test started with the participant standing on the testing leg with the great toe on the starting line. The participant was asked to perform three, consecutive, maximal hops forward and land on the same leg. A trial was considered successful when the triple hop was completed without losing balance and when the other leg did not touch the ground. The distance (cm) from the starting line to the heel of the final landing hop was measured with a tape measure (Ross, et al., 2002).

Data Analysis

Participants

Mild (< 3cm) limb length discrepancies have been shown to possibly affect loading patterns (White, Gilchrist, & Wilk, 2004). Therefore the participants' limb length discrepancy will be analyzed to determine if there are differences of greater than 1.5 cm. Those participants will be grouped and a separate statistical analysis will be conducted to determine if the limb length discrepancy has a significant effect on the propulsive and vertical impulse measures. Repeated measures analysis of variance will be used to determine whether significant differences exist between the dominant and non-dominant or the shorter and longer limb. If significance is found the limb length will be used as a covariate in the statistical analysis of the dependent variables.

Star excursion balance test

The reach distance in each direction was recorded separately for each leg. The total reach distance of the three test trials was averaged and normalized to leg length (total SEBT reaching distance / leg length = SEBT score).

Ground reaction force

Vertical and propulsive impulse was determined from the ground reaction force, according to the method of Seeley, et al., (2008). The vertical impulse was calculated by integrating the vertical GRF over the stance time. The propulsive impulse was calculated by integrating the anterior-posterior GRF over the time that the force is oriented in the anterior direction. The impulse values from the three successful trials were averaged for each leg.

Triple hop distance test

The total distance hopped in each of the three test trials were averaged for each leg.

Statistical Analysis

Statistical analysis was performed using SPSS 17.0 (SPSS Inc, Chicago, IL). Descriptive data (means, standard deviations, and range values) were calculated for each of the dependent variables (vertical impulse, propulsive impulse, SEBT score, THD score) for each limb (dominant and non-dominant). The variables VID, VIND, PID, PIND, SEBTD, SEBTND, THDD, and THDND were tested for normal distribution with the Shapiro-Wilk test statistic. Two-tailed, paired *t*-tests, with a Bonferroni adjustment were used to detect significant differences between limbs in each of the dependent variables. Statistical significance was set at $p \leq .0125$. An absolute asymmetry index was calculated to determine differences in the test measures, regardless of direction (Figure 4).

$$ASI = \frac{|X_D - X_{ND}|}{\frac{1}{2}(X_D + X_{ND})} \times 100\%$$

Figure 4 Absolute Asymmetry Index: X_D = parameter recorded from the dominant limb, X_{ND} = corresponding parameter from the non-dominant limb.

RESULTS

Twenty eight (male 14, female 14) healthy runners (mean ± sd, age 27.39 ± 6.39 years; weight 67.48 ± 9.15 kg; weekly training 37.35 ± 24.51 km; training pace 5.32 ± 0.68 minutes/km; 5k race pace 4.72 ± 0.80 minutes/km; running history 8.88 ± 6.99 years) volunteered to participate in the study (Table 1). All participants met the criteria for leg length discrepency less than 1.5 cm, (mean ± sd, 0.09 ± 0.23 cm; range: 0.00 to 1.00 cm), therefore the data was pooled for statistical analysis. Four participants were identified as left leg dominant and 24 participants as right leg dominant. Running velocity in the trials measuring the dominant and non-dominant limb were within 0.57% of each other (mean ± sd, 3.51 ± 0.09 and 3.53 ± 0.10 meters/second, respectively).

Table 1. Descriptive Statistics, Mean ± SD, n = 28

Age (years)	27.39 ± 6.39
Weight (kg)	67.48 ± 9.15
Training Pace (min/km)	5.32 ± 0.68
5k Race Pace (min/km)	4.72 ± 0.80
Weekly Distance (km)	37.35 ± 24.51
Running History (years)	8.88 ± 6.99

Results of the Shapiro-Wilk tests ($p > 0.05$) indicated that the variables VID, VIND, PID, PIND, SEBTD, SEBTND, THDD, and THDND were normally distributed. Means and standard deviations of the test variables are reported in Table 2.

Table 2. Mean SEBT, THD, VI and PI Scores of the D and ND limbs, Mean ± SD, n = 28

	Dominant	**Non-dominant**
SEBT (cm)	2.69 ± 0.26	2.71 ± 0.22
THD (cm)	445.26 ± 90.38	444.54 ± 92.12
VI (Ns)	179.69 ± 25.28	180.99 ± 26.75
PI (Ns)	21.22 ± 6.32	19.93 ± 5.43

Note: SEBT (Star Excursion Balance Test), THD (Triple Hop Distance), VI (Vertical Impulse), PI (Propulsive Impulse)

Two-tailed, paired samples *t*-tests were calculated to compare the mean scores between the dominant and non-dominant limbs in each of the following measures: SEBT, THD, VI, and PI. No significant differences were found between dominant and non-dominant limbs in any of the tests. The results of the t-tests are reported in Table 3.

Table 3. Paired Samples T-Test Results

	Mean ± SD	***t(27)***	**Sig. (2-tailed)**
SEBT	-0.01 ± .14	-0.420	0.678
THD	0.71 ± 25.46	0.148	0.883
VI	-1.30 ± 12.21	-0.561	0.579
PI	1.29 ± 3.96	1.721	0.097

Note: SEBT (Star Excursion Balance Test), THD (Triple Hop Distance), VI (Vertical Impulse), PI (Propulsive Impulse)

An absolute asymmetry index (ASI) (Karamanidis, et al., 2003) was calculated for the SEBT, THD, VI and PI to further elucidate the findings in this study (Figure 4, Table 4).

Table 4. Absolute Asymmetry Index (%) of the SEBT, THD, VI, and PI

	Mean ± SD	**Range**
SEBT %	3.80 ± 3.30	0.00 – 12.29
THD %	4.76 ± 4.46	0.07 – 15.86
VI %	4.61 ± 4.77	0.09 – 22.83
PI %	16.73 ± 15.13	2.17 – 70.64

Note: SEBT (Star Excursion Balance Test), THD (Triple Hop Distance), VI (Vertical Impulse), PI (Propulsive Impulse)

DISCUSSION

The purpose of the study was to test the functional asymmetry hypothesis, asymmetry in functional strength and asymmetry in dynamic balance in healthy, recreational runners. It was hypothesized that the participants in this study would demonstrate greater values in the dominant limb in the Triple hop distance (THD) and propulsive impulse (PI) tests. Additionally, it was hypothesized that the participants would demonstrate greater values in the non-dominant limb in the Star excursion balance test (SEBT) and vertical impulse (VI) tests. However, there were no significant differences found in the measurements between the dominant and non-dominant limbs in this study (Table 3).

The results of this study did not support the functional asymmetry hypothesis proposed by Sadeghi, et al., (1997). Rather, the data was generally in agreement with Goble, et al., (2003) and Seeley, et al., (2008). There was no significant difference in vertical impulse between the D and ND limbs while running. Likewise, Seeley found no significant difference in vertical impulse at any of the three walking speeds tested. Also, Goble found that symmetry was generally sustained in measures of braking and propulsive force during 3 walking velocities. Moreover, the participants in this study exhibited no significant difference in propulsive impulse while running, which corresponds to results by Seeley who found no difference in propulsive impulse at the slow and preferred walking speed. However, Seeley did find a significant bilateral difference in propulsive impulse during the fast walking condition in which PI was 7% greater in the dominant limb. Correspondingly, Goble found that peak vertical force occurring during the propulsive phase was greater for the right leg at the slow velocity.

Interestingly, in the present study, the mean PI of the D limb was 6.26% greater than the mean PI of the ND limb, although there was no significant difference.

Sadeghi, et al., (1997) identified unique task discrepencies between the dominant and non-dominant or right and left limbs using muscle powers, muscle energies and Principal Component Analysis (PCA). The prioritization of the tasks of the flexors and extensors at the hip, knee and ankle indicated that the right limb provides more propulsion, while the left limb provides more support during normal walking (Sadeghi, 2003; Sadeghi, et al., 2002; Sadeghi, Prince, et. al., 2000). While, it is not possible to directly compare the results of the present study to Sadeghi, et al., (1997), it appears that using GRF measures that are specifically related to the support and propulsion of the body's center of mass does not support the functional asymmetry hypothesis. The conflicting results of this study with those of Sadgehi could possibly be explained by the concept of local and global symmetry (Sadeghi, 2003). The apparently symmetrical actions of the limbs together are the result of unique asymmetry at each joint during ambulation, which suggests differing levels of within and between muscle actions (Sadeghi, 2003). Accordingly, compensation can be identified as the reason for local asymmetry.

The hypotheses that the participants in this study would demonstrate greater values in the non-dominant limb in the SEBT and greater values in dominant limb in the THD were rejected. These hypotheses were formulated to test the functional asymmetry hypothesis in the context of dynamic balance and functional strength. Hence, it was assumed that the functional tasks of support and propulsion would be performed better by the non-dominant and dominant limb, respectively. However, there was no significant difference between the dominant and non-dominant limb in these measures. The participants' performance in the SEBT in this study is in agreement with previous research involving healthy athletes (Bressel, et al., 2007; Thorpe & Ebersole, 2008). No significant limb effect was found in SEBT reach performance in collegiate soccer, basketball, and gymnastic athletes (Bressel, et al., 2007). Similarly, Thorpe and Ebersole, (2008) found that limb preference did not result in limb differences in SEBT performance in female collegiate soccer athletes. Accordingly, the participants' performance on the SEBT did not seem to be influenced by limb dominance in the present study. Likewise, the lack of a significant difference in the THD, indicated that limb dominance did not affect the participants performance in this measure. In contrast, female, collegiate, softball players exhibited significantly greater dominant limb distance hopped in a 5-hop test (Newton, et al., 2006). Intriguingly, the softball players demonstrated significantly greater dominant limb peak and average force in a bilateral squat and vertical jump. However, the asymmetry in these softball players could be attributed to the specific demands of the sport, such as the preferred batting side (Newton, et al., 2006). Additonally, Jacobs, et al., (2005) found significantly greater dominant limb hip abductor strength in healthy participants. Moreover, Siqueria, et al., (2001) found that runners had significantly stronger non-dominant knee extensor average power during open chain isokinetic tests. Nonetheless, the recreational runners in this study did not seem to be affected by limb dominance in the closed chain THD test.

The results of this study do not provide support for the functional asymmetry hypothesis and are in agreement with other studies that have not associated asymmetry with lateral dominance. For instance, gait asymmetries were not correlated with lateral dominance (Gundersen, et al., 1989) and arm-swing asymmetry was not correlated to hand dominance or asymmetrical leg movements (Kuhtz-Buschbeck et al., 2008). Even though, the present study was not correlational, the hypotheses regarding laterality's affect on the measures tested were rejected. However, pooling the data may have hidden important information regarding asymmetries of this population of runners (Ferber, et al., 2004; Gundersen, et al., 1989; Herzog, et al., 1989; Ounpuu & Winter, 1989). After careful observation of the individual participant data, it was evident that asymmetries existed. Therefore, an absolute asymmetry index (ASI) was calculated to facilitate a greater understanding of the results of this study. The ASI is the absolute difference between a test measure in the dominant and non-dominant limb, in which a value of zero indicates perfect symmetry (Karamanidis, et al., 2003) (Figure 4).

The participants in this study exhibited some level of asymmetry in all of the measures tested (Table 4). The mean level of asymmetry for the test variables were as follows: SEBT 3.80%, THD 4.76%, VI 4.61%, PI 16.73%. Large standard deviations and ranges indicate a high level of variablity in asymmetry levels in these participants. The mean asymmetry levels were low (ASI < 8%) (Karamanidis, et al., 2003) for the SEBT, THD, and VI. Although, several participants demonstrated ASI levels greater than 8% in those measures. Intriguingly, the PI asymmetry levels were high (ASI > 15%) (Karamanidis, et al., 2003), and only 7 participants exhibited less than 8% asymmetry in this measure.

The asymmetry levels of the runners in this study in VI (4.61 ± 4.77%) and PI (16.73 ± 15.13%) are similar to findings in previous studies that involved GRF measures of runners. For instance, runners exhibited asymmetry values of ~ 1.0% to ~5.0% in impact peak, active peak, and impulse of the VGRF (Gales & Challis, 2005), 3.9% for peak VGRF (Williams, et al., 1987), 6.9, 3.0, 5.1, and 12.8% for peak shock, impack peak GRF, instantaneous loading rate of the GRF and knee stiffness (Zifchock & Davis, 2008), 11.4, 3.1, and 23.3% for peak braking GRF, peak VGRF and average vertical loading rate (Zifchock, et al., 2006), and 5.8, 3.0, and 5.6% for peak tibial shock, impact peak of the GRF and average loading rate (Zifchock, Davis, Higginson, et al., 2008). Thus, the present study supports the assumption that the seemingly symmetrical process of running is not completely uniform and that local compensations can result in globally, symmetrical forward ambulation.

The asymmetry levels of the participants in the SEBT (3.80 ± 3.30%) were small and in agreement with previous studies that found no significant difference between limbs in reach distance (Bressel, et al., 2007; Thorpe & Ebersole, 2008). Although, four participants in the present study exhibited greater than 8% asymmetry in SEBT. Additionally, the asymmetry levels of the participants in the THD (4.76 ± 4.46%) were small and in agreement with Newton, et al.'s, (2006), 4.24% difference between limbs in the 5-hop test. Interestingly, Jacobs, et al., (2005) found that there was an 11% difference in mean hip abductor strength of healthy individuals. Moreover, Jacobs found that 12 participants illustrated strength imbalance greater than 15% and 6 participants were greater than 20% imbalanced. In the present study, six participants demonstrated ASI levels greater than 8% in the THD and one participant was over 15% imbalanced. Seemingly, in measures of functional strength and dynamic balance healthy runners are not completely symmetrical. Interestingly, researchers continue to suggest that bilaterally elevated strength imbalance found in previously injured runners is an injury risk factor, even though no cause and effect has been established (Niemuth et al., 2005; Zifchock, et al., 2006; Zifchock, et al., 2008).

The hypotheses of this study concerning lateral dominance were rejected, yet asymmetry was found in the runners in all the measures tested. Furthermore, there were large standard deviations and ranges in the level of asymmetry in the runners. Therefore, it appears that asymmetries exist, but are random and unpredictable in this population of runners. Likewise, asymmetries occurred in an unpredictable fashion in individual participants while walking (Gundersen, et al., 1989; Ounpuu & Winter, 1989). Thus, it appears that the asymmetries in functional strength, dynamic balance, vertical impulse and propulsive impulse are highly individualized and reflect the specific movement strategies developed in the individual. Interestingly, an asymmetry in one measure does not denote that asymmetry will occur in another measure. For instance, the ASI scores (SEBT 0.68%, THD 11.13%, VI 1.04%, PI 22.85%) of a participant in the present study were typical of the group. Individuals may incorporate entirely different compensation patterns for the same type of movement. A possible explanation for this phenomenon is that lateral dominance is on a continuum and that no one individual is completely right or left leg dominant (Ounpuu & Winter, 1989). Sadeghi, et al., (2000) questioned if a single definition is suitable for limb dominance and noted that postural support in one limb is activated prior to a dexterous task performed by the other limb. Gundersen, et al., (1989) used a kicking, balance and hopping test to determine limb dominance, in which agreement in two or more scores indicated strong dominance. No participant had complete agreement in the mobility, stability or the combined mobility/stability tasks. Hamilton, et al., (2008) defined the dominant limb as the stance limb used while kicking a ball, since it is used to change the momentum of the body during ground contact. Accordingly, the participants in the present study reflect the concept that laterality is on a continuum and highly individualized, due to the high variability of the results. Interestingly, the high ASI of the propulsive impulse in the participants indicates that one limb possibly provided more propulsion while running, yet was different for each participant.

The major findings of this study are that asymmetries exist in healthy recreational runners, but they are not related to dominance. The asymmetries could be the result of individual compensations or individual differences in lateral dominance in varying tasks. Levels of asymmetry can vary greatly between and within individuals in different tests. Perfect symmetry should not be expected in healthy individuals, and asymmetry does not necessarily implicate a pathological condition. Furthermore, the high ASI of the propulsive impulse in the participants indicates that a functional asymmetry might exist, but is unique for each individual.

The implications of this study are that pooling data can hide asymmetries that exist in healthy individuals. Researchers should analyze individual participant data and utilize an asymmetry index when making left/right or dominant/non-dominant comparisons. Also, researchers that examine side to side differences in pathological conditions should use caution when referencing pooled normative data of healthy controls. Moreover, a clear definition of lateral dominance should be developed that enables comparison of multiple studies. Furthermore, perfect symmetry may not necessarily be the optimal goal for unilaterally injured persons or unilateral amputees. In fact, the energy cost and walking asymmetry increased in unilateral transtibial amputees as their prosthetic limbs were matched in mass and moment of inertia to the intact limb (Mattes, Martin, & Royer, 2000).

Additionally, researchers who conduct retrospective studies should use caution when suggesting strength imbalance as a possible risk of injury. Moreover, future research should determine what level of functional strength and dynamic balance asymmetry might cause performance decrements or predispose runners to injury. Coaches and trainers can address the specific demands of the individual limbs and/or decrease asymmetries, if desired, by having their athletes perform unilateral training, such as single leg squats, single leg dead lifts, multidirectional lunges and single leg plyometric exercises. Consequently, the individual kinetics and kinematics of the limbs will more closely replicate that which is performed while running.

This study has a number of limitations that may have affected the results. First, the study consisted of a heterogeneous group of recreational runners with large variation in weekly training distance, training and racing paces, and running history. The participants' activity prior to the testing and strength training experience was not controlled. Participants were able to see the markings in the SEBT and THD, which may have affected their scores. Lastly, the participants were confined to the dimensions of the Barry Biomechanics Laboratory, which may have affected their GRF measures.

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Appendix A

IRB Consent Form

Approved by Barry University IRB:
Date: MAY 2 0 2009
Signature: [signature], MD, FACEP

Barry University
Informed Consent Form

Your participation in a research project is requested. The title of the study is: Kinetic, Functional Strength and Dynamic Balance Asymmetry in Healthy Recreational Runners. The research is being conducted by Wesley Windham, a student in the Sport and Exercise Science department at Barry University, and is seeking information that will be useful in the field of running biomechanics. The aims of the research are to investigate the ground reaction force, functional strength and dynamic balance asymmetry between the dominant and non-dominant limbs of recreational runners. We expect 50 participants in the study, male or female, aged 18 to 45, recreational runners averaging a minimum of 15 miles per week for the past 3 months, self-reported ability to achieve the target velocity of 7.8 mph ±5%, and absence of pain or injury to the lower extremities and low back at the time of data collection.

If you decide to participate in this research, you will be asked to be present for approximately one hour of laboratory testing. All testing will take place in the Barry University Biomechanics Laboratory in Miami Shores.

In accordance with the aims of the study, the following procedures will be used: Informed consent will be signed prior to the involvement of any activities related to the biomechanical investigation, a brief demographic questionnaire will be filled out, and a testing day will be chosen at your convenience. You will be asked to wear your normal running clothes and shoes on testing day.

First, you will be asked to lie on your back and leg length will be measured from a point on your hip to a point on your ankle. Next, you will be asked to stand on a force plate (a device set flush with the floor that allows us to measure your force at contact with the ground) and body weight will be measured. Then, you will be asked to perform the Star Excursion Balance Test (SEBT), a test of stability in the standing single leg position. You will be asked to maintain a single leg stance with the test leg and reach for maximal distance in three directions (forwards, backwards, and sideways) with the other leg. The toe of the reach leg must land on the tape without providing support, and the stance leg must remain in a stable position. Participants start the test in a two-footed stance with the test leg aligned on the center of the grid and return to the two-foot stance after each reach. There will be a 5 second rest between each reach direction and a one minute rest between trials.

Following the SEBT, ground reaction force will be measured. A reflective marker will be placed on the clothing on your back to track your running speed. Only the reflective light of the marker will be recorded by the motion analysis system. First, you will be asked to warm up on a treadmill for five minutes while the speed is gradually increased to 3.5 m/s (7.8 mph). While you run at 7.8 mph a metronome will be set to coincide with your foot strike cadence. Subsequently, the metronome will be used to help you maintain the velocity of 7.8 mph while running across the force plate. You will be asked to run through the lab and strike the force plate with the testing foot without breaking stride. The test will be performed until three successful trials are recorded for each foot. Selected trials will be evaluated by the researcher. Participants will be unaware of the trial being analyzed while performing the skill.

Next, you will be asked to perform the Triple Hop Distance Test (THD), a single leg strength test that requires the participant to perform three maximal hops forward on the same leg. You will start the test standing on the testing leg with the great toe on the starting line. You will be asked to perform three, consecutive, maximal hops forward and land on the same leg. A trial will be considered successful when the triple hop is completed without losing balance and when the other leg does not touch the ground. There will be 1 to 3 practice trials on each leg to familiarize yourself with the protocol, followed by 3 test trials on each leg. A rest time of 1 minute will be allowed between each trial.

Your consent to be a research participant is strictly voluntary and you can decline to participate or drop out at any time, without any adverse effects.

The risks of involvement in this study are minimal and include muscle strains and soreness that is normally a risk of exercise. The following procedures will be used to minimize these risks: an interview will be conducted to ensure the participants meet the criteria of the study, proper warm-up will be used, and practice repetitions or familiarity with procedures will reduce the risks involved. The benefits to you for participating in this study are knowledge regarding the differences between your dominant and non-dominant leg in strength and the generation of propulsive and supportive forces. Your participation in this study may also help our understanding of the asymmetry in ground reaction force and strength imbalance and their relation to dominance.

As a research participant, information you provide will be held in confidence to the extent permitted by law. Any published results of the research will refer to correlation data and participant codes only and no names will be used in the study. Data will be kept in a locked file in the research laboratory. All data will be stored securely in a locked cabinet at Barry University for the duration of 7 years. Assistants involved in helping with the data collection will be required to sign a confidentiality agreement. Your signed consent form will be kept separate from the data. All data will be destroyed after 7 years.

If you have any questions or concerns regarding the study or your participation in the study, you may contact me, Wesley Windham, at 786-210-4608, my supervisor, Dr. Kathy Ludwig, at 305-899-4077, or the Institutional Review Board point of contact, Barbara Cook, at (305)899-3020. If you are satisfied with the information provided and are willing to participate in this research, please signify your consent by signing this consent form.

Voluntary Consent

I acknowledge that I have been informed of the nature and purposes of this experiment by Wesley Windham and that I have read and understand the information presented above, and that I have received a copy of this form for my records. I give my voluntary consent to participate in this experiment.

Signature of Participant	Date

Researcher	Date	Witness	Date

(Witness signature is required only if research involves pregnant women, children, other vulnerable populations, or if more than minimal risk is present.)

Appendix B

Article Format

Windham, W. R. (2009). Running impulse, functional strength and dynamic balance asymmetry in healthy recreational runners.

Abstract

Studies on running mechanics have assumed that normal healthy running is a symmetrical process, yet bilateral asymmetry has been found in healthy individuals. The causes of asymmetries remain unclear, but could be the result of lateral dominance, in which the dominant limb (D) provides more propulsion and the non-dominant limb (ND) provides more support. The purpose of the study was to test the functional asymmetry hypothesis, asymmetry in functional strength and dynamic balance in healthy, recreational runners. Twenty eight (male 14, female 14) healthy runners (mean ± sd, age 27.4 ± 6.39 years; weight 67.48 ± 9.15 kg; weekly training 37.35 ± 24.51 km miles; running history 8.88 ± 6.99 years) volunteered to participate in the study. Participants were asked to run across a force plate at 3.5 ± 5% m/s, in which vertical (VI) and propulsive impulse (PI) were measured. The Star excursion balance test (SEBT) and triple hop distance test (THD) were used to test dynamic balance and functional strength. A two-tailed, paired samples *t*-test was calculated to compare the mean scores between the D and ND limbs in each of the measures. No significant differences were found between D and ND limbs in any of the tests. However, an absolute asymmetry index (ASI) revealed that the participants in this study exhibited some level of asymmetry in all of the measures tested. Asymmetries exist in healthy recreational runners, but they are not related to dominance. Levels of asymmetry can vary greatly between and within individuals in different tests. The asymmetries could be the result of individual compensations or individual differences in lateral dominace in varying tasks.

Introduction

Running mechanics have been studied to explain the causes of injury (Zifchock, Davis, & Hamill, 2006), describe the kinetics and kinematics of elite performers (Williams, Cavanagh, & Ziff, 1987) and to determine differences between males and females (Ferber, Davis, & Williams, 2003). It has been assumed that normal healthy running is a symmetrical process, thus data is collected from only one side (Ferber, et al., 2003) Asymmetry of gait is normally studied as a result of a pathological condition or injury (Ferber, Osternig, Woollacott, Wasielewski, & Lee, 2004; Silverman, Fey, Portillo, Walden, Bosker, & Neptune, 2008; White, Gilchrist, & Wilk, 2004). However, kinetic, kinematic and electromyographic (EMG) asymmetries have been found in healthy participants during normal walking (Ferber, et al., 2004; Gundersen, Valle, Barr, Danoff, Stanhope, & Snyder-Mackler, 1989; Herzog, Nigg, Read, & Olsson, 1989; Ounpuu & Winter, 1989) and running (Gales & Challis, 2005; Karamanidis, Arampatzis, & Bruggemann, 2003; Zifchock & Davis, 2008).

Researchers have utilized various forms of a symmetry index (SI) to quantify the level of asymmetry in runners and have reported a wide range of values (Gales & Challis, 2005; Karamanidis, et. al., 2003; Williams, et. al., 1987; Zifchock & Davis, 2008; Zifchock, et. al., 2006; Zifchock, Davis, Higginson, McCaw, & Royer, 2008). Gales and Challis (2005) found SI values in experienced runners that ranged from ~ 1.0% to ~5.0% in impact peak, active peak, and impulse of the vertical ground reaction force (VGRF). Elite female distance runners had SI values that ranged from 3.9% for peak VGRF to 28.3% for change in lateral velocity (Williams, et. al., 1987). Male and female runners exhibited SI values that ranged from 5.0% for instantaneous loading rate of the GRF to 24.3% for knee adduction angle (Zifchock & Davis, 2008). Female long distance runners had SI values that ranged from 2.95% for knee angle at touchdown to 54.68% for hip angle velocity at ground contact (Karamanidis, et. al., 2003). Zifchock, et. al., (2006) reported SI values in healthy controls that ranged from 3.1% for peak VGRF to 49.8% for peak lateral GRF. Likewise, uninjured runners exhibited SI values that ranged from 3.0% for impact peak GRF to 19.3% for hip internal rotation velocity (Zifchock, Davis, Higginson, et. al., 2008). However, gait asymmetries have not been correlated with lateral dominance (Gundersen, et. al., 1989; Kuhtz-Buschbeck, Brockmann, Gilster, Koch, & Stolze, 2008) and the causes of bilateral asymmetries remains elusive.

Sadeghi, Allard, and Duhaime (1997) proposed the functional asymmetry hypothesis, in that one limb is principally responsible for propulsion while the contralateral limb is largely responsible for support. They used principal component analysis (PCA) to distinguish which muscle powers and associated mechanical energies were related to the support and propulsion functions of each leg. They found altered task priorities at the ankle, knee and hip level for the right and left lower extremities during able-bodied walking (Sadeghi, 2003; Sadeghi et al., 2002; Sadeghi, Prince, Sadeghi, & Labelle, 2000). Sadeghi, Allard, Prince, and Hubert (2000) postulated that the functional asymmetry could be related to limb dominance.

Seeley, Umberger, and Shapiro (2008) tested the functional asymmetry hypothesis using ground reaction force (GRF) measures that were directly related to the support and propulsion of the body's center of mass. Verticle (VI) and propulsive impulse (PI) were measured during slow, preferred and fast walking speeds. No significant differences were found between limbs for VI or PI at the slow or preferred walking speeds. Conversely, dominant limb propulsive impulse was 7% greater at the fast walking speed. Goble, Marino, and Potvin (2003) measured eleven gait parameters at slow, normal and fast walking velocities and determined that generally, symmetry was sustained across parameters and velocities. However, stance time was longer for the left leg and peak vertical force occurring during the propulsive phase was greater for the right leg. Even though the studies are not completely in agreement with one another they offered limited support for the functional asymmetry hypothesis.

Bilateral lower body strength imbalance has been associated as a risk factor for injury (Nadler, et al., 2001; Niemuth, Johnson, Myers, & Thieman, 2005). However, strength imbalance has been found in able-bodied participants, as well (Jacobs, Uhl, Seeley, Sterling, & Goodrich 2005; Newton et al., 2006; Siqueria, Pelegrini, Fontana, & Greve 2001; Zifchock, Davis, Higginson, et. al., 2008). Jacobs, et al., (2005) found that hip abductor strength was significantly larger in the dominant leg of healthy subjects with an average side-to-side strength difference of approximately 11 percent. Siqueria, et al., (2001) found that runners exhibited significantly higher knee extensor power in the non-dominant leg and suggested it was due to the greater muscular action of the knee in the supportive leg. Zifchock, Davis, Higginson, et. al., (2008) found similar symmetry indexes in hip external rotation strength and hip abduction strength in injured and healthy controls. Female, collegiate, softball players exhibited significantly greater dominant leg strength in peak and average vertical force during parallel back squat and bilateral vertical jump, peak force during unilateral vertical jump, peak torque during isokinetic flexion and extension, and distance hopped in a 5-hop test (Newton, et al., 2006). Although, strength imbalance is found in injured participants, no cause and effect has been established and strength imbalance is found in healthy populations, as well.

Currently, the functional asymmetry hypothesis has only been tested in walkers and has not been tested in the context of functional strength or dynamic balance. Therefore, the purpose of this study was to test the effect of limb dominance on propulsive and vertical impulse, dynamic balance and functional strength in healthy, recreational runners. The hypotheses were that the participants would demonstrate greater values in the dominant limb in the THD and PI tests and greater values in the non-dominant limb in the SEBT and VI tests.

Methods

Participants

Twenty eight (male 14, female 14) healthy runners (mean ± sd, age 27.4 ± 6.39 years; weight 67.48 ± 9.15 kg; weekly training 37.35 ± 24.51 km; running history 8.88 ± 6.99 years) volunteered to participate in the study (Table 1). Participants read and signed an informed consent prior to participation. Participation criteria were as follows: male or female, aged 18 to 45, recreational runners averaging a minimum of 15 miles per week for the past 3 months, and absence of pain or injury to the lower extremities and low back at the time of data collection.

Table 1. Descriptive Statitstics, Mean ± SD, n = 28

Age (years)	27.39 ± 6.39
Weight (kg)	67.48 ± 9.15
Weekly Distance (km)	37.35 ± 24.51
Running History (years)	8.88 ± 6.99

Instrumentation

The Star excursion balance test (SEBT) has been described as a unilateral, functional joint-stability task that measures dynamic postural control, lower extremity balance and neuromuscular control (Thorpe & Ebersole, 2008). The SEBT has a reliability coefficient range of 0.82 to 0.87 (Plisky, Rauh, Kaminski, & Underwood, 2006). Thorpe and Ebersole (2008) found that strength was not highly correlated to SEBT performance. The testing grid is composed of 8 lines, each 120 cm in length that extend from a common point at 45 degree angle increments (Bressel, Yonker, Kras, & Heath, 2007). The SEBT requires participants to maintain a single leg stance with the test leg and reach for maximal distance in eight directions with the other leg. Only three reach directions were used in this study (Gribble, Hertel, Denegar, & Buckley, 2004; Plisky, et al., 2006; Thorpe & Ebersole, 2008)

The Triple hop distance test (THD) is a clinical measure that is used to detect strength imbalance in the lower extremities (Hamilton, Shultz, Schmitz, & Perrin, 2008; Reid, Birmingham, Stratford, Alcock, & Giffin, 2007; Ross, Langford, & Whelan, 2002). The THD has a reliability coefficient range of 0.88 to 0.97 (Ross, et al., 2002; Reid, et al., 2007). The THD has correlated significantly with vetical jump height and isokenetic strength, but not with static balance (Hamilton, et al., 2008). The testing grid is composed of a 6 m long by 15 cm wide marking on the floor (Reid, et al., 2007). The THD requires the participant to perform three maximal hops forward on the same leg (Hamilton, et al., 2008).

Ground reaction force (GRF) was measured with an AMTI force plate (Advanced Mechanical Technologies, Inc., Watertown, MA) that is located in the floor of the Barry University Biomechanics Laboratory. The data was sampled at 2400Hz, streamed through a Vicon analog to digital interface unit (Centennial, CO) and processed with Vicon Nexus (Centennial, CO) software.

Procedures

All testing procedures were performed at the Barry University Biomechanics Laboratory and took approximately one hour to complete. Participants filled out a brief history questionaire and informed consent was obtained. Participants wore their normal running clothes and shoes. Testing order was as follows: (1) anthropometric measurements and leg dominance, (2) Star excursion balance test, (3) ground reaction force, (4) Triple hop distance test. The testing order was chosen according to the level of physical demand of each test, so that fatigue would not affect the subseqent test and each test provided a progressive warm-up for the next test.

First, leg length was measured from the anterior superior iliac spine to the medial malleolus to normalize the SEBT scores (Seeley, et al., 2008; Thorpe & Ebersole, 2008). The dominant limb was noted by the limb used to kick a ball (Seeley, et al., 2008).

Next, participants performed up to six practice attempts before three test trials of the SEBT. Participants started the test in a two-footed stance with the test leg aligned on the center of the grid and returned to the two-foot stance after each reach. There was a 5 second rest between each reach direction and a one minute rest between trials. Participants were asked to place their hands on their hips and to reach maximally with the contralateral leg in the test direction and lightly touch the line with the distal part of the foot. A trial was discarded if the reaching foot touched the ground for support or the stance foot moved during any part of the reach or return phase. Reach distance was marked by a piece of colored tape at the site of distal foot contact. The distance (cm) from the center of the grid to the colored tape was measured with a tape measure. The total reach distance of the three test trials was averaged and normalized to leg length (total SEBT reaching distance / leg length = SEBT score).

Next, participants warmed up on a treadmill (Life Fitness 97Ti, Schiller Park, IL) and speed was gradually increased to 7.8 mph. While the participant ran at 7.8 mph a metronome was set to coincide with their foot strike cadence. Subsequently, the metronome was used to help the participant maintain the velocity of 3.5 m/s while running across the force plate (Ferber, et al., 2004). The actual velocity of the participants was calculated after data collection from the tracked motion of a reflective marker placed on the clothing at the sacrum using a Vicon Nexus (Centennial, CO) motion analysis system. The participants were asked to run through the lab and strike the force plate with the testing foot without breaking stride. The test was performed until three successful trials were recorded for each foot. A trial was considered successful when the velocity is within ±5% (Ferber, et al., 2004; Zifchock & Davis, 2008; Zifchock, Davis, & Hamill, 2006) of the targeted velocity (3.5 m/s), and the foot struck the force plate during normal a running stride.

Finally, the participants performed up to 3 practice trials on each leg to familiarize themselves with the protocol, followed by 3 test trials on each leg of the THD. A rest time of 1 minute was allowed between each trial. The test started with the participant standing on the testing leg with the great toe on the starting line. The participant was asked to perform three, consecutive, maximal hops forward and land on the same leg. A trial was considered successful when the triple hop was completed without losing balance and when the other leg did not touch the ground. The distance (cm) from the starting line to the heel of the final landing hop was measured with a tape measure (Ross, et al., 2002). The total distance hopped in each of the three test trials were averaged for each leg.

Data Analysis

Vertical and propulsive impulse was determined from the ground reaction force, according to the method of Seeley, et al., (2008). The vertical impulse was calculated by integrating the vertical GRF over the stance time. The propulsive impulse was calculated by integrating the anterior-posterior GRF over the time that the force is oriented in the anterior direction. The impulse values from the three successful trials were averaged for each leg.

Statistical analysis was performed using SPSS 17.0 (SPSS Inc, Chicago, IL). Descriptive data (means and standard deviations) were calculated for the dominant and non-dominant SEBT, THD, VI and PI. A two-tailed, paired *t*-tests, with a Bonferroni adjustment was used to detect significant differences between limbs in the VI, PI, SEBT score, and THD score. Statistical significance was set at $p \leq .0125$.

Results

Means and standard deviations of the test variables were SEBTD 2.69 ± .26 cm, SEBTND 2.71 ± .22 cm, THDD 445.26 ± 90.38 cm, THDND 444.54 ± 92.12 cm, VID 179.69 ± 25.28 Ns, VIND 180.99 ± 26.75 Ns, PID 21.22 ± 6.32 Ns, PIND 19.93 ± 5.43 Ns (Table 2).

Table 2. Mean SEBT, THD, VI and PI Scores of the D and ND limbs, Mean ± SD, n = 28

	Dominant	**Non-dominant**
SEBT (cm)	2.69 ± .26	2.71 ± .22
THD (cm)	445.26 ± 90.38	444.54 ± 92.12
VI (Ns)	179.69 ± 25.28	180.99 ± 26.75
PI (Ns)	21.22 ± 6.32	19.93 ± 5.43

No significant differences were found between dominant and non-dominant limbs in any of the tests. The results of the t-tests (Table 3) were as follows: SEBT ($t(27)$ = -

.420, $p = .678$), THD ($t(27) = .148$, $p = .883$), VI ($t(27) = -.561$, $p = .579$), VI ($t(27) = 1.721$, $p = .097$).

Table 3. Paired Samples T-Test Results

	Mean ± SD	*t*	Sig. (2-tailed)
SEBT	-.01 ± .14	-.420	.678
THD	.71 ± 25.46	.148	.883
VI	-1.30 ± 12.21	-.561	.579
PI	1.29 ± 3.96	1.721	.097

An absolute asymmetry index (ASI) (Karamanidis, et al., 2003) was calculated for the SEBT, THD, VI and PI to further elucidate the findings in this study (Table 4). The ASI were as follows: (mean ± sd, SEBT 3.80 ± 3.30%, THD 4.76 ± 4.46%, VI 4.61 ± 4.77%, PI 16.73 ± 15.13%).

Table 4. Absolute Asymmetry Index (%) of the SEBT, THD, VI, and PI

	Mean ± SD	Range
SEBT %	3.80 ± 3.30	.00 – 12.29
THD %	4.76 ± 4.46	.07 – 15.86
VI %	4.61 ± 4.77	.09 – 22.83
PI %	16.73 ± 15.13	2.17 – 70.64

Discussion

The results of this study did not support the functional asymmetry hypothesis proposed by Sadeghi, et al., (1997). Rather, the data was generally in agreement with Goble, et al., (2003) and Seeley, et al., (2008). There was no significant difference in vertical or propulsive impulse between the D and ND limbs. Seeley found no significant difference in verticle impulse at any of the three walking speeds tested, but PI was 7% greater in the dominant limb during the fast walking condition. Also, Goble found that symmetry was generally sustained in measures of braking and propulsive force during 3 walking velocities, yet peak vertical force occurring during the propulsive phase was greater for the right leg at the slow velocity.

While, it is not possible to directly compare the results of this study to Sadeghi, et al., (1997), it appears that using GRF measures that are specifically related to the support and propulsion of the body's center of mass does not support the functional asymmetry hypothesis. The conflicting results of this study with those of Sadgehi could possibly be explained by the concept of local and global symmetry (Sadeghi, 2003). The apparently symmetrical actions of the limbs together are the result of unique asymmetry at each joint during ambulation, which suggests differing levels of within and between muscle actions (Sadeghi, 2003). Accordingly, compensation can be identified as the reason for local asymmetry.

The assumption that the functional tasks of support and propulsion would be performed better by the non-dominant and dominant limb, respectively, was rejected. The participants' performance on the SEBT did not seem to be influenced by limb dominance and is in agreement with previous research involving healthy athletes

(Bressel, et al., 2007; Thorpe & Ebersole, 2008), in which no significant limb effect was found in SEBT reach performance. Likewise, the lack of a significant difference in the THD, indicated that limb dominance did not affect the participants performance in this measure, as well. In constrast, healthy individuals have exhibited significantly greater dominant limb hip abductor strength (Jacobs, et al., 2005) and distance hopped in a 5-hop test (Newton, et al., 2006). Additonally, Siqueria, et. al., (2001) found that runners had significantly stronger non-dominant knee extensor average power during open chain isokinetic tests. Nonetheless, the recreational runners in this study did not seem to be affected by limb dominance in the closed chain THD test.

The results of this study do not provide support for the functional asymmetry hypothesis and are in agreement with other studies that have not been able to associate asymmetry with lateral dominance (Gundersen, et. al., 1989; Kuhtz-Buschbeck et al., 2008). However, pooling of the data may have hid important information regarding asymmetries of this population of runners (Ferber, et al., 2004; Gundersen, et. al., 1989; Herzog, et. al., 1989; Ounpuu & Winter, 1989). Therefore, an absolute asymmetry index was calculated to facilitate a greater understanding of the results of this study.

The participants in this study exhibited some level of asymmetry in all of the measures tested. Levels of asymmetry were as follows: SEBT 3.80 ± 3.30% (range: .00 to 12.29%), THD 4.76 ± 4.46% (range: .07 to 15.86%), VI 4.61 ± 4.77% (range: .09 to 22.83%), PI 16.73 ± 15.13% (range: 2.17 to 72.81%) (Table 4). Large standard deviations and ranges indicate a high level of variablity in asymmetry levels in these participants. The mean asymmetry levels were low (ASI < 8%) (Karamanidis, et al., 2003) for the SEBT, THD, and VI. Although, several participants demonstrated ASI levels greater than 8% in those measures. Intriguingly, the PI asymmetry levels were high (ASI > 15%) (Karamanidis, et al., 2003), and only 7 participants exhibited less than 8% asymmetry in this measure.

The asymmetry levels of the runners in this study in VI 4.61 ± 4.77% and PI 16.73 ± 15.13% are similar to findings in previous studies that involved GRF measures of runners. (Gales & Challis, 2005; Williams, et. al., 1987; Zifchock & Davis, 2008; Zifchock, et. al., 2006; Zifchock, Davis, Higginson, et. al., 2008). Thus, the present study supports the assumption that the cyclic process of running is not completely symmetrical.

The asymmetry levels of the participants in the SEBT 3.80 ± 3.30% were small and in agreement with previous studies that found no significant difference between limbs in reach distance (Bressel, et al., 2007; Thorpe & Ebersole, 2008). Although, four participants in the present study exhibited greater than 8% asymmetry in SEBT. Additionaly, the asymmetry levels of the participants in the THD 4.76 ± 4.46% were small and in agreement with Newton, et al., (2006), 4.24% difference between limbs in the 5-hop test. Interestingly, Jacobs, et al., (2005) found an 11% difference in mean hip abductor strength in healthy individuals. Moreover, Jacobs found that strength imbalance was greater than 15 and 20 percent in 12 and 6 participants, respectively. In the present study six participants demonstrated ASI levels greater than 8% in the THD and one participant was over 15% imbalanced. Seemingly, in measures of functional strength and dynamic balance healthy runners are not completely symmetrical, as well.

The hypotheses of this study concerning lateral dominance were rejected, yet asymmetry was found in the runners in all the measures tested. Furthermore, there were large standard deviations and ranges in the level of asymmetry in the runners. Therefore, it appears that asymmetries exist, but are random and unpredictable in this population of runners. Likewise, asymmetries occurred in an unpredictable fashion in individual participants while walking (Gundersen, et al., 1989; Ounpuu & Winter, 1989). Thus, it appears that the asymmetries in functional strength, dynamic balance, vertical impulse and propulsive impulse are highly individualized and reflect the specific movement strategies developed in the individual. Interestingly, an asymmetry in one measure does not denote that asymmetry will occur in another measure. Apparently, individuals may incorporate entirely different compensation patterns for the same type of movement. A possible explanation for this phenomenon is that lateral dominance is on a continuum and that no one individual is completely right or left leg dominant (Ounpuu & Winter, 1989). Sadeghi, et al., (2000) questioned if a single definition is suitable for limb dominance and noted that postural support in one limb is activated prior to a dexterous task performed by the other limb. Gundersen, et al., (1989) used a kicking, balance and hopping test to determine limb dominance, in which agreement in two or more scores indicated strong dominance. No participant had complete agreement in the mobility, stability or the combined mobility/stability tasks. Hamilton, et al., (2008) defined the dominant limb as the stance limb used while kicking a ball, since it is used to change the momentum of the body during ground contact. Accordingly, the participants in the present study reflect the concept that laterality is on a continuum and highly individualized, due to the high variability of the results. Interestingly, the high ASI of the propulsive impulse in the participants indicates that one limb possibly provided more propulsion while running, yet was different for each participant.

The major findings of this study are that asymmetries exist in healthy recreational runners, but they are not related to dominance. The asymmetries could be the result of individual compensations or individual differences in lateral dominace in varying tasks. Levels of asymmetry can vary greatly between and within individuals in different tests. Perfect symmetry should not be expected in healthy individuals, and asymmetry does not necessarily implicate a pathological condition. Furthermore, the high ASI of the propulsive impulse in the participants indicates that a functional asymmetry might exist, but is unique for each individual.

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Appendix C

Screening Questionnaire

Participant #: ____________

Sex: ___________ Age: ___________ Weight: __________

What is your typical steady training running pace? _____________min/mile

What is your typical steady racing pace? 5k _____________ min/mile

10k _____________ min/mile

What is your typical weekly mileage? _____________miles/week

How long have you been running? _____________years

<u>Have you ever experienced or been diagnosed with the following running-related injuries? Circle</u>

IT band syndrome (outside of the knee) Stress fracture

Piriformis syndrome (deep inside buttocks) Plantar fasciitis

Patellofemoral pain (Runner's knee) Hamstring strain

Medial Tibial Stress syndrome (Shin splints) Compartment syndrome

Low back pain Others:_______________

If you circled any of the above please provide the dates that they occurred:

____

Appendix D

Data Collection Sheet

Participant #:________

Sex:________ Age:________ Weight:________

Leg length Right:_______cm Leg length Left:________cm Dif:______cm

Dominant leg:______ Non-dominant leg:______ Testing leg order:______

SEBT Right Left

Anterior 1____ 2____ 3____ A____ 1____ 2____ 3____ A____

Posterior 1____ 2____ 3____ A_____ 1____ 2____ 3____ A_____

Lateral 1____ 2____ 3____ A____ 1____ 2____ 3____ A____

Tot _____/LL_____=______ Tot _____/LL_____=______

THD

Right 1_______ 2_______ 3_______ A_______

Left 1_______ 2_______ 3_______ A_______

Vertical Impulse

Right 1____V____ 2____V____ 3_____V____ A____V____

Left 1____V____ 2____V____ 3____V____ A____V____

Propulsive Impulse

Right 1____V____ 2____V____ 3____V____ A____V____

Left 1____V____ 2____V_____ 3____V____ A_____V____