THE RELATIONSHIP BETWEEN HIP STRENGTH AND HIP, PELVIS, AND TRUNK KINEMATICS IN HEALTHY RUNNERS

by

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THESIS ABSTRACT

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Title: The Relationship Between Hip Strength and Hip, Pelvis, and Trunk Kinematics in Healthy Runners

This study examined the relationship between hip strength and hip, pelvis, and trunk kinematics in healthy runners. Whole body kinematic data were collected while subjects ran in the laboratory. Isometric hip abduction, flexion, external rotation, and internal rotation torques were measured bilaterally using a dynamometer. Subjects were divided into strong and weak groups for each muscle strength parameter. Differences in hip, pelvis, and trunk motion were then examined using independent sample *t*-tests. Pearson correlation coefficients were used to assess these relationships for all subjects.

Most notably, runners with weak abductors displayed greater hip adduction and pelvic rotation compared to the strong abductor group, while runners with weak external rotators displayed greater trunk rotation compared to the strong external rotator group. Moderate, negative correlations were observed for the above relationships. While data from this study help clarify the relationship between hip strength and running kinematics, no causal conclusions can be made.

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CHAPTER I

INTRODUCTION

Running Injuries: Incidence and Prevalence

According to a 2013 survey conducted by the National Sporting Goods Association, over 9 million Americans run at least 110 days per year, with an additional 9 million running between 25 and 109 days per year (Running USA, 2013). The number of runners in the United States continues to grow, evidenced by an approximate 4% increase in the total number of recreational runners from 2011 to 2012 (Running USA, 2013). Additionally, approximately 15.5 million Americans completed a road race in 2012, an 80% increase since the year 2000 (Running USA, 2013).

Despite the increased participation rate in running and road racing, the injury rate among runners has been relatively consistent for decades. Depending on the definition of a running-related injury and the running experience of subjects, studies have approximated that 19.4% to 79.3% of runners sustain an injury in a given year (van Gent, 2007). Studies have also found between 41-70% of runners seek medical treatment for their injuries, suggesting significant medical costs associated with these injuries (Jacobs & Berson, 1986; van Middelkoop et al., 2007).

While many factors appear to contribute to injury incidence, including systemic factors (age, sex, height, weight), health factors (history of previous injury, medical conditions), lifestyle factors (drinking and smoking, other sport participation), and training factors (running frequency, distance, pace, and shoe selection) (Hreljac, 2005; van Gent et al., 2007; Buist et al., 2010), hip muscle strength (Prins & van der Wurff, 2009) and proximal kinematics of the hip, pelvis, and trunk (Noehren et al., 2007; Ford et al., 2013) have recently been suggested as additional potential factors. Before discussing the research on hip muscle strength, a description of hip muscle function during running is warranted.

Functional Anatomy of the Hip Musculature During Running

The hip joint is the articulation between the femoral head and the acetabulum of the pelvis. The acetabulum is deepened by a fibrocartilaginous labrum, which increases joint stability and helps prevent joint subluxation. A strong ligamentous capsule surrounding the femoral head and neck adds further stability to the hip joint. A layer of articular cartilage covers the femoral head and helps accommodate full range of motion (Byrne et al., 2010).

Many muscles surround the hip and influence hip motion. Posteriorly, the gluteus maximus and hamstring group (biceps femoris, semimembranosus, and semitendinosus) are responsible for hip extension. The gluteus maximus is also the main external rotator, but has assistance from a group of deep, smaller muscles, discussed later. The gluteus maximus and hamstring group are active mainly during late swing and early stance phases. In late swing, gluteus maximus acts eccentrically in order to decelerate the thigh as the hip flexes prior to initial contact (McClay et al., 1990; Milliron & Cavanagh, 1990). Gluteus maximus then acts concentrically during early stance to help initiate hip extension and to stabilize the thigh and pelvis (McClay et al., 1990).

Laterally, the gluteus medius, gluteus minimus, and tensor fascia latae act to stabilize the hip and pelvis during stance phase, controlling both hip adduction and contralateral drop. These muscles are also thought to internally rotate the hip when the hip is flexed (Gottschalk et al., 1989; McClay et al., 1990).

Anteriorly, the iliopsoas, rectus femoris, and sartorius collectively assist in hip flexion. Iliopsoas appears to be active mainly during mid- to late-swing to help flex the hip after terminal hip extension (Dugan & Bhat, 2005). Rectus femoris and sartorius are also active during this time, but continue to contract from initial contact to late stance, assisting vastus lateralis, vastus intermedius, and vastus medialis in absorbing the forces of impact and stabilizing the knee (McClay et al., 1990).

A medial group of muscles including the adductor magnus and adductor longus are active during all stages of running gait, playing a role in hip stabilization to counteract the torque caused by the abductor muscles (McClay et al., 1990; Byrne et al., 2010). Another group of stabilizing muscles is the external rotator group, which includes the piriformis, obturator internus and externus, gemellus superior and inferior, and quadratus femoris. While the exact firing pattern of these muscles during running is difficult to study due to their deep location and small size, evidence suggests these muscle are active throughout stance phase, assisting the gluteus maximus in stabilizing the hip and pelvis and preventing excessive hip internal rotation (Krebs et al., 1998; Byrne et al., 2010).

Hip Strength and Running-Related Injuries

As previously mentioned, weak hip muscles have been suggested as contributing factors for many running-related injuries. Of the running injuries suffered, evidence suggests that up to 50% of these injuries occur at the knee, making it the most frequently injured body part (van Gent et al., 2007). Several studies have found a relationship between hip strength and patellofemoral pain syndrome (PFPS), an injury characterized by pain around the kneecap during running. Retrospective studies have shown that individuals with PFPS displayed significantly weaker hip abductors and/or external rotators, either compared to healthy controls (Ireland et al., 2003; Robinson & Nee, 2007; Bolgla et al., 2008; Dierks et al., 2008; Souza & Powers, 2009; Ferber et al., 2011) or to the unaffected limb of the same subject (Tyler et al., 2006; Cichanowski et al., 2007). In addition, a prospective study by Finnoff et al. (2011) found that runners who developed PFPS displayed significantly weaker hip abductor and hip external rotator strength post-injury compared to pre-season measurements.

Other injuries besides PFPS have been studied in relation to muscle strength. Fredericson et al. (2000) found that runners suffering from iliotibial band friction syndrome (ITBS) displayed significantly weaker hip abductors compared to healthy controls. Injured track and field and basketball athletes were prospectively shown to have weaker hip abductors and external rotators compared to uninjured athletes in a 2003 study by Leetun and colleagues. Niemuth et al. (2005) studied runners suffering from various injuries, finding that the injured limb was weaker in hip abduction and flexion compared to the unaffected limb. Finally, a 2013 prospective study found that runners with exertional medial tibial pain (EMTP) displayed decreased hip abductor strength compared to runners who did not develop EMTP (Verrelst et. al, 2013).

It is important to note that a few studies found no significant differences between injured runners and controls in regard to hip abduction and external rotator strength. However, each of these studies had inherent differences compared to the previously cited literature. Piva et al. (2005), who found no differences in strength between PFPS subjects and controls, measured external rotation strength prone with the hip at 0-degrees. This position differed from other studies which measured external rotator strength seated with the hip and knee at 90-degrees, and may have compromised the muscle's ability to produce force (Prins & Wurff, 2009). Thijs et al. (2011), who also found no differences in strength between PFPS and healthy runners, measured hip abduction supine instead of side-lying or standing. Grau et al. (2008), who found no differences in hip abductor strength between ITBS and healthy subjects, measured strength isokinetically at 30-degrees/second, while all previously cited literature measured strength isometrically (note: Dierks et al., 2008, measured both isometric and isokinetic strength).

Despite these contradictory findings, the collective results of all previous studies suggest a relationship between reduced hip abduction and external rotation strength and running-related injuries, particularly at the knee. The influence of testing position on muscle strength appears to be an important consideration, however, and warrants a discussion on proper muscle strength testing procedures.

Measurement of Muscle Strength

The purpose of measuring muscle strength is to predict the ability of a muscle or group of muscles to perform their function, whether that is movement or stability. Several methods exist for quantifying muscle strength, the easiest and most inexpensive method being manual muscle testing (MMT) (Cuthbert & Goodheart, 2007). In MMT, a clinician places the subject in a position that isolates the function of a muscle or group of muscles (Lawson & Calderon, 1997). Most resources suggest the optimal position for one-joint muscles is at end-range of motion, while the optimal position for two-joint muscles is generally at mid-range of motion (Kendall et al., 2005). The clinician must then place their hands on a patient so that the clinician can apply a force that opposes the movement being tested. Generally, that force is applied near the distal end of muscle insertion, although there are exceptions to this rule. One such exception is testing the hip abductors, where the clinician applies force just proximal to the ankle to create a longer lever arm (Kendall et al., 2005).

Depending on the purpose of the test and subject being tested, different levels of force may be applied. For healthy subjects demonstrating average or above muscle strength, a “break test” can be used where the clinician gradually increases pressure until they can overcome the effort of the subject. At this point, the test is stopped. For very weak patients or some muscle groups (ex: trunk and neck muscles), much less force is needed to test the patient’s strength. In these cases, the patient may be simply asked to hold or move a body segment against gravity. For either type of test, the clinician needs to grade the subject, usually on a 0-5 scale (Clarkson, 2000).

The major limitation of manual muscle testing is the limited grading scale and relative subjectivity of the measurement. This lack of objectivity, however, can also been seen as a strength, as the clinician is able to assess the quality of the subject’s movement. For example, subjects may attempt to compensate for a lack of strength by substituting one or more muscles in addition to the muscle or muscle group being tested. Experienced clinicians can detect these substitution patterns, which may otherwise go undetected using computerized dynamometry (Kendall et al., 2005).

Handheld dynamometry (HHD) partially solves this problem of objectivity by allowing the clinician to manually test muscle strength while also quantifying the force produced by the patient. HHD is performed in the same manner as MMT, but with the clinician holding a dynamometer in their force-applying hand. The clinician then has to match the force applied by the patient, which is measured by the dynamometer (Thorburg et al., 2010).

While HHD has been shown to have high intra-tester (Bohannon et al., 2008; Thorburg et. al, 2010) and inter-tester reliability (Thorborg et al., 2013), its major limitation is that the clinician has to match the subject's force, which can become problematic, especially when the subject is at a mechanical advantage compared to the clinician (Le-Ngoc & Janssen, 2012). Additionally, HHD is restricted to isometric evaluations, as the reliability of HHD decreases substantially with dynamic testing (Le-Ngoc & Janssen, 2012). Therefore, while HHD can be useful for clinical measurements, large-scale computerized dynamometers are considered the gold standard in muscle strength testing (Martin et al., 2006). Despite their large size and higher cost, machines made by Cybex (Cybex International, Inc., Medway MA) and Biodex (Biodex Medical Systems, Shirley NY) are able to objectively and reliably quantify muscle strength both isometrically and isokinetically. These machines are not limited by the clinician's strength, and can measure not only torque, but also power generation and energy expenditure (Le-Ngoc & Janssen, 2012).

Lower Leg Kinematics and Running Injuries

In addition to muscle strength, proximal kinematics has recently been suggested as a factor in developing a running-related injury. Literature on the relationship between proximal running kinematics and running injuries is currently very limited, however, as researchers have only begun investigating this topic in earnest since 2007. Of the few studies to date focusing on proximal kinematics, most have focused on PFPS. The first such study by Dierks et al. (2008) measured hip strength and kinematics before and after a fatiguing run, finding runners with PFPS displayed greater peak hip adduction compared to controls, as well as a strong relationship between hip abductor strength and peak hip adduction (r = -0.74) at the end of a fatiguing run. Noehren et al. (2011) also found that females suffering from PFPS displayed greater peak hip adduction compared to controls, as well as greater hip internal rotation. No differences were found in regard to pelvic drop or trunk lean between groups. Greater hip internal rotation for PFPS patients compared to controls was also found in a study by Souza and Powers (2009).

In addition to PFPS, one study has examined proximal kinematics in patients suffering from ITBS. This study by Noehren et al. (2007) showed that ITBS patients displayed greater peak hip adduction and knee internal rotation compared to controls (Noehren et al., 2007).

Methodological Inconsistencies

One important note regarding many of the aforementioned studies is the methodological inconsistency in reporting joint and segment angles. There seems to be a fairly large disparity among studies in the parameters of joint and segment angles reported, making it difficult to directly compare results between studies (Table 1).

Table 1. Parameters of joint and segment motion reported in previous literature.

Authors (Year)	Measurements Reported
Noehren et al. (2007)	Peak hip adduction angle
Willson & Davis (2008)	Hip angles at the instance of peak knee extension moment
Dierks et. al (2008)	Peak hip angles
Heinert et. al (2008)	Initial contact, minimum, and toe-off hip and pelvis angles
Souza & Powers (2009)	Average hip rotation during the first 50% of stance phase
Snyder el. al (2009)	Hip range of motion
Noehren et al. (2011)	Peak hip and pelvis angles
Willy & Davis (2011)	Peak hip and pelvis angles
Wouters et. al (2012)	Peak hip and pelvis angles; hip and pelvic excursion
Ford et. al (2013)	Pelvic and trunk range of motion

Purposes and Hypotheses of the Study

The relationship between injury and both muscle strength and kinematics has led researchers to hypothesize that poor hip strength may be causing the observed kinematic patterns, which may be causing injury. However, few studies to date have specifically studied the relationship between hip strength and running kinematics to support this hypothesis (Heinert et al., 2008; Souza & Powers, 2009; Ford et al., 2013). Additionally, recent research focused on strengthening the hip musculature in an attempt to alter poor kinematics has yielded mixed results (Snyder et al., 2009; Willly & Davis, 2011; Ferber et al., 2012; Wouters et al., 2012), which further calls into question the relationship between hip strength and proximal kinematics.

Therefore, the first purpose of this study is to quantify the relationship between hip strength and hip and pelvis kinematics in healthy runners. Based on previous research, for the group analysis, it is hypothesized that runners with weak hip abductors will display greater hip abduction and contralateral pelvic drop compared to runners with strong hip abductors. It is also hypothesized that runners with weak hip external rotators will display greater hip internal rotation and anterior pelvic rotation compared to runners with strong hip external rotators. No differences are hypothesized in regards to hip flexion or internal rotator strength. For the correlation analysis, moderate, significant correlations are hypothesized between hip abductor strength and both hip adduction and contralateral pelvic drop range of motion, and between hip external rotator strength and both hip internal rotation and anterior pelvic rotation range of motion.

To date, the overwhelming majority of running biomechanics literature is focused on the lower extremity (Ford et al., 2013). However, the trunk and upper extremity should not be ignored, as trunk strength and positioning has been shown to have a significant effect on an athlete's ability to transfer force to the lower extremities (Shinkle et al., 2012). Therefore, a second goal of this study is to examine the relationship between hip strength and trunk kinematics, as there is little evidence that currently defines this relationship. Based on the limited research available (Noehren et al., 2011), it is hypothesized that runners with weak abductors will display greater lateral trunk lean compared to runners with strong abductors, and that there will be a significant, moderate correlation between hip abductor strength and lateral trunk lean.

Lastly, the third purpose of this study is to address the previously discussed methodological inconsistencies in reporting joint and segment angles (Table 1). This study aims to identify which parameters of hip, pelvis, and trunk motion are most strongly related to hip strength and offer a recommendation to resolve future disparity among studies.

CHAPTER II

METHODS

Subjects

Subjects for this study were retrospectively included as part of a larger study on running biomechanics and injuries at the University of Oregon. Inclusion criteria for this particular study were running at least 20 miles per week and being injury free at the time of testing. Previous history of musculoskeletal injury did not exclude subjects from participation. Of 102 total subjects in the database, 60 subjects met these inclusion criteria. All subjects read and signed an informed consent form prior to participation in this study. This form can be found in Appendix A.

Experimental Equipment

Motion Capture System

A ten-camera motion capture system (Motion Analysis Corp., Santa Rosa CA) sampling at 200 Hz recorded three-dimensional marker trajectories.

Force Plates

Three force plates (Advanced Mechanical Technologies Inc., Watertown MA) located in series along a 10m runway collected ground reaction forces at 1000 Hz.

Dynamometer

A Biodex System 3 Dynamometer (Biodex Medical Systems Inc., Shirley NY) measured isometric maximal torque generation about the hip joint.

Data Collection and Experimental Procedures

Overground Running

A total of 39 reflective markers were placed on subjects using a modified Helen Hayes marker set (Kadaba et al., 1990) and multi-segmented foot model (Carson et al., 2001). Each subject was modeled using 17 body segments – forefoot (2), rearfoot (2), shank (2), thigh (2), pelvis, trunk, arm (2), forearm (2), hand (2), and head.

Subjects were instructed to wear their normal training shoes for the entire protocol. Markers for the forefoot were placed on subjects' shoes over the following bony landmarks: the space between the 1st and 2nd metatarsal heads, the base of the 5th metatarsal, and the navicular tuberosity. For the rearfoot, two markers were placed on the vertical bisection of the heel counter and one marker was placed over the lateral aspect of the heel (Carson et. al, 2001, McClay & Manal, 1998; Noehren et al., 2007).

Shank markers were placed on the medial and lateral malleoli as well as a medial shank marker collinear with the medial malleolus and medial femoral epicondyle. Thigh markers were placed on the medial and lateral femoral condyles as well as a marker collinear with the lateral femoral epicondyle and the greater trochanter. The hip joint center was defined based on anthropometric measurements of ASIS breadth (Vaughan, et al., 1999). Pelvic markers were placed on the left and right anterior superior iliac spines (ASIS) and the sacrum at the midpoint between the posterior superior iliac spines (PSIS). The anatomic coordinate systems for the shank, thigh, and pelvis were defined per recommendations by the International Society of Biomechanics (Wu, 2002).

The trunk segment was defined by two markers placed on bilateral acromion processes as well as a virtual marker at the pelvis center of mass. This marker was defined as the midpoint between the sacral marker and the virtual marker existing at the midpoint between the left and right ASIS. The origin for the trunk anatomic coordinate system was defined at the pelvis center of mass. The y-axis was the line between the pelvis center of mass and the midpoint between the acromion processes, pointing superiorly. The z-axis was perpendicular to the y-axis and in the plane of the pelvic center of mass and acromion process markers, pointing right. The x-axis was the cross-product of the y- and x-axes, pointing forward.

Additional upper extremity markers were placed on bilateral lateral epicondyles of the humerus, bilateral wrists at the posterior midpoint between the ulnar and radial styloids, and bilateral hands on the posterior surface. Two markers were also placed directly above the ears.

A static calibration trial was collected with the subject centered in the capture volume, feet shoulder-width apart and arms abducted to 90-degrees. After static calibration, markers on the medial malleoli and medial femoral condyles were removed.

Subjects ran laps overground in the Motion Analysis Laboratory, each lap being approximately 40-meters in length. Data were collected when the subjects passed through a straight 10-meter region in the center of the capture volume. Subjects were instructed not to alter their stride to hit the three AMTI force plates located in series in this region. Subjects ran continuously until they cleanly struck a force plate with each foot approximately ten times, resulting in approximately 25 to 40 complete laps per subject.

Muscle Strength Testing

Isometric muscle strength was measured for hip flexion, hip abduction, hip external rotation, and hip internal rotation. Hip flexion was tested with subjects standing perpendicular to the dynamometer with the ipsilateral hip aligned with the axis of the dynamometer. Hip abduction was similarly tested, but with subjects standing parallel to the dynamometer with the ipsilateral ASIS aligned with the axis of the dynamometer. For both the flexion and abduction tests, the arm of the dynamometer was strapped tightly to the thigh approximately 3-4 finger lengths above the superior border of the patella and was moved to 30-degrees of hip flexion or 10-degrees of hip abduction just prior to each respective test. For hip external and internal rotation, subjects were seated facing the dynamometer with the hip and knee flexed to 90-degrees. The height of the chair was adjusted so that the dynamometer was aligned with the ipsilateral knee.

For all tests, subjects were instructed to push against the dynamometer with maximal force three times for five seconds, with a minimum of five seconds rest between trials. While hip flexion and abduction were tested separately, hip internal and external rotation were measured during the same test, alternating between internal and external rotation.

Data Analysis

Overground Running

Marker trajectories were identified using Cortex 4.0 motion capture software (Motion Analysis Corp., Santa Rosa CA) and were smoothed using a low-pass, fourth order Butterworth filter with an 8 Hz cutoff. Only stance phase was analyzed, defined using the ground reaction force data from the force plate. Heel strike was defined as the first frame the vertical ground reaction force (F_z) was greater than or equal to 50 Newtons. Toe-off was defined as the first frame F_z was less than 50 Newtons (Cavanagh & Lafortune, 1980).

A custom LabView program (National Instruments, Austin TX) was used to calculate joint and segment angles during stance phase. Cardan angles for the hip were calculated using a joint coordinate system (Grood & Suntay, 1983; Wu. 2002). A ZXY rotation sequence was used for the hip, pelvis, and trunk. For the hip, this corresponded to flexion/extension, abduction/adduction, and internal/external rotation. For the pelvis, this corresponded to anterior/posterior pelvic tilt, contralateral pelvic drop/rise, and contralateral anterior/posterior rotation. For the trunk, this corresponded to trunk flexion/extension, trunk lateral/medial lean, and trunk internal/external rotation.

Specific parameters of hip, pelvis, and trunk angles were calculated and analyzed for this study. The angle at contact was defined as the angle of the joint or segment at heel strike. The peak angle was defined as the most extreme angle of the joint or segment during stance phase. For some parameters, the percentage of stance phase when the peak angle occurred was calculated. Range of motion was defined as the difference between angle at contact and peak angle. The angle at toe-off was defined as the joint or segment angle during the last frame of stance phase. These parameters of joint and segment motion are labeled in Figures 1-9.

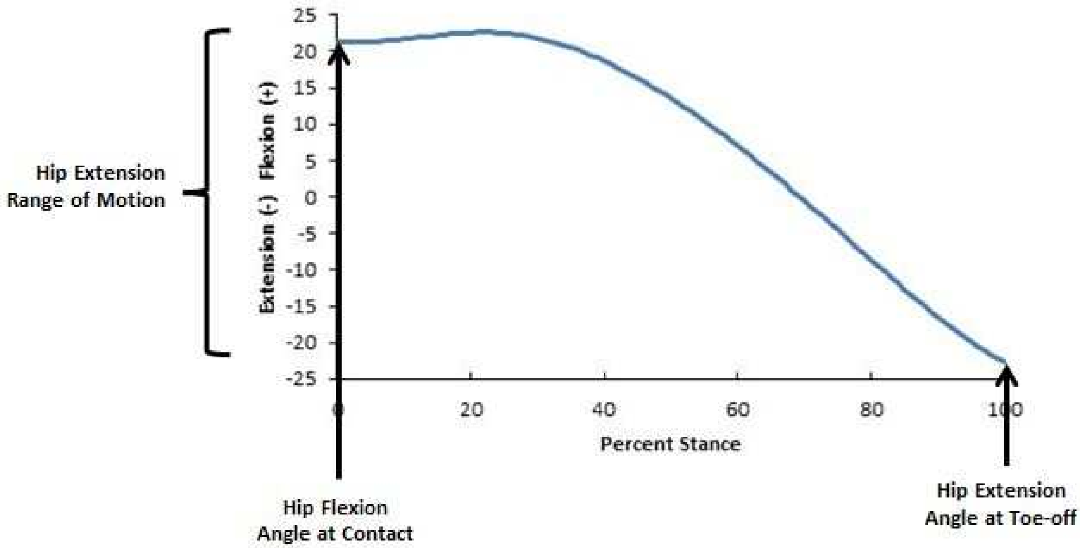

Figure 1. Example graph of hip flexion/extension during stance phase with variables of interest labeled.

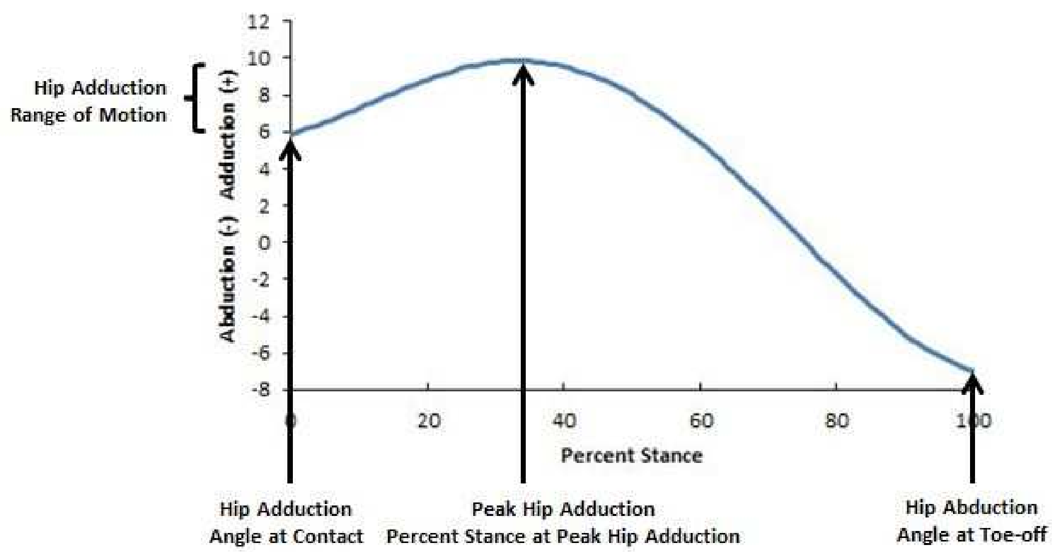

Figure 2. Example graph of hip abduction/adduction during stance phase with variables of interest labeled.

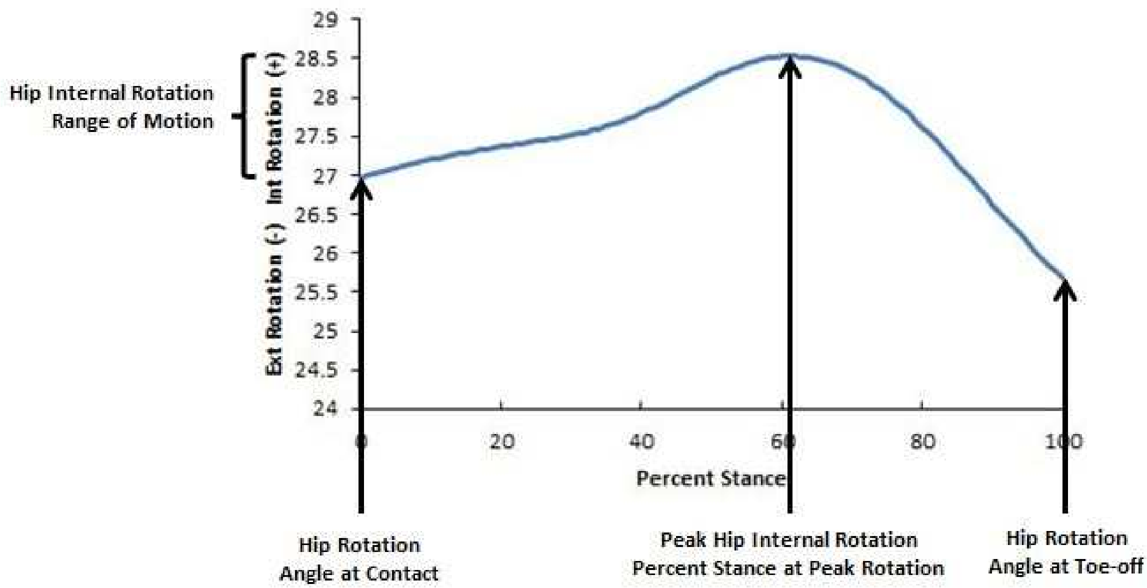

Figure 3. Example graph of hip rotation during stance phase with variables of interest labeled.

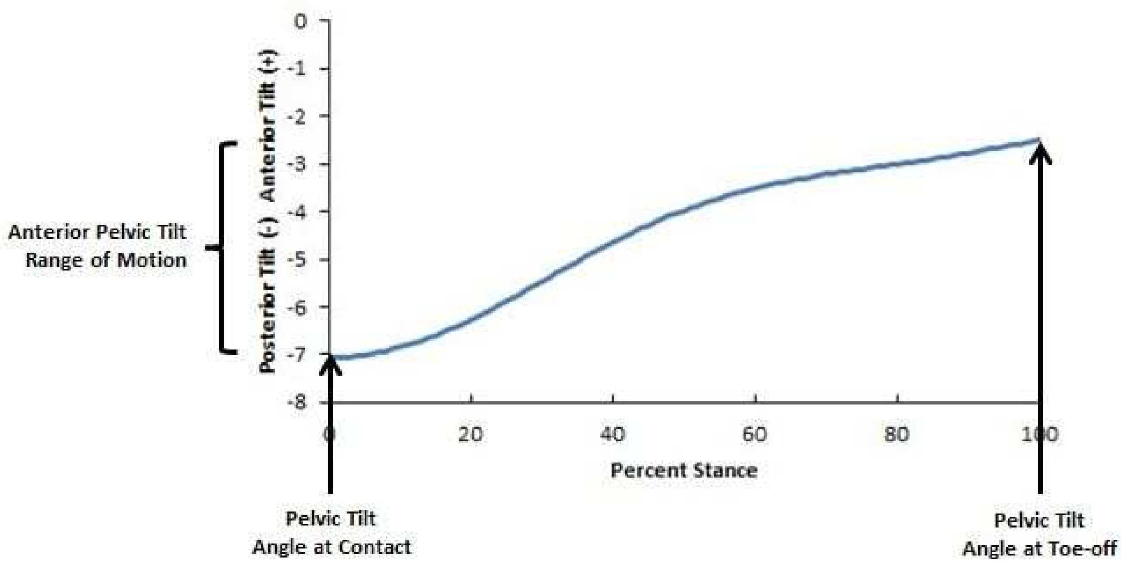

Figure 4. Example graph of pelvic tilt during stance phase with variables of interest labeled.

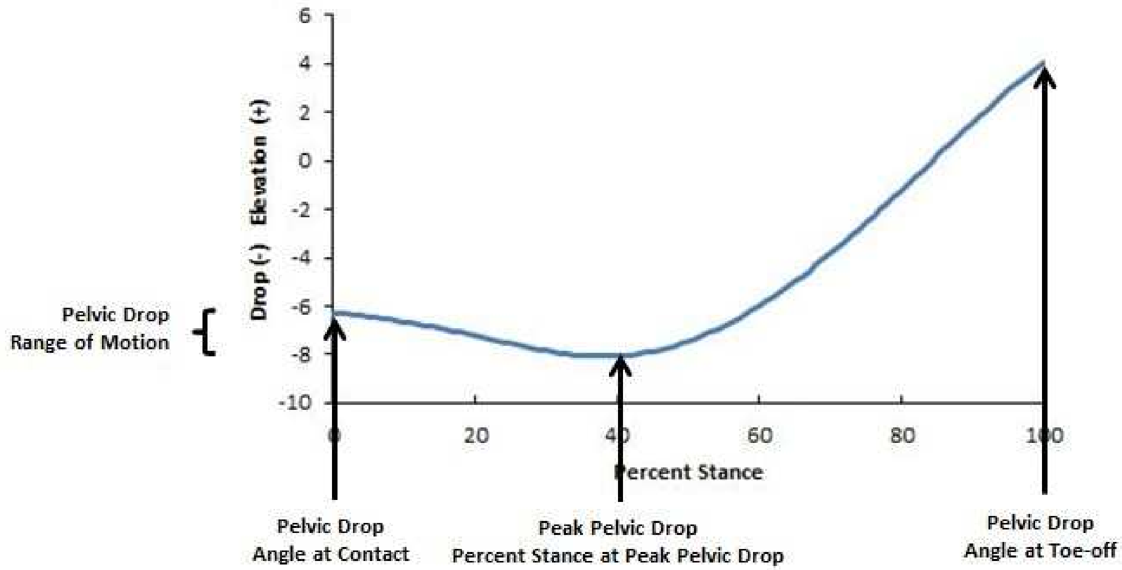

Figure 5. Example graph of contralateral pelvic drop during stance phase with variables of interest labeled.

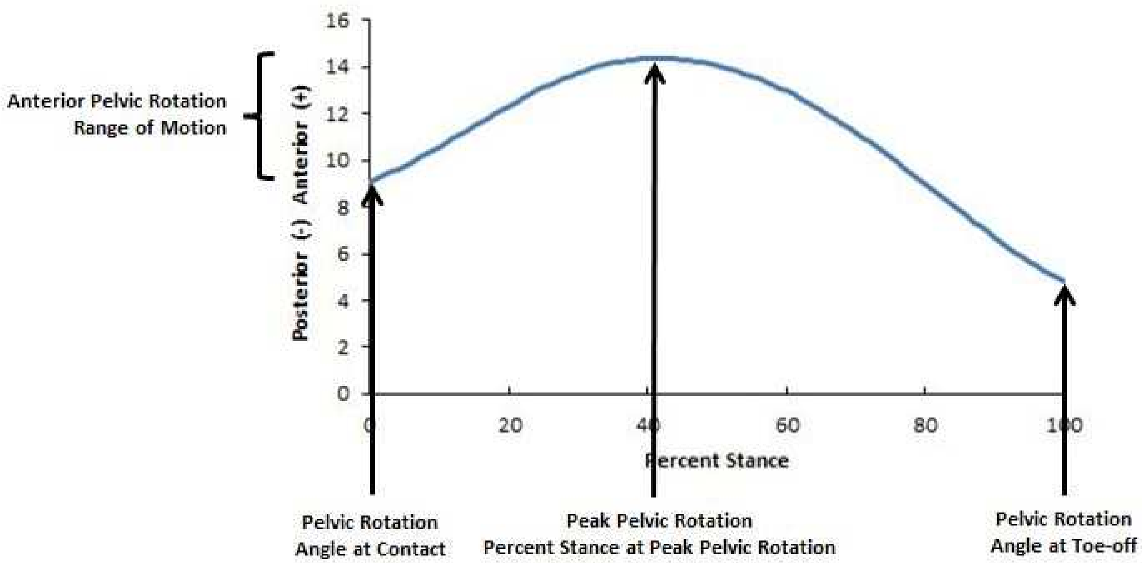

Figure 6. Example graph of contralateral pelvic rotation during stance phase with variables of interest labeled.

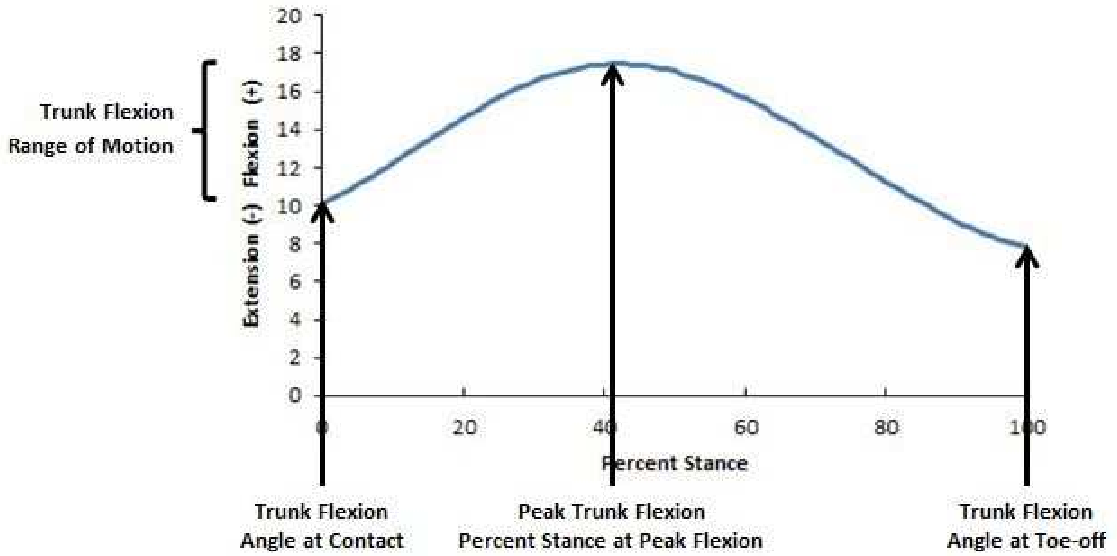

Figure 7. Example graph of trunk flexion during stance phase with variables of interest labeled.

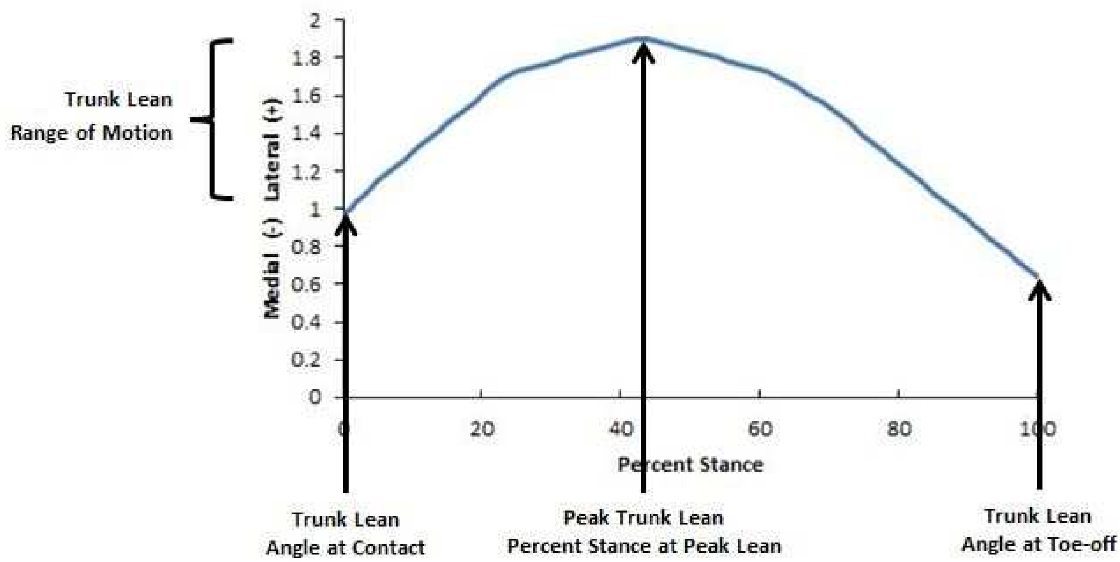

Figure 8. Example graph of trunk lean during stance phase with variables of interest labeled.

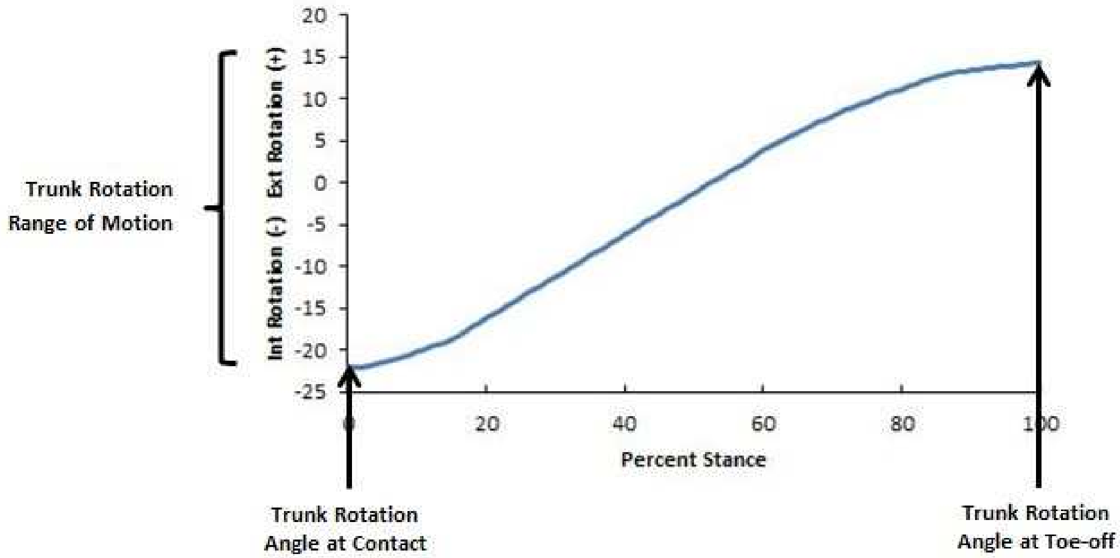

Figure 9. Example graph of trunk rotation during stance phase with variables of interest labeled.

Muscle Strength Testing

For each limb, mean maximal torque was calculated for each strength parameter by averaging the maximal torque generated from all three trials. This mean value was normalized by body mass for analysis.

Statistical Analysis

Two methods of statistical analysis were used: group analysis and correlation analysis. For group analysis, limbs were divided into strong and weak groups for each muscle strength parameter. For each muscle strength parameter, limbs with strength greater than 1 standard deviation above the sample mean were classified as "strong" while runners with muscle strength less than 1 standard deviation below the sample mean were classified as "weak". Limbs falling between 1 standard deviation above and below the sample mean were not analyzed. In some cases, a subject had both limbs qualify into 1 group. In these cases, only the subject's stronger limb was considered for analysis in the strong group, while only the weaker limb was considered for analysis in the weak group.

Hip, pelvis, and trunk motion during stance phase were then compared between groups. Independent sample *t*-tests were performed to quantify group differences unless one of the demographic variables was found to be significantly different between groups. If a demographic variable was significantly different between groups, an analysis of covariance was used to assess significant differences, with the covariate being the demographic variable found to be different between groups. In addition, Levene's test for homogeneity of variance was calculated for all comparisons. The adjusted *p*-value was reported in cases where unequal variance was found. Significance level of $p < .05$ was used for all tests.

For the correlation analysis, Pearson correlation coefficients were used to assess the relationship between hip strength and hip, pelvis, and trunk motion during stance phase for all runners. In addition to stance phase range of motion, angle at contact, peak angle, percent stance at peak angle, and angle at toe-off were analyzed for the correlation analysis. These variables were not analyzed for the group comparison analysis for fear that performing excessive *t*-tests raises the risk of committing a Type I error. Significance level of $p < .05$ was used for all tests. Correlation coefficients (r) between ±0.10 to 0.30 were considered weak relationships, while correlation coefficients above 0.30 and below -0.30 were classified as moderate relationships.

CHAPTER III

GROUP COMPARISON RESULTS

Group Inclusion

Mean muscle strengths, as well as the thresholds for normalized muscle strength, are summarized in Table 2. For hip abductor strength, independent sample *t*-tests were performed to quantify group differences. For the three other comparisons, one of the demographic variables was found to be significantly different between groups, and was added as a covariate in the analysis. Subject group demographics are summarized in Tables 3-6.

Table 2. Average muscle strength (Nm/kg) for all 60 subjects

	Abductors	Flexors	External Rotators	Internal Rotators
Mean	0.812	1.694	0.538	0.686
Standard Deviation	0.214	0.457	0.160	0.208
Mean + 1 SD	1.026	2.150	0.697	0.894
Mean – 1 SD	0.599	1.237	0.378	0.478

Table 3. Subject characteristics of strong and weak abductor groups

	Strong Abductors (n=8)	Weak Abductors (n=12)	*p*-value
Sex	4 males, 4 females	9 males, 3 females	
Age (years)	25.75 ± 10.22	27.67 ± 8.89	.669
Height (cm)	171.625 ± 11.57	175.03 ± 10.17	.507
Weight (kg)	62.14 ± 11.94	70.83 ± 15.14	.203
Mileage (miles/week)	43.75 ± 11.88	45.17 ± 14.36	.825
Running Speed (m/s)	3.61 ± 0.47	3.37 ± 0.46	.281

Table 4. Subject characteristics between strong and weak external rotator groups

	Strong Ext. Rotators (n=16)	Weak Ext. Rotators (n=15)	*p*-value
Sex	15 males, 1 female	6 males, 9 females	
Age (years)	31.07 ± 13.13	28.07 ± 9.88	.481
Height (cm)	178.89 ± 11.08	171.63 ± 10.79	.075
Weight (kg)	69.79 ± 11.57	68.70 ± 15.93	.830
Mileage (miles/week)	50.63 ± 23.80	44.80 ± 16.90	.441
Running Speed (m/s)	3.63 ± 0.34	3.24 ± 0.41	.006*

*Indicates a significant difference between groups, $p < .05$

Table 5. Subject characteristics between strong and weak hip flexor groups

	Strong Flexors (n=13)	Weak Flexors (n=15)	*p*-value
Sex	8 males, 5 females	7 males, 8 females	
Age (years)	23.08 ± 3.82	29.27 ± 10.46	.047*
Height (cm)	171.52 ± 11.52	172.72 ± 9.74	.767
Weight (kg)	63.36 ± 11.73	64.78 ± 13.21	.768
Mileage (miles/week)	57.85 ± 21.49	43.13 ± 17.18	.055
Running Speed (m/s)	3.66 ± 0.31	3.38 ± 0.45	.070

*Indicates a significant difference between groups, $p < .05$

Table 6. Subject characteristics between strong and weak internal rotator groups

	Strong Int. Rotators (n=16)	Weak Int. Rotators (n=14)	*p*-value
Sex	13 males, 3 females	7 males, 7 females	
Age (years)	26.94 ± 8.90	27.29 ± 9.13	.917
Height (cm)	175.14 ± 11.30	172.00 ± 9.81	.427
Weight (kg)	66.27 ± 11.24	70.77 ± 14.57	.348
Mileage (miles/week)	52.50 ± 23.09	42.07 ± 13.04	.135
Running Speed (m/s)	3.68 ± 0.32	3.23 ± 0.41	.002*

*Indicates a significant difference between groups, $p < .05$

Group Comparisons

Hip Abduction Strength

Between the strong and weak hip abductor groups, significant differences were found for hip adduction, pelvic drop, pelvic rotation, and trunk lean range of motion, $p < .05$ (Table 7; Figure 10).

Table 7. Range of motion differences between strong and weak abductor groups

	Strong Abductors	Weak Abductors	Levene's Test	*p*-value
Hip Extension	42.22 ± 4.65	42.35 ± 4.39	0.985	0.951
Hip Adduction	4.00 ± 1.75	5.90 ± 1.75	0.355	0.032*
Hip Internal Rotation	5.98 ± 2.83	11.20 ± 7.62	0.017*	0.055
Pelvic Tilt	5.49 ± 2.53	4.87 ± 1.52	0.079	0.507
Pelvic Drop	2.15 ± 0.84	3.65 ± 2.75	0.016*	0.032*
Pelvic Rotation	1.84 ± 1.64	4.22 ± 1.50	0.932	0.004*
Trunk Flexion	3.92 ± 1.05	4.53 ± 1.50	0.109	0.348
Trunk Lean	0.56 ± 0.42	1.55 ± 0.83	0.080	0.007*
Trunk Rotation	26.25 ± 3.02	26.25 ± 4.71	0.194	0.999

* Indicates a significant difference between groups, $p < .05$

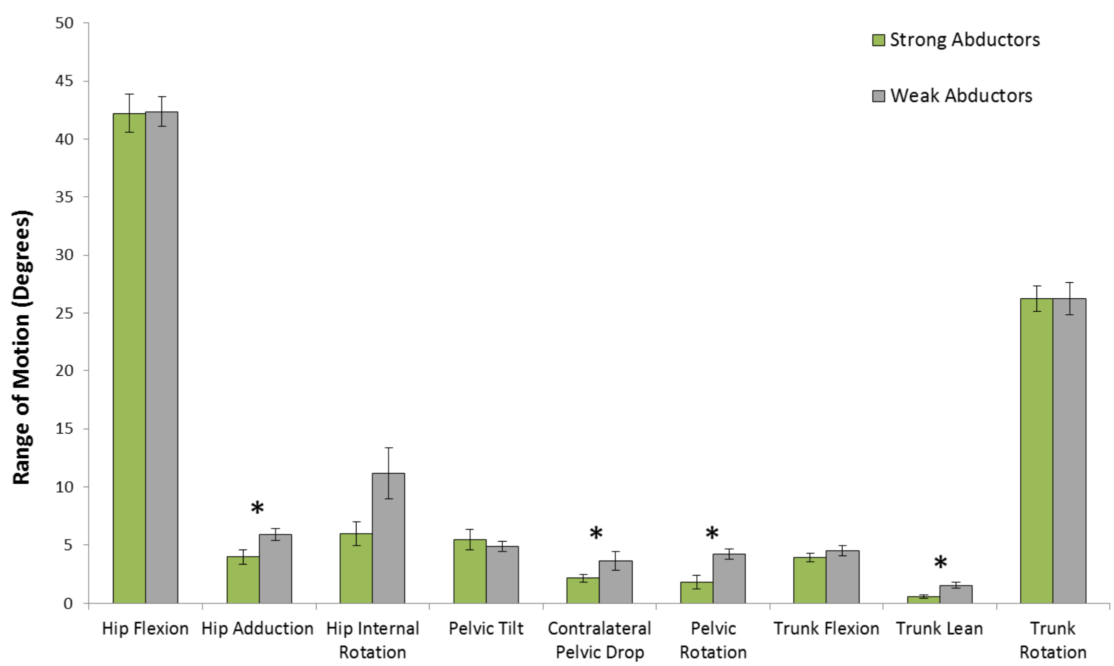

Figure 10. Differences in hip, pelvis, and trunk range of motion between strong and weak hip abductor groups.

Hip External Rotation Strength

When running speed was accounted for as a covariate, significant differences were found for trunk rotation range of motion between strong and weak hip external rotator groups, $p < .05$ (Table 8; Figure 11).

Table 8. Range of motion differences between strong and weak external rotator groups

	Strong External Rotators	Weak External Rotators	Levene's Test	*p*-value
Hip Extension	41.29 ± 3.61	43.01 ± 3.38	0.848	0.150
Hip Adduction	4.36 ± 2.55	5.67 ± 3.11	0.407	0.527
Hip Internal Rotation	7.09 ± 6.84	9.03 ± 5.47	0.967	0.764
Pelvic Tilt	5.06 ± 1.48	6.10 ± 1.23	0.997	0.501
Pelvic Drop	2.56 ± 2.09	3.38 ± 1.55	0.501	0.897
Pelvic Rotation	2.89 ± 2.11	3.31 ± 1.92	0.981	0.808
Trunk Flexion	3.89 ± 1.69	4.65 ± 1.42	0.913	0.337
Trunk Lean	1.23 ± 0.85	1.44 ± 0.79	0.669	0.766
Trunk Rotation	24.00 ± 5.34	30.14 ± 4.01	0.181	0.003*

* Indicates a significant difference between groups, $p < .05$

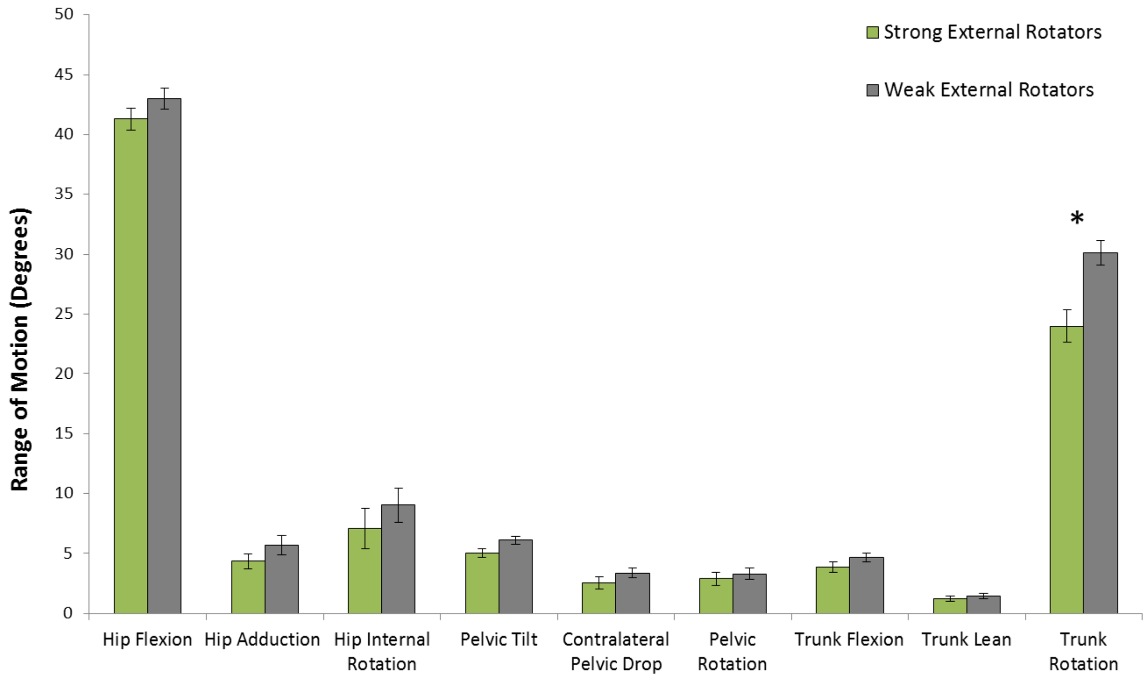

Figure 11. Differences in hip, pelvis, and trunk range of motion between strong and weak hip external rotator groups.

Hip Flexion Strength

When age was accounted for as a covariate, significant differences were found in regard to pelvic rotation range of motion between strong and weak hip flexor groups, $p < .05$ (Table 9; Figure 12).

Table 9. Range of motion differences between strong and weak hip flexor groups

	Strong Hip Flexors	Weak Hip Flexors	Levene's Test	*p*-value
Hip Extension	43.06 ± 5.06	43.09 ± 3.50	0.150	0.552
Hip Adduction	4.10 ± 2.02	4.79 ± 2.06	0.580	0.605
Hip Internal Rotation	7.70 ± 3.79	9.46 ± 5.52	0.089	0.923
Pelvic Tilt	6.00 ± 1.84	5.12 ± 1.65	0.545	0.257
Pelvic Drop	2.66 ± 1.43	2.57 ± 1.25	0.957	0.493
Pelvic Rotation	1.87 ± 1.45	3.46 ± 1.66	0.666	0.047*
Trunk Flexion	4.20 ± 1.30	4.41 ± 0.96	0.330	0.982
Trunk Lean	0.84 ± 0.66	1.04 ± 0.86	0.307	0.232
Trunk Rotation	26.41 ± 5.43	28.42 ± 5.06	0.751	0.562

* Indicates a significant difference between groups, $p < .05$

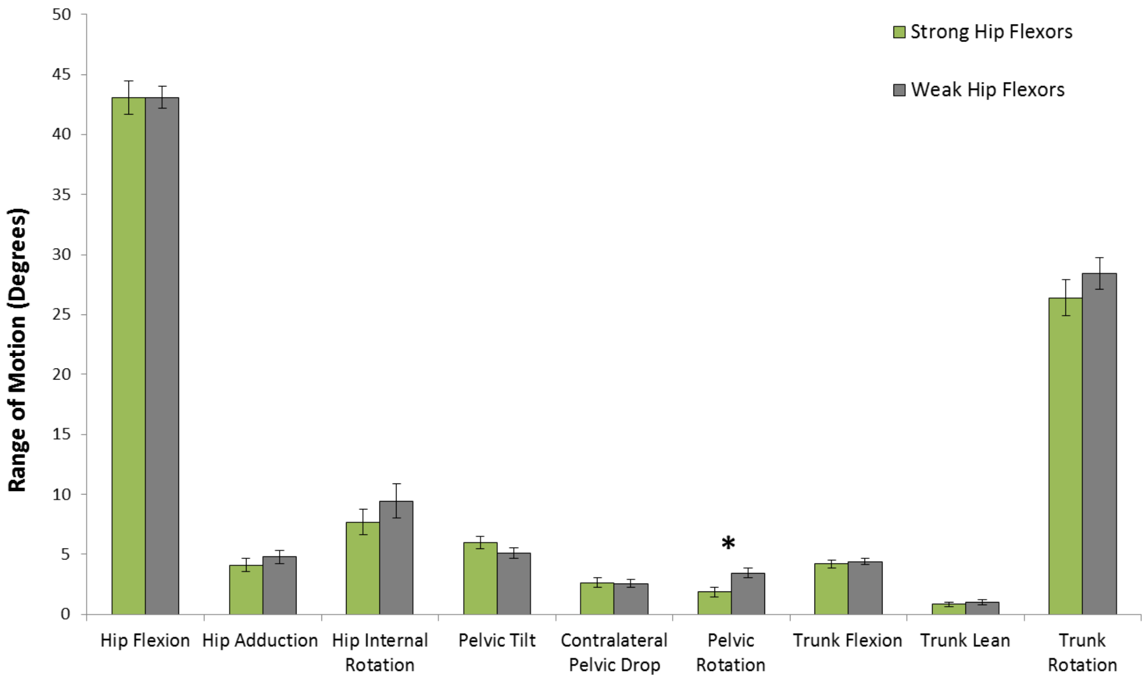

Figure 12. Differences in hip, pelvis, and trunk range of motion between strong and weak hip flexor groups.

Hip Internal Rotation Strength

When running speed was accounted for as a covariate, significant differences were found in regard to hip adduction and pelvic drop between strong and weak hip internal rotator groups, $p < .05$ (Table 10; Figure 13).

Table 10. Range of motion differences between strong and weak internal rotator groups

	Strong Internal Rotators	Weak Internal Rotators	Levene's Test	*p*-value
Hip Extension	41.87 ± 3.93	43.04 ± 2.46	0.169	0.276
Hip Adduction	3.64 ± 2.11	5.85 ± 3.21	0.044*	0.048*
Hip Internal Rotation	8.80 ± 3.94	8.33 ± 5.52	0.071	0.417
Pelvic Tilt	5.49 ± 1.89	5.54 ± 1.72	0.741	0.587
Pelvic Drop	1.85 ± 1.68	3.96 ± 2.24	0.225	0.043*
Pelvic Rotation	2.05 ± 2.09	3.35 ± 2.06	0.978	0.092
Trunk Flexion	4.87 ± 3.55	3.27 ± 2.59	0.461	0.129
Trunk Lean	0.74 ± 1.20	1.06 ± 1.01	0.617	0.569
Trunk Rotation	17.72 ± 7.42	21.82 ± 9.55	0.199	0.342

* Indicates a significant difference between groups, $p < .05$

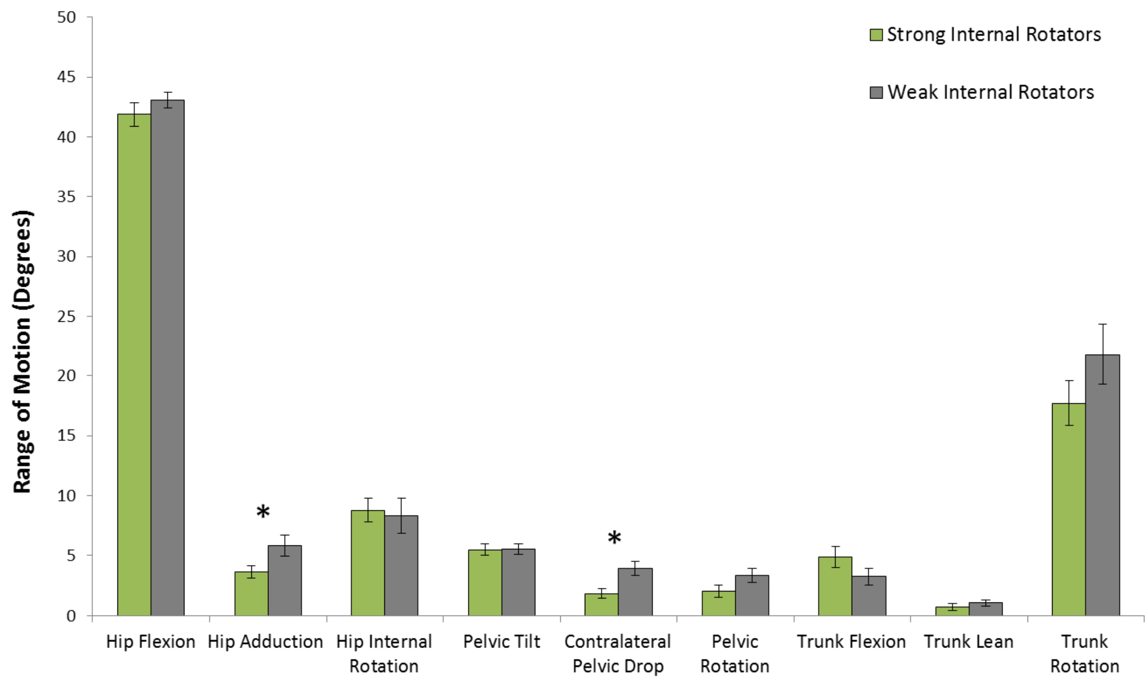

Figure 13. Differences in hip, pelvis, and trunk range of motion between strong and weak hip internal rotator groups.

CHAPTER IV

CORRELATION ANALYSIS RESULTS

Pearson correlation coefficients for all variables are represented in the tables below. Moderate correlations, defined as correlation coefficients (*r)* above 0.30 or below -0.30, are also represented graphically.

Angle at Contact

Pearson correlation coefficients for the hip, pelvis, and trunk angle at contact are summarized in Tables 11-13 and Figures 14-16.

Table 11. Pearson correlation coefficients for hip angle at contact.

	Hip Flexion	Hip Adduction	Hip Rotation
Hip Abductor Strength	0.157	0.233*	0.149
Hip Flexor Strength	0.123	0.067	0.202*
Hip External Rotator Strength	0.040	0.080	0.211*
Hip Internal Rotator Strength	0.049	0.170	0.082

Table 12. Pearson correlation coefficients for pelvis angle at contact.

	Pelvic Tilt	Pelvic Drop	Pelvic Rotation
Hip Abductor Strength	0.035	-0.091	0.324*
Hip Flexor Strength	-0.017	-0.033	0.238*
Hip External Rotator Strength	0.095	-0.177	0.151
Hip Internal Rotator Strength	-0.119	-0.135	0.120

Table 13. Pearson correlation coefficients for trunk angle at contact.

	Trunk Flexion	Trunk Lean	Trunk Rotation
Hip Abductor Strength	0.190*	0.118	0.111
Hip Flexor Strength	0.272*	0.127	0.197*
Hip External Rotator Strength	0.309*	0.322*	0.263*
Hip Internal Rotator Strength	0.148	0.062	0.143

* Indicates a significant correlation, $p < .05$

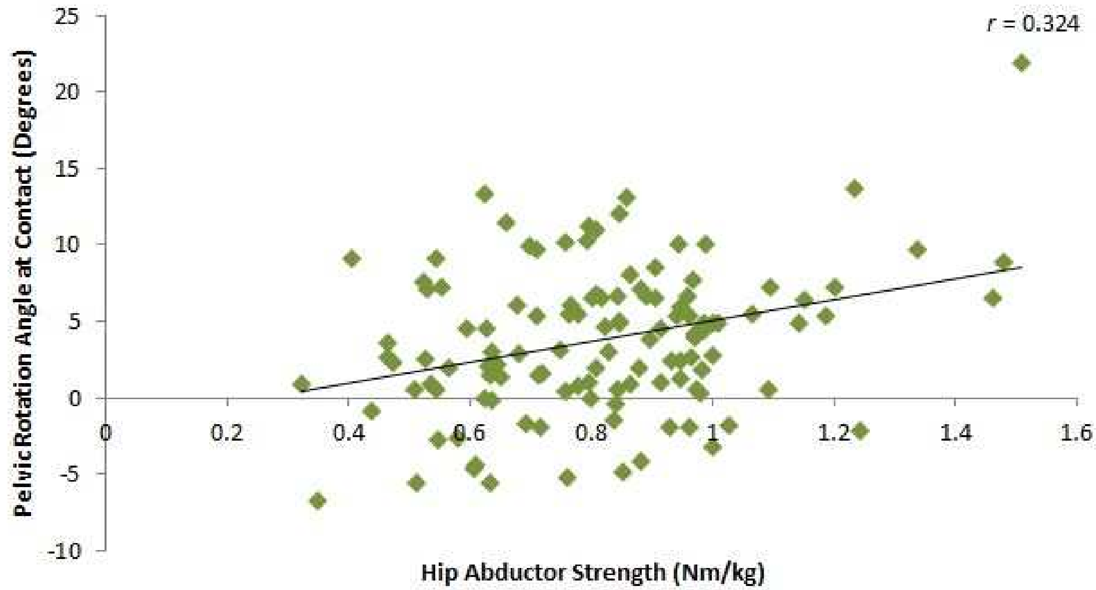

Figure 14. Significant moderate correlation between hip abductor strength and pelvic rotation angle at contact.

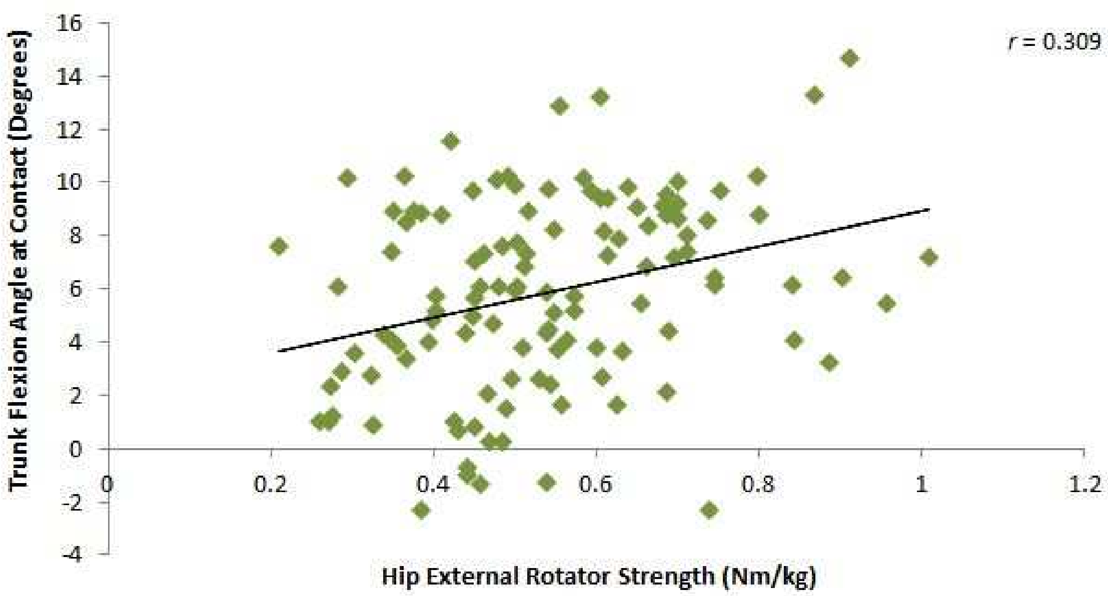

Figure 15. Significant moderate correlation between hip external rotator strength and trunk flexion angle at contact.

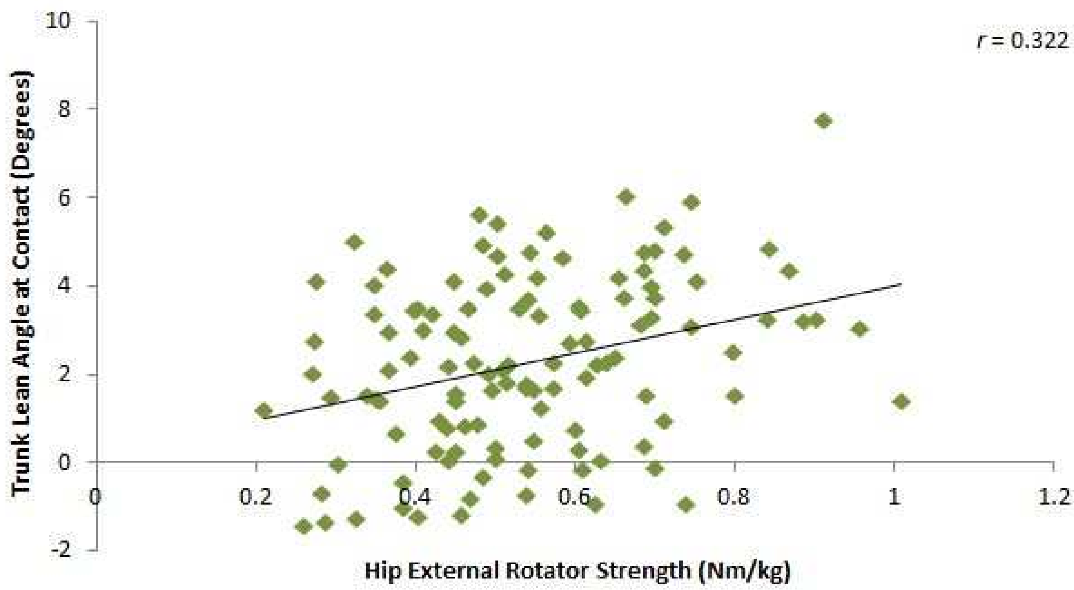

Figure 16. Significant moderate correlation between hip external rotator strength and trunk lean angle at contact.

Peak Angle

Pearson correlation coefficients for hip, pelvis, and trunk peak angles are summarized in Tables 14-16. Peak hip extension and peak trunk rotation were not included in this table because these variables are the same as the angle at toe-off.

Table 14. Pearson correlation coefficients for peak hip angles.

	Hip Adduction	Hip Rotation
Hip Abductor Strength	0.041	0.076
Hip Flexor Strength	-0.040	0.087
Hip External Rotator Strength	-0.087	0.083
Hip Internal Rotator Strength	0.042	0.089

Table 15. Pearson correlation coefficients for peak pelvic angles.

	Pelvic Tilt	Pelvic Drop	Pelvic Rotation
Hip Abductor Strength	0.042	0.065	0.191*
Hip Flexor Strength	0.007	-0.030	0.132
Hip External Rotator Strength	0.126	-0.010	0.099
Hip Internal Rotator Strength	-0.105	0.033	0.043

Table 16. Pearson correlation coefficients for peak trunk angles.

	Trunk Flexion	Trunk Lean
Hip Abductor Strength	0.134	0.016
Hip Flexor Strength	0.289*	0.080
Hip External Rotator Strength	0.256*	0.287*
Hip Internal Rotator Strength	0.081	-0.060

* Indicates a significant correlation, $p < .05$

Range of Motion

Pearson correlation coefficients for hip, pelvis, and trunk range of motion are summarized in Tables 17-19 and Figures 17-19.

Table 17. Pearson correlation coefficients for hip range of motion.

	Hip Flexion	Hip Adduction	Hip Rotation
Hip Abductor Strength	0.026	-0.324*	-0.148
Hip Flexor Strength	-0.070	-0.176	-0.232*
Hip External Rotator Strength	-0.166	-0.270*	-0.258*
Hip Internal Rotator Strength	-0.104	-0.214*	0.012

Table 18. Pearson correlation coefficients for pelvic range of motion.

	Pelvic Tilt	Pelvic Drop	Pelvic Rotation
Hip Abductor Strength	-0.013	-0.278*	-0.352*
Hip Flexor Strength	0.135	-0.021	-0.279*
Hip External Rotator Strength	-0.175	-0.289*	-0.144
Hip Internal Rotator Strength	-0.064	-0.291*	-0.198*

Table 19. Pearson correlation coefficients for trunk range of motion.

	Trunk Flexion	Trunk Lean	Trunk Rotation
Hip Abductor Strength	-0.161	-0.213*	0.039
Hip Flexor Strength	-0.017	-0.107	-0.104
Hip External Rotator Strength	-0.181	-0.095	-0.412*
Hip Internal Rotator Strength	-0.179	-0.256*	-0.184*

* Indicates a significant correlation, $p < .05$

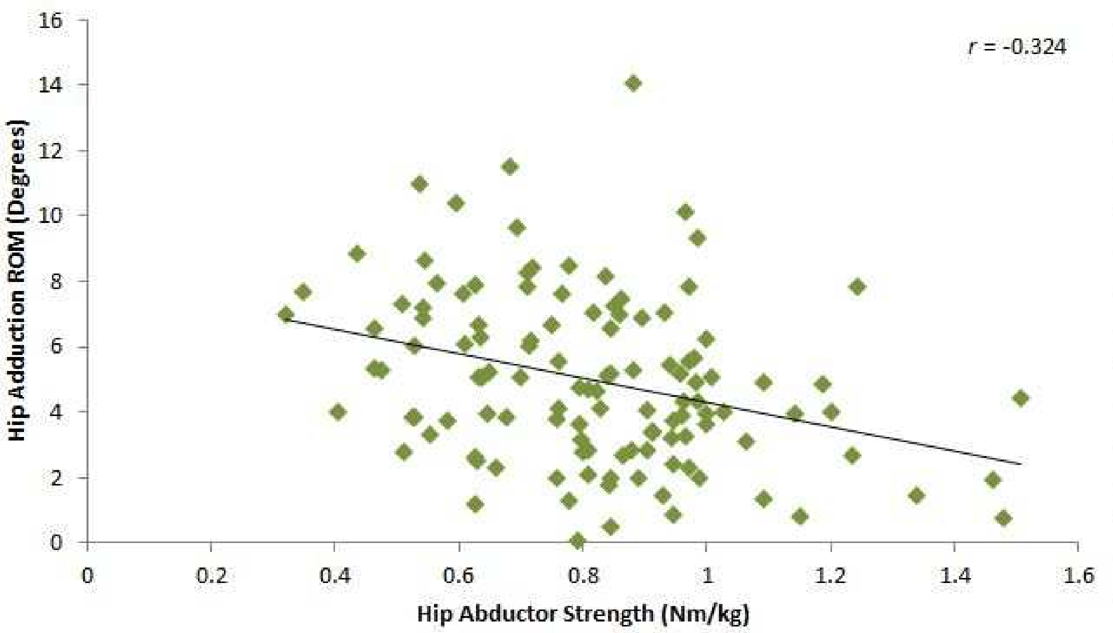

Figure 17. Significant moderate correlation between hip abductor strength and hip adduction range of motion.

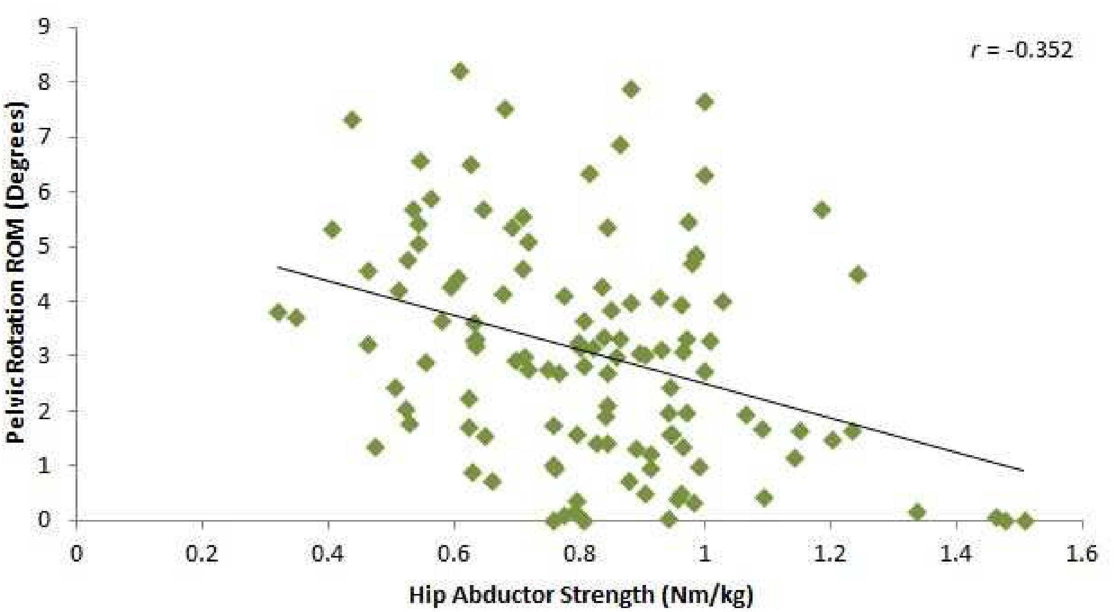

Figure 18. Significant moderate correlation between hip abductor strength and pelvic rotation range of motion.

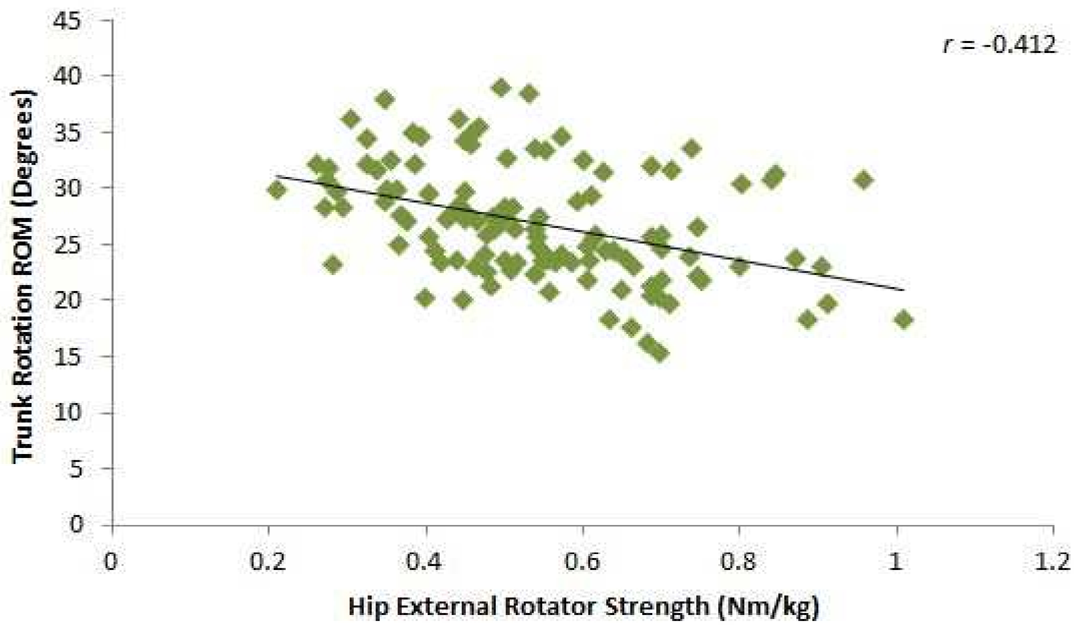

Figure 19. Significant moderate correlation between hip external rotator strength and trunk rotation range of motion.

Percent Stance at Peak Angle

Pearson correlation coefficients for the percent stance at peak hip, pelvis, and trunk angles are summarized in Tables 20-22 and Figure 20. In addition to hip flexion and trunk rotation, pelvic tilt was omitted here. While peak anterior pelvic tilt occurs before toe-off in some subjects, it usually occurs at toe-off, skewing this value towards 100 percent.

Table 20. Pearson correlation coefficients for the percent stance at peak hip angles.

	Hip Adduction	Hip Rotation
Hip Abductor Strength	-0.236*	-0.030
Hip Flexor Strength	-0.080	-0.002
Hip External Rotator Strength	-0.195*	-0.013
Hip Internal Rotator Strength	-0.007	0.080

Table 21. Pearson correlation coefficients for the percent stance at peak pelvic angles.

	Pelvic Drop	Pelvic Rotation
Hip Abductor Strength	-0.158	-0.413*
Hip Flexor Strength	0.005	-0.131
Hip External Rotator Strength	-0.194*	-0.080
Hip Internal Rotator Strength	0.025	-0.076

Table 22. Pearson correlation coefficients for the percent stance at peak trunk angles.

	Trunk Flexion	Trunk Lean
Hip Abductor Strength	-0.167	-0.175
Hip Flexor Strength	-0.048	-0.182
Hip External Rotator Strength	0.014	-0.093
Hip Internal Rotator Strength	-0.053	-0.115

* Indicates a significant correlation, $p < .05$

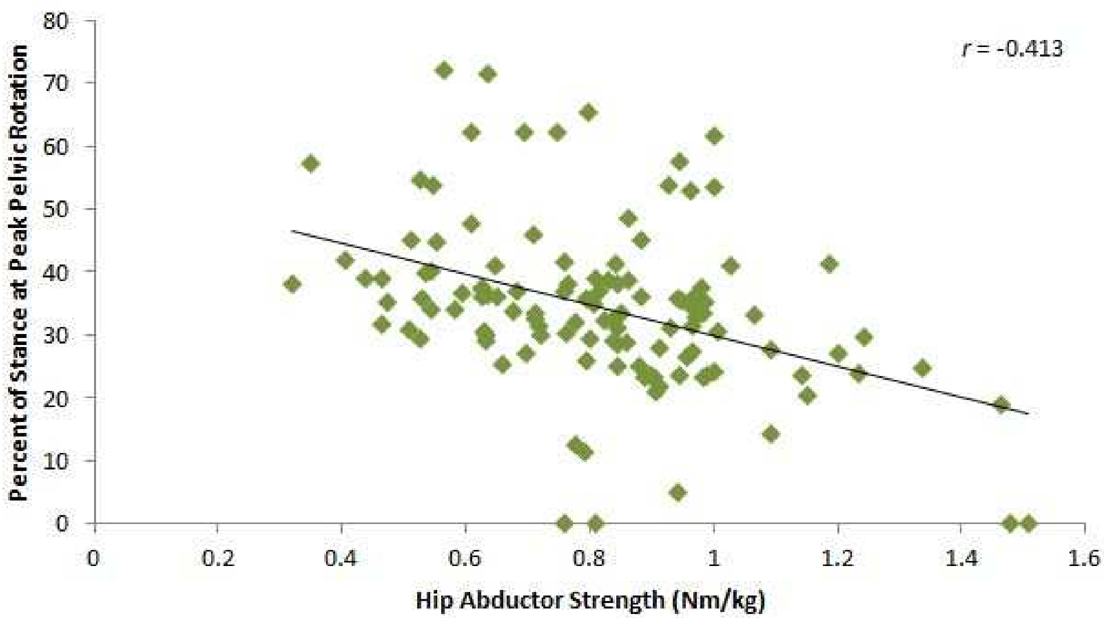

Figure 20. Significant moderate correlation between hip abductor strength and the percent of stance phase at peak pelvic rotation.

Angle at Toe-Off

Pearson correlation coefficients for the hip, pelvis, and trunk angle at toe-off are summarized in Tables 23-25.

Table 23. Pearson correlation coefficients for hip angle at toe-off.

	Hip Flexion	Hip Adduction	Hip Rotation
Hip Abductor Strength	0.139	0.082	0.066
Hip Flexor Strength	0.202*	-0.028	0.120
Hip External Rotator Strength	0.214*	-0.014	0.089
Hip Internal Rotator Strength	0.126	0.013	0.077

Table 24. Pearson correlation coefficients for pelvis angle at toe-off.

	Pelvic Tilt	Pelvic Drop	Pelvic Rotation
Hip Abductor Strength	0.038	-0.012	-0.087
Hip Flexor Strength	0.009	-0.041	0.095
Hip External Rotator Strength	0.129	-0.102	0.118
Hip Internal Rotator Strength	-0.111	-0.003	0.004

Table 25. Pearson correlation coefficients for trunk angle at toe-off.

	Trunk Flexion	Trunk Lean	Trunk Rotation
Hip Abductor Strength	0.099	-0.034	-0.154
Hip Flexor Strength	0.233*	0.004	-0.150
Hip External Rotator Strength	0.250*	0.170	-0.174
Hip Internal Rotator Strength	0.086	-0.040	-0.032

* Indicates a significant correlation, $p < .05$

CHAPTER V

DISCUSSION

Range of Motion Results

The main focus of this study was to examine the relationship between hip strength and proximal kinematics in healthy runners. In the group difference analysis, individuals with weak hip abductors displayed significantly greater hip adduction, contralateral pelvic drop, lateral trunk lean, and anterior pelvic rotation compared to runners with strong abductors, $p < .05$. The relationship between hip abductor strength and hip adduction ($r = -0.324$) and pelvic rotation ($r = -0.352$) range of motion were strongest when analyzing all 60 runners.

The sagittal plane results supported the hypothesis and were expected considering the functional anatomy of the hip musculature. Gluteus medius, the primary hip abductor, fires its posterior, middle, and anterior fibers sequentially during stance phase to prevent hip adduction and contralateral pelvic drop (Gottschalk et al., 1989; McClay et al., 1990). Weakness of the gluteus medius, as well as the gluteus minimus and tensor fascia latae, would logically lead to excessive motion for these two parameters.

Greater lateral trunk lean also supported the hypothesis, but requires a bit more investigation, as lateral trunk lean occurs in the opposite sagittal plane direction compared to pelvic drop. The most likely explanation is that lateral trunk lean is a compensatory mechanism aimed to move the whole body center of mass closer to the hip axis of rotation. This would effectively decrease the moment arm for the center of mass and reduce the hip abductor torque needed to counteract the center of mass torque. Thus, it appears logical that runners with weak hip abductors would demonstrate this pattern in an attempt to unload the weak muscles. Two previous studies looking at trunk lean in runners found contrasting results. Noehren et. al (2011) found a trend towards greater lateral trunk lean (p = .071) in runners with PFPS, who have also been shown to display weak hip abductors. Ford et al., however, reported that as hip abductor strength increased, lateral trunk lean range of motion also increased (r = 0.25). More research is undoubtedly needed to clarify this relationship.

Greater pelvic rotation for the weak abductor group was initially an unexpected result, as the only study to date relating hip abductor strength to pelvic rotation reported a relatively weak relationship (r = -0.22) (Ford et al., 2013). However, for our study, the Pearson correlation coefficient for pelvic range of motion rotation was higher than all three sagittal plane parameters (r = -0.352)

The results of studies on gluteus medius function during walking may help explain this finding. During walking, the gluteus medius has been shown to be the primary muscle responsible for the initiation of anterior pelvic rotation (Gottschalk et al., 1989). Of particular importance are the posterior fibers of the gluteus medius, which attach on the posterior portion of the iliac crest and insert on the posterolateral surface of the greater trochanter (Figure 21). These posterior fibers activate first during early- and mid-stance, pulling from distal to proximal and controlling anterior pelvic rotation due to their line of pull (Figure 22) (Gottschalk et al., 1989). Studies have found that gluteus medius onset is delayed in runners with PFPS (Willson et al., 2011; Barton et al., 2012). Because runners with PFPS are known to often present with reduced abductor strength, the posterior fibers of these runners may not be firing early enough to control anterior pelvic rotation.

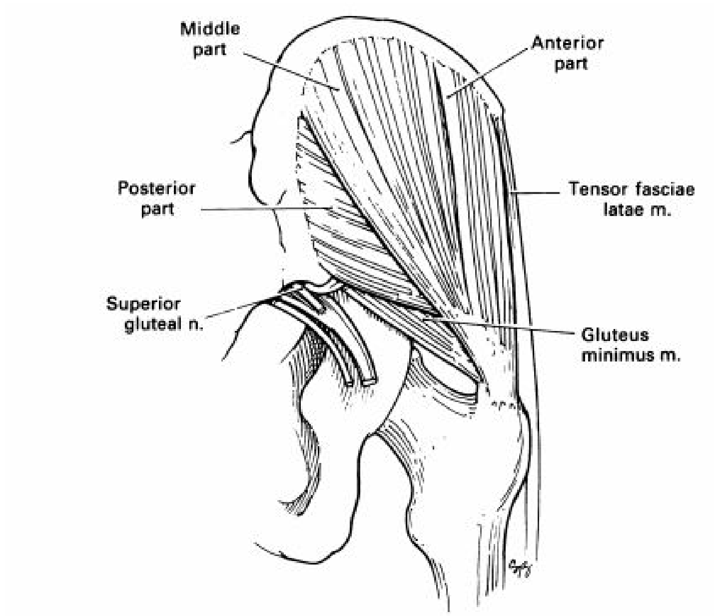

Figure 21. Anatomy of the gluteus medius, gluteus minimus, and tensor fascia latae muscles (Gottschalk et al., 1989).

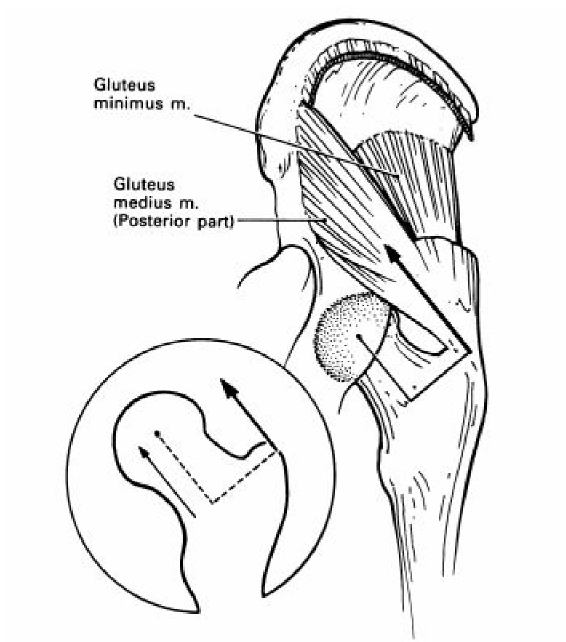

Figure 22. Line of action of the posterior gluteus medius muscle (Gottschalk et al., 1989).

It is also important to note that some runners in this study attempted to flex the hip and trunk during hip abductor strength testing, possibly a compensatory movement for poor strength in the posterior part of the gluteus medius. This also supports the theory that runners testing weak for hip abduction may lack either strength or neuromuscular control in the posterior gluteus medius, leading to difficulty controlling anterior pelvic rotation during the first half of stance phase. More evidence is needed, however, to support this theory.

Hip external rotator strength was hypothesized to control hip internal rotation and anterior pelvic rotation range of motion. However, group differences were only seen for trunk rotation range of motion, as the weak hip external rotator group displayed significantly more trunk rotation compared to the strong external rotator group ($p = .003$).

While it's not illogical that external rotator strength could influence trunk rotation in the transverse plane, it's surprising that we see this result without differences in pelvic rotation. The correlation coefficient between trunk rotation and hip external rotator strength was moderately strong ($r = -.412$), but no significant correlation was found between pelvic rotation and hip external rotator strength ($r = -0.144$). The limited research quantifying lumbo-pelvic coupling during running may partially explain this findings, as the lumbar spine and pelvis are out of sequence for approximately 21% of the gait cycle, or about half of stance phase (Schache et. al, 2002). While this study examined whole trunk motion, the same pattern appears to be true when qualitatively assessing the sample graphs for pelvic and trunk rotation. For most runners, the pelvis anteriorly rotates until peak rotation around midstance, and then begins to posteriorly rotate until toe-off (Figure 6). The trunk, however, externally rotates throughout the entirety of stance phase (Figure 9).

The external rotator group is thought to eccentrically control hip internal rotation and stabilize the pelvis during single limb support (McClay et al., 1990). Again, since the thigh is relatively fixed, this means that the external rotators would control anterior pelvic rotation in the transverse plane. One theory is that weak external rotators lead to instability but not necessarily excessive anterior rotation at the pelvis. Excessive external trunk rotation could then be seen as a compensatory pattern in an attempt to generate forward momentum, as the pelvic-hip girdle is too unstable to generate force for push-off via pelvic rotation. More research appears to be needed in this area to better explain this phenomenon.

Surprisingly, this study found differences between groups for hip flexion and internal rotator strength, which had not been cited heavily in previous literature. In regard to hip flexion strength, the weak hip flexor group demonstrated greater pelvic rotation compared to the strong hip flexor group. Two of the hip flexors, sartorius and iliopsoas, play a role in hip external rotation in addition to the main actions as hip flexors. Because the leg is fixed during stance phase, this means that these two muscles assist in posterior pelvic rotation in the transverse plane, and as such, eccentrically control anterior pelvic rotation (Niemuth et al., 2005). While this contribution was not previously thought to be large, the results from this study suggest that their contribution to pelvic rotation may be larger than previously theorized.

Runners with weak hip internal rotators displayed greater hip adduction and pelvic drop range of motion compared to runners with strong hip adductors ($p < .05$).

This result, while not previously cited in the literature, was not surprising, as the gluteus medius and minimus are the primary internal rotators when the hip is flexed (Schmitz et al., 2002). Weak gluteus medius function, as previously discussed, is likely related to poor sagittal plane stability during running (McClay et al., 1990).

Additional Parameters of Joint and Segment Motion

A few moderate correlations were seen for the angle at contact parameter, which is thought to be a measure of segment control and positioning during terminal swing. Hip abductor strength was shown to be moderately correlated to pelvic rotation angle at contact ($r = 0.324$), suggesting that runners with strong hip abductors tend to land with the hip in a more anteriorly-rotated position. Landing in a more anteriorly-rotated position likely requires increased stability at the hip and pelvis, which is evidenced by the moderate relationship with increased strength.

A moderate, positive correlation was found between hip external rotator strength and both trunk flexion angle at contact ($r = 0.309$), and trunk lean angle at contact ($r = 0.322$). These results seem paradoxical, as excessive trunk flexion and trunk lean at contact are thought to occur in runners with decreased proximal stability (Noehren et. al, 2011). Assuming these relationships were not due to chance, more research appears to be needed to explain this finding.

Lastly, the largest Pearson correlation coefficient in this study was seen between hip abductor strength and the percent stance at peak pelvic rotation ($r = -0.413$). This means that as hip abductor strength increased, the percent of stance phase that peak anterior pelvic rotation occurred decreased. The same rationale as to why decreased pelvic rotation range of motion was different between hip abductor strength groups can be cited here. The hip abductors appear to play a significant role not only limiting anterior pelvic rotation, but shortening the time from initial contact to peak pelvic rotation.

Statistical Significance versus Clinical Relevance

While the discussion to this point has been statistically based, one must also consider the clinical relevance of the findings. For many parameters, significant group differences were seen with only 1-2 degrees separating the groups. Likewise, while moderate relationships were seen between some variables, the coefficient of determination (r^2) values did not exceed 0.17 in magnitude, meaning that 17% or less of the variance in hip strength accounted for the variance in kinematic parameters. Thus, while many results of this thesis were expected and make sense anatomically, the major question that remains is whether a few degrees of motion makes a difference between staying healthy and developing an injury. Unfortunately, the current research in this area is not advanced enough to discriminate what constitutes a clinically relevant finding. As the evidence begins to mount in this area, the picture may become clearer.

Study Limitations

A major question that remains is the transferability of static muscle strength measurements to the dynamic action of muscles during running. While many of the relationships reported in this study make anatomical sense, patient positioning for muscle testing may still be called into question. For example, hip abductor strength was measured in an open-chain position, while the hip abductors must fire in a closed-chain position during stance phase. For open-chain hip abduction, the proximal end is fixed, meaning that contraction abducts the leg. In contrast, the distal end is fixed during running, meaning that the hip abductors contract to prevent pelvic drop. The same objection can be made for internal and external rotation strength testing, as the seated, open-chain position of this test may not mimic the demands of the muscle during closed-chain movement. These differences in test position compared to running position can be seen as a main limitation of this study.

A second limitation of this thesis is related to marker positioning. Fortunately, range of motion should not be affected by error in marker placement, as this measurement is simply the difference between the angle at contact and peak angle. However, correct maker placement plays a role in angle at contact, peak angle, and angle at toe-off parameters, however. For example, placing the sacrum marker lower than recommended will decrease the apparent anterior pelvic tilt in a standing position.

While careful consideration was given to marker placement for every subject, inconsistent marker placement has been shown to account for 75-90% of between-day reliability (Gorton et al., 2009). Also, while between-day repeatability has been shown to be relatively high for sagittal plane walking kinematics, frontal and transverse plane repeatability is markedly lower (Kadaba et. al, 1989). This variability in marker placement needs to be considered when extrapolating angle at contact, peak angle, and angle at toe-off results, and can also be seen as an inherent limitation to this study. For this reason, and for the number of moderate correlations seen between hip strength and range of motion parameters, this study recommends reporting hip, pelvis, and trunk range of as the main outcome measure in future studies.

A third limitation is the absence of hip extension and adduction strength measurements in the analysis. Previous research has suggested a strong, significant, negative correlation between hip extension strength and both pelvic drop and trunk rotation (Ford et al., 2013). The addition of hip extension strength measurements would create a more complete picture of the relationship between hip strength and kinematics, and can be seen as a third limitation of this study.

Conclusions and Future Directions

There were many noteworthy findings in this study. For each strength parameter, differences were seen for certain measures of hip, pelvis, and trunk range of motion Moderate correlations were also found between several measures of strength and kinematics, most notably between hip abductor strength and hip adduction range of motion, between hip abductor strength and pelvic rotation range of motion, and between hip external rotation strength and trunk rotation range of motion.

While data from this study help elucidate the relationship between hip strength and kinematics, no causal conclusions can be gleaned. In order to study this question of cause and effect, future studies should examine the effect of muscle strengthening on kinematics in healthy runners. Mixed data from such studies to date (Snyder et. al, 2009; Ferber et al., 2011; Willy & Davis, 2011) suggests that hip muscle strength may not be the sole determinant of proximal kinematics (Noehren et al., 2010; Wouters et al., 2011).

Thus, future studies should also examine the effect of factors other than muscle strength on kinematics, such as motor control, flexibility, and anthropometric variation.

APPENDIX

INFORMED CONSENT

CONSENT FORM

You are invited to participate in a research study conducted by Drs. Li-Shan Chou, Louis Osternig, Stan James, and graduate student James Becker regarding the role of foot pronation in running injuries. We hope to understand how the duration of foot pronation can be quantified from both clinical and biomechanical perspectives, how it may be different in injured and uninjured runners, and how it may affect muscle forces in the lower limb while running. You are being invited to participate because you are either a currently healthy runner or because you are currently an injured runner with either medial tibial stress syndrome or an Achilles tendon injury.

If you decide to participate, you will be tested in the Motion Analysis Laboratory at the University of Oregon. This study is longitudinal in nature, meaning we will follow up and retest you at regular intervals throughout the year. It is expected that the follow up visits will be conducted approximately every three months; however there is some leeway in this time frame depending on your individual schedule and needs. **We anticipate recruiting a total of 150 subjects for this study, 20 currently symptomatic with medial tibial stress syndrome or Achilles tendinopathy, and 130 healthy subjects.**

TESTING PROCEDURES: The assessments in the Motion Analysis Lab will include both clinical and biomechanical evaluations. The clinical evaluation will include measures of your body alignment, joint range of motion, and muscle strength. For the running gait analysis reflective markers will be placed on selected bony landmarks to record the motion of each individual body segment. You will run laps around the laboratory space and your body movement (indicated by motion of reflective makers) during running will be recorded by our cameras for further analysis. We will also record your running with traditional video cameras and, with your permission, may take photographs of the marker set up placed on your body. Your will run both while wearing running shoes and barefoot. When you run with shoes on we will cut holes in the shoe to allow us to place markers directly on your foot. Therefore you will be required to provide an old pair of running shoes you do not mind having cut up. It is expected that you will run approximately 30 short laps around the laboratory under each condition, with each lap being approximately 25 meters. You will also be asked to complete short bouts of treadmill running, also with and without shoe. Finally, while running on a treadmill we will measure the pressure distribution under your foot using specialized insoles which we will place inside your shoe.

You will wear normal running shoes for these procedures. You will be asked to wear a pair of paper physical therapy shorts and sleeveless shirt (tank top) or equivalent clothing of your choice during testing to allow the cameras to clearly see the markers. It is expected each testing session will require approximately 2.5 hours of your time.

COMPENSATION: You will be compensated $20 for each visit to the laboratory. You should understand that your old shoes will no longer be usable after your participation in the study.

RISKS AND DISCOMFORTS: We expect that there will be no more risk for you during these tests than there normally is for you when outside of the laboratory. However, running in the laboratory is different than running outside. You will be asked to speed up then slow down over a 25 meter distance. Running laps in the laboratory will require negotiating tight corners. We will do our best to arrange the lab equipment and furniture to minimize any discomforts and provide as much room as possible. If you are not comfortable you may stop the trials at any time. Additionally, running on a treadmill is also not the same as running outside, however you may stop the treadmill at any time if you feel uncomfortable. You may feel fatigue during or after the testing. Our staff member will check with you frequently and provide any required assistance. You will be given frequent breaks as requested. Cutting the holes in your running shoes will require the removal of the inner lining so there is the possibility of rubbing or discomfort on your feet. We will do our best to reduce these effects, and should they still be present you may request additional modifications or stop the trials at any time. There is also the possibility of discomfort involved in removing adhesive tape (used for marker placement) from skin at the end of the experiment.

ADDITIONAL INFORMATION: Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will not be shared without your permission.
Subject identities will be kept confidential by coding the data as to study, subject pseudonyms, and collection date. The code list will be kept separate and secure from the actual data files.

Your participation is completely voluntary. Your decision whether or not to participate will not affect your relationship with the Department of Human Physiology or University of Oregon. You do not waive any liability rights for personal injury by signing this form. In spite of all precautions, you might develop medical complications from participating in this study. If such complications arise, the researchers will assist you in obtaining appropriate medical treatment. In addition, if you are physically injured because of the project, you and your insurance company will have to pay your doctor bills. If you are a University of Oregon student or employee and are covered by a University of Oregon medical plan, that plan might have terms that apply to your injury. If you have any questions about your rights as a research subject, you can contact Research Compliance Services, 5237 University of Oregon, Eugene, OR 97403, (541) 346-2510. This office oversees the review of the research to protect your rights and is not involved with this study.

If you decide to participate, you are free to withdraw your consent and discontinue participation at any time without penalty. This includes discontinuing your participation anytime during the initial visit or not returning for follow up visits. If you choose not to return for follow up visits the researchers may discontinue your participation in the study. **Additionally, the researchers may discontinue your participation in this study if you are not able to provide an old pair of shoes, or are not capable of running the amount required to complete the testing, either on the treadmill or overground.**

If you have any questions, please feel free to contact Dr. Li-Shan Chou, (541) 346-3391, Department of Human Physiology, 112C Esslinger Hall, University of Oregon, Eugene OR, 97403-1240. You will be given a copy of this form to keep. Your signature indicates that you have read and understand the information provided above, that you willingly agree to participate, that you may withdraw your consent at any time and discontinue participation without penalty, that you will receive a copy of this form, and that you are not waiving any legal claims, rights or remedies.

Name: ____

Signature: ____

Date: ________________________________

AGREEMENT FOR PHOTOGRAPHING OR VIDEOTAPING

I have received an adequate description of the purpose and procedures for photographing or videotaping sessions during the course of the proposed research study. I give my consent to allow myself to be photographed or videotaped during participation in the study, and for those photographs or videotapes to be viewed by persons involved in the study, as well as for other professional purposes, including conference presentation and scientific publication of findings from the study, as described to me. I understand that all information will be kept confidential, that the photographs and videotapes will be edited to protect my confidentiality, and will be reported in an anonymous fashion. I further understand that I may withdraw my consent at any time.

___________________________________ ___________________________

Printed name of research participant Date

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Signature of research participant

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