A Master’s Thesis

titled

Core Muscular Endurance Differences in Recreational Runners With a Previous History of Running-Related Musculoskeletal Injuries and Healthy Runners

by

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Submitted to the Graduate Faculty as partial fulfillment of the requirements for the

Master of Science Degree in Exercise Science

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An Abstract of

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**Context:** Identification of core strength deficits in runners with running-related musculoskeletal injuries (RRMI) has been documented. However, as running is typically a long distance, endurance sport, core muscular endurance should be evaluated within the RRMI population. Specifically, hip abduction (HABD) and external rotation (HER) endurance, as well as lateral trunk flexion (LTF), trunk flexion (TFX), extension (TEX), as these muscles are responsible for controlling the pelvis during running and maintaining a neutral center of mass. **Objective:** To examine core muscular endurance differences between recreational runners who have a previous history of a RRMI compared to healthy matched controls. **Methods and Measures:** 12 recreational runners with a previous history of RRMI (6 females, 6 males, 31.78 ± 8.72yrs, 174.28 ± 10.02cm, and 69.82 ± 11.52kg) and 13 healthy (7 females, 6 males, 30 ± 8.28yrs, 170.82 ± 8.67cm, 68.34 ± 12.8kg) runners participated in this study. HER, and LTF endurance measures were collected at one session, while HABD, TFX and trunk extension TEX endurance measures were collected at the second session, with sessions 2-5 days apart. All tests were isometric fatiguing tests and were recorded in seconds. A mixed model repeated
measures ANOVA for HER, HABD, and LTF endurance, and a 2x2 ANOVA for TFX and TEX endurance were used for analyses, and paired samples t-tests were used for post-hoc testing as needed. **Results:** A statistically significant limb by group interaction was observed with LTF endurance (p=0.01). LTF endurance of the injured limb of the RRMI group was greater than the injured limb of the healthy group (p=0.03); also the LTF endurance of the injured limb of the RRMI group was greater than the contralateral, non-injured limb (p=0.02). Although not statistically significant, HABD endurance in RRMI females was lower than healthy females while HABD endurance in RRMI males was greater than healthy males (p=0.08), and females displayed greater HER endurance compared to males (p=0.08). No other statistical significances were observed.

**Conclusion:** Recreational runners with a history of a RRMI displayed greater LTF endurance in the injured limb compared both to the contralateral non-injured limb and also to the injured limb of the healthy group. Additionally, health females and RRMI males displayed greater HABD endurance compared to their counterparts, and females displayed greater HER endurance compared to males. These findings are clinically relevant as this shows that clinicians should incorporate both endurance components as well as strength components to rehabilitation of RRMI.
Thank you to my parents, Yoshihisa and Isoko Kitagawa, and my brother, Jun Kitagawa, for their continued love and support.
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List of Abbreviations

HABD ....................Hip abduction
HER...........................Hip external rotation

LTF ............................Trunk lateral flexion

TEX ...........................Trunk extension
TFX.........................Trunk flexion
Chapter One

Introduction

Running is one of the most common forms of exercise in the United States.\textsuperscript{1-9} Unfortunately, overuse injuries are also common, as repetitive motions such as running can cause insidious damage to the structures involved.\textsuperscript{7} There are a variety of overuse injuries that runners experience, but the most commonly seen running-related musculoskeletal injuries (RRMIs) include patellofemoral pain (PFP), iliotibial band friction syndrome (ITBFS), medial tibial stress syndrome (MTSS) and stress fractures of the lower leg.\textsuperscript{6,8,10-12}

The rates of each injury in various populations of runners differ; however, they are uniformly high making overuse running injuries the most common ailment across all ages and intensities of runners. In the younger population of high school runners, researchers have found injury rates of up to 47\% as well as 2.4 injuries per 1000 athlete exposures.\textsuperscript{13,14} In the college age population, Daoud et al.\textsuperscript{15} found that 75\% of 52 Harvard cross country subjects incurred an overuse injury within one year of competition.\textsuperscript{15} High injury rates are also documented in the recreational runners’ population with a rate of up to 70\%.\textsuperscript{16,17}

It is evident that RRMIs are widespread among runners, but researchers disagree on the etiology behind these injuries. PFP is thought to originate from multiple sources. Some authors have implicated excessive rearfoot eversion, while others attribute PFP to decreased vastus medialis obliquus (VMO) strength and motor recruitment.\textsuperscript{18-22} However, more recent research has cited poor hip and core muscle strength and kinematics as a likely origin.\textsuperscript{23-25} Various researchers believe ITBFS originates from tightness of the
iliotibial band and excessive pronation, while others suggest it is caused by friction between the lateral femoral condyle and the iliotibial band during running. More recently, researchers have also cited decreased thigh abduction and external rotation due to hip abductor weakness as a source of ITBFS. Bennell et al. explain that stress fractures develop due to the imbalance between bone loading and bone remodeling where the loading outweighs the remodeling and therefore creates a deficiency in the bone strength and structure. Friberg as well as Bennell et al. found that leg length discrepancy may have a significant effect on the development of lower extremity stress fractures due to asymmetrical skeletal alignments and the resulting uneven wear to the bony structures and muscular attachments at the hip. Beck et al. theorized that medial tibial stress syndrome results from muscle or fascial traction on the periosteum and tibial bending with weight-bearing, while Couture et al. found that pronation is a more likely origin of MTSS.

Nonetheless, it is clear that with each of these RRMIs, there is a recurring pattern of poor strength and kinematics of the lower extremity, perhaps most interestingly at the hip, which may be a causative factor.

**Statement of the Problem**

A large portion of the recreationally active population has a previous history of RRMI, and evidence shows that strength deficits exist within this RRMI population compared to healthy controls. However, most existing studies have given more emphasis to muscular strength measurements compared to muscular endurance measurements. It is unknown what impact muscular endurance, especially in the hip and core, may have on running mechanics and the development of RRMI.
Statement of the Purpose

The purpose of this study was to examine core muscular endurance in recreational runners with a previous history of RRMI compared to healthy matched controls.

Significance of the Study

The significance of this study was to provide clinicians with information on whether they need to emphasize correcting endurance deficits in the prevention of RRMI in a recreationally active population.

Specific Aim and Hypotheses

A1- To examine core muscular endurance differences in recreational runners with a previous history of a RRMI compared to healthy matched runners. Specifically we hypothesized that recreational runners with previous history of an RRMI, when compared with healthy controls, will exhibit:

H1: Decreased hip external rotator endurance
H2: Decreased hip abductor endurance
H3: Decreased trunk lateral flexor endurance
H4: Decreased trunk flexor muscular endurance
H5: Decreased trunk extensor muscular endurance
Chapter Two

Literature Review

Epidemiology

Overall RRMI rates range between 19-79%. Across multiple populations of runners, the 4 most common overuse injuries include patellofemoral pain (PFP), iliotibial band friction syndrome (ITBFS), stress fractures of the lower leg, and medial tibial stress syndrome (MTSS). Looking at rates of specific injuries, PFP accounts for up to 43% of sports medicine and physician’s office visits. Other injury rates include ITBFS between 1.6-52% of RRMI, stress fractures between 6-56%, and lastly, MTSS at 4-35% of RRMI. These 4 specific overuse injuries are all located at the knee or below, accounting for 50-75% of all RRMI.

Defining Running-Related Musculoskeletal Injuries

There are many variations of the definition of RRMI within the literature. Some definitions are very broad, such as “any physical complaint developed in relation to running activities and causing restriction in running distance, speed, duration, or frequency.” This definition is very generic and could potentially include unwarranted ailments such as simple aches and pains associated with running, versus a true running-related musculoskeletal injury or structural damage. Buist et al. uses a stricter definition, “any musculoskeletal pain of the lower limb or back causing a restriction in running (mileage, pace, or duration) for at least 1 day.” Taunton et al. defines it as “pain during or immediately after a run, feeling that the injury was running related, experiencing pain at beginning of running regimen, stopped running, decreased mileage, or sought medical
attention.”

These definitions are all individually valid; however, to be more thorough with the definition, components of these definitions should be combined.

**Specific Running-Related Musculoskeletal Injuries**

*Patellofemoral pain*

Fulkerson\(^{12}\) cites the patellar retinaculum, subchondral bone, the synovium, as well as the skin, muscles, and nerve around the knee as the anatomy involved in the development of patellofemoral pain.\(^{61}\)

PFP is defined as an insidious onset of pain of the retropatellar region, that is aggravated with weight bearing exercises.\(^{19,24,25,43,62}\) Pain is commonly exacerbated with ascending and descending stairs, squatting, running, walking, and sitting for a prolonged period of time. Multiple etiologies at multiple joints have been speculated as contributing factors to PFP. Previous authors have suggested excessive rearfoot eversion as a possible contributing factor.\(^{18,20,63}\) It is theorized that excessive eversion creates an exaggerated internal rotation of the tibia which in turn causes the femur to internally rotate in order to properly reach knee extension, creating increased lateral patellofemoral joint stress. This chain of events causes lateral patellar tracking to increase and subsequently, PFP to develop.

Other researchers believe PFP to originate from dysfunction at the knee joint itself. Fulkerson et al.\(^{12}\), found that PFP is a result of overload on the patellar retinaculum and subchondral bone from the malalignment of the extensor mechanism.\(^{12}\) A malalignment of the extensor mechanism is an altered extension motion and coupled with the patellar retinaculum and subchondral bone overload it can potentially lead to PFP.\(^{12}\) Additionally, Powers\(^{25}\) found that PFP is associated with VMO strength and motor
recruitment. This causes a timing delay within the quadriceps muscle complex during contraction leading the lateral section, namely the vastus lateralis, to have a stronger contraction in contrast to the medial section. Repeated lop-sided contractions ultimately lead the patella to track laterally and subsequently, PFP develops.

More recently researchers have investigated the hip as a primary factor in the etiology of PFP. Multiple researchers suggest that PFP may be a result of hip weakness and a lack of functional control of the femur during weight bearing. More specifically, several authors have found hip abductor and hip external rotators to be weak in subjects with PFP.

A new avenue in research of etiologies associated with PFP is the contribution of the core. The abdominal muscles in conjunction with the lumbar extensors increase the stability of the spine. Increased stability at the spine is essential in providing the lower extremities with a stiff base of support for muscle contractions. A stable base of support may prevent the body’s center of mass from deviating while also providing dissipation of the forces generated at the lower extremities. Ireland et al. found that the abdominal muscles limit excessive anterior pelvic tilt, which increases femoral internal rotation, ultimately creating improper lateral patellar tracking and pain.

Iliotibial band friction syndrome

ITBFS involves a thick band of fascia, originating at the lateral iliac crest and inserts on Gerdy’s tubercle on the lateral tibia.

ITBFS is defined as pain over the distal, lateral aspect of the knee, or over the greater trochanter of the femur, that is aggravated with activity, including running down hills. Recently, researchers have found a relationship between ITBFS and the
surrounding hip musculature. When the tensor fascia latae (TFL) and gluteus maximus contract during knee flexion, the iliotibial band will actually push inward toward the femur.\textsuperscript{68,69} In slight knee flexion, the TFL pulls with more force compared to the gluteus maximus which causes the anterior portion of the iliotibial band (ITB) to become more prominent and taut. As knee flexion increases, the opposite occurs, the posterior portion of the ITB then becomes more prominent. This shift between the anterior and posterior protrusions of the ITB is what was mistaken as a “snapping” back and forth of the ITB in previous etiologies. Noble\textsuperscript{27} was one of the first to describe the etiology of ITBFS as training errors including excessive distances, poor running technique, and running on hard surfaces, which result in friction of the iliobibial band against the lateral epicondyle of the femur. Similarly, Racioppi and Gulick\textsuperscript{29} cite repetitive snapping of the iliobibial band over the lateral femoral epicondyle as the cause of ITBFS.

Other researchers have reported that muscle weakness, specifically hip abductor weakness, can lead to the development of ITBFS.\textsuperscript{26,31,70} Weakness of the hip abductors causes the antagonist hip adductors to create excessive force, leading to increased tension at the iliobibial band, ultimately leading to development of ITBFS.\textsuperscript{26,31,70}

**Stress fractures**

Symptoms of stress fractures typically accumulate gradually beginning with mild discomfort over the site of the fracture during palpation and progressing to include pain during running. Palpable swelling and calluses over the site may be present after some time as well.\textsuperscript{71-73} Stress fractures account for 6 to 15.6\% of all RRMIs, with the tibia being the most common site accounting for 35 to 56\% of all stress fractures.\textsuperscript{71-75} The etiology has been linked to diet and sex in the past, but more recently, has been linked to
running mechanics. Pohl et al. found that excessive eversion along with increased hip adduction and femoral eversion have a significant effect on the development of tibial stress fractures. Other factors associated with stress fractures include training errors such as an increase in frequency, duration, or intensity of runs as well as running on hard surfaces. Bennell et al. suggests that because muscles of the lower extremities function as shock absorbers during running, when they lack strength or endurance they cannot properly dissipate the forces across the bony structures which can potentially lead to the development of stress fractures.

**Medial tibial stress syndrome**

Medial tibial stress syndrome is exercise-related pain on the posteromedial side of the middle to distal tibia. The official AMA definition is pain or discomfort in the leg from repetitive running on hard surfaces or forcible excessive use of the foot flexors. Like many of the other overuse RRMI, the onset of pain related to MTSS is insidious with no traumatic event preceding the pain. Originally, MTSS was thought to be caused by traction-related periostitis, or a swelling of the membrane surrounding the bone, but more recent research found that the when the rate of bone resorption is faster than bone replacement, MTSS starts to develop. Other researchers have cited stress microfractures caused by tibial bending from repetitive contact with hard surfaces as the cause of MTSS. Histological and anatomical studies have reported that the soleus and flexor digitorum were the main contributors to traction-induced MTSS, especially while the heel is in a pronated state. The aponeurosis connects the medial aspect of the soleus to the medial border of the tibia and carries with it the potential for creating traction stress on the attachment. Activities involving excessive repetitive
contractions and stretching to the soleus and flexor digitorum complex can ultimately cause the muscle complex to avulse from its attachment causing bony damage. When this bony damage is created at a higher rate than the replacement, MTSS develops. More recently, poor lower extremity mechanics, such as pronation, have been linked to poor core stability via the kinetic chain.\textsuperscript{31,36,66,80}

Although each of these injuries have seemingly separate etiologies, all share a common factor in that they originate from biomechanically altered kinematics of the lower extremities. Each of these alterations can be tied to recent research into the role of core muscles and core stability in the proper function of lower limb mechanics. Without the ability of the core to stabilize properly, the lower extremities are unable to perform biomechanically sound movements.\textsuperscript{81-83} Repeated inapt movements created at the lower extremities, ultimately create damage to each of the structures involved in the movement, leading to the development of running related injuries.\textsuperscript{24,31,84,85}

**Visual Analog Pain Scale**

The visual analog pain scale is a subjective tool commonly used in health care to assess the level of pain a patient is experiencing.\textsuperscript{86-89} The reliability has been established in several studies (ICC = 0.60-0.96).\textsuperscript{87-92} It consists of a 10-centimeter horizontal line with two ends labeled with words expressive of opposite ends of the pain spectrum (ie: no pain on one end and unbearable pain on the other). The patient is asked to mark a vertical line at a portion of the horizontal line they feel is most accurately representative of their pain. The terminology of the labels may differ slightly between users, however the concept is the same.\textsuperscript{87-89} Participants in this study will be asked to fill out a VAS assessing their pain during running over the past week.
Endurance tests

Measuring strength of a muscle group can give clinicians insight on the origin of a pathology. However, strength is not the only aspect that should be examined. The endurance of a muscle group may be just as important a component in assessing the kinematics of movement. This is especially true when examining the core muscle group. The structures that stabilize the core are a complex of osseous and soft tissue systems in the lumbopelvic region. Although there is not currently a universal definition, most researchers use the term “core stability” to refer to the ability of the core muscles to keep the spine stiff and maintain a steady level of intra-abdominal pressure during muscular contractions. The core is responsible for providing stability for the extremities as well as providing strength and balance to optimize musculoskeletal function. If the extremities are unable to work off of a solid surface, miniscule biomechanical changes occur throughout the kinetic chain in order for the extremities to compensate for the lack of stability at the core. Because running requires numerous and continuous muscular contributions at the lower extremity, repetitive improper running mechanics can potentially cause RRMIs to develop. Therefore, core endurance measures are an important aspect of injury that needs evaluating.

To test trunk flexor endurance the most reliable method involves the use of a wedge that has been premade to measure 60 degrees (ICC = 0.97). The participant will sit with the hips and knees flexed to 90 degrees while the back lies on the wedge in order for the participant to “feel” what 60 degrees of trunk flexion feels like without having to hold the position and fatigue the muscles. The wedge is moved back 10 cm to start the
test as the clinician stabilizes the feet. The test will be measured in time until the trunk angle falls below 60 degrees.\textsuperscript{97,98}

Trunk extension endurance is most reliably measured by using the modified Beiring-Sorensen test (ICC = 0.97, 0.98).\textsuperscript{97-101} This test is also measured using time, specifically until the trunk falls below the level of the table, with stabilization over the lower extremities.

The side-bridge hold is a very reliable method of testing lateral trunk flexor endurance (ICC=0.99).\textsuperscript{97} The participant is asked to perform a side-bridge and hold for as long as possible. There is no stabilization requirement for this test.\textsuperscript{97}

There are variations in the literature on how much time should be given between each test to prevent fatigue from overlapping between tests. Lanning\textsuperscript{100} has suggested waiting 1 minute between tests citing that it was enough time to provide adequate rest;\textsuperscript{100} while Reiman\textsuperscript{98} and McGill\textsuperscript{97} used 5 minutes between endurance tests in order to ensure the participant had enough time to rest and to prevent fatigue.\textsuperscript{97,98} Much larger rest periods were used by Jacobs et al.\textsuperscript{102} with 15-minute break between tests, while Ito et al.\textsuperscript{99} utilized the longest break period with 72 hours between endurance tests to prevent fatigue.\textsuperscript{99,102} With this information, it seems a rest period of 5 minutes is the most logical as it will not over estimate or under estimate rest time providing optimal recovery.

**Conclusion**

Throughout the literature, the most common etiological factors in the development of RRMIIs are weak hip muscular strength and altered lower extremity running kinematics. Newer avenues of research have begun to examine the kinetic chain, more specifically the core, and its contributions to these injuries. However, there is
currently very limited research on the effect that core strength has on RRMI and no research on the effect of hip and core muscular endurance on the development of RRMI.
Chapter Three

Methodology

Study Design

Retrospective, Case control

Participants

This study included 25 volunteers (12 male, 13 female) recruited from the University of Toledo community, the local Toledo community, local sports medicine and physical therapy clinics, and local physicians’ offices. All demographic data are reported in Table 1.

All participants were between the ages of 18 and 45 and ran a minimum of 10 miles per week. Participants included in the RRMI group reported a previous history of an RRMI including MTSS, PFP, ITBS and tibial stress fractures. Definition of an RRMI consisted of the following: 1) one of the four specific RRMIs diagnosed by a physician, physical therapist, or athletic trainer, and 2) rest or removal from running activity (training or races) for at least 3 consecutive days at the time of injury. Exclusion criteria for the RRMI group were as follows: 1) had a current RRMI in which the individual was not approved to run by his/her physician 2) had a previous history of lower extremity injury other than the specific RRMI within the last year, 3) had a surgical procedure that would have caused major structural changes to the lower extremities, and 4) were receiving rehabilitation during the study period. Participants included in the healthy control group did not have a history of an RRMI within the past 12 months.
Instrumentation

- Stop watch
- Visual analog pain scale
- Biodex dynamometer (Biodex Medical Systems, Inc., Shirley, NY and System 2, Version 4.6.0)

Independent Variables

- Group
  - RRMI
  - Healthy
- Side
  - Injured
  - Non-injured
- Sex
  - Female
  - Male

Dependent Variables

Endurance Measurements:

- Hip External Rotation (HER)
- Hip Abduction (HABD)
- Lateral Trunk Flexion (LTF)
- Trunk Flexion (TFX)
- Trunk Extension (TEX)
Procedures

Volunteers who participated in this study were asked to report to the Musculoskeletal Health and Movement Science Laboratory located in the Health and Human Services building on the main campus of the University of Toledo. The volunteers first reviewed and signed the informed consent form and were given the opportunity to ask questions to the researchers. Participants completed two separate sessions spaced 2-5 days apart, with the first session lasting approximately 1 hour, and the second a half an hour. Upon reporting to the laboratory, the participant completed an injury history form to determine group placement and injury diagnosis when applicable. For both sessions participants were asked to wear shorts and a short-sleeved shirt for ease of movement and measuring. Next, the participant’s height, weight, and age were recorded.

At each session, prior to starting the endurance testing, participants completed a 5-minute warm up on the treadmill. At the first session, the participants performed endurance tests for the bilateral hip external rotators and lateral trunk flexors. At the second session, the participants performed endurance tests for the bilateral hip abductors and trunk flexors and extensors. Verbal encouragement to continue performance was provided during the endurance tests. Within-day randomization was performed, as well as side randomization for participants.

Participant positioning for the HABD test was in the side-lying position on a treatment table, with the head resting on a pillow and the test leg on top of the other side. The axis of the Biodex was positioned at the hip joint center, and the Biodex attachment arm was secured proximal to the lateral femoral condyle on the test leg. The pelvis was
secured to the table with a stabilizing strap to minimize compensatory movements.
(Figure 1)

The HER endurance test was performed in the prone position on a treatment table, with the head resting on a pillow. The testing side was in a neutral hip position, with the knee at 90 degrees of flexion. The axis of the Biodex was aligned through the femur, and the Biodex attachment arm was placed approximately 5 cm proximal to the lateral malleolus of the testing side. (Figure 2)

For HABD and HER endurance testing, the participant performed 3 maximal voluntary isometric contractions (MVIC) of the respective muscle groups. Then an average of the 3 trials was calculated, and the participant’s 50% MVIC was extracted. During the HABD and HER tests the participant was instructed to maintain 50% of his or her MVIC for as long as possible. A stationary line indicating the participant’s 50% MVIC appeared on a monitor positioned in front of the participant. As the participant provided a force against the Biodex, a line tracking the participant’s contraction appeared on screen to provide real-time visual feedback. The test ended when the volunteer could no longer hold a contraction at or above 50% MVIC consecutively for 3 seconds, or if the participant compensated by activating additional muscle groups and altering his or her position. This was monitored visually by the evaluator.

The TFX endurance test started with the participant sitting with the back resting against a 60° wedge, both hips and knees at 90° of flexion, and arms folded across the chest. One tester stabilized the feet, while the other held onto the wedge and monitored positioning. The participant was then told to activate his or her core and maintain the 60° trunk flexion position as the wedge was pulled back 10 cm. Time (in seconds) started
when the wedge no longer supported the participant, and ended when the volunteer could no longer maintain 60° of trunk flexion. (Figure 3)

For the TEX endurance test (aka the modified Biering-Sorensen test) the participant was positioned in the prone position on a stable surface about 1.5 ft above the ground. The participant’s anterior superior iliac spine was aligned with the edge of the platform and the upper body suspended in a cantilevered fashion. A pillow was placed under the participant’s ankles and a tester provided support on the participant’s calves. When the participant was ready, he then crossed his arms over his chest, raised his upper body up until it was parallel with the floor, and held this position for as long as possible. Time started when the upper body was no longer supported, and ended when the upper body fell below parallel. Verbal encouragement was given to maintain the position as well as to raise up or down for proper positioning. (Figure 4)

The LTF test (aka the side plank) started with the participant in the side-lying position with the legs extended, the top foot resting on top of the bottom foot, and the upper body supported on the elbow and forearm. The side to be tested was the side providing support from the elbow and bottom foot. The participant then lifted his trunk off of the mat to support his entire weight on just the feet, elbow, and forearm of the bottom arm, while the uninvolved arm lay straight on his side. The test started when the participant’s trunk was lifted off of the ground, and ended when the participant could no longer maintain proper positioning. Verbal encouragement was provided as well as feedback to lift up or lower the hip, and to lean forward or backward at the torso to maintain the correct testing position (Figure 5). All participants were given 5 minutes of rest between tests.
Data Analysis

Group means and standard deviations from each assessment were used for analysis. To remove any outliers from the data, we ran descriptive statistics and created stem and leaf plots. Those values that were 2 or greater standard deviations away were then removed and the subsequent data were used for the remainder of the analyses. We ran paired samples t-tests between sides of the healthy control group for the following variables, HER, HABD, and LTF endurance measures. To examine the dependent variables of HER, HABD, and LTF, a mixed model repeated measures analysis of variance (ANOVA) was used (group by sex by side). For the remainder of the dependent variables, TFX and TEX, we ran a 2x2 ANOVA (group by sex). For statistically significant interactions, a post hoc univariate analysis with pairwise comparison was conducted to ascertain the location of significant differences. All statistical analyses were performed with SPSS 19.0 software (IBM Corporation, Armonk, NY). Statistical significance was set a priori at $P \leq 0.05$. 
Chapter 4

Results

No statistically significant differences in age, height, or mass were found between groups (Table 1). There were no statistically significant differences between sides within the healthy control group for HER, HABD, and LTF endurance. Therefore, we were confident in matching sides of the healthy controls to the RRMI group for statistical comparison without concern of an influence of side dominance.

**Hip endurance measures**

The means and standard deviations for HER can be found in Table 2, while the main effect and interaction information can be found in Table 7. There were no statistically significant main effects or interactions for HER. However, the main effect for sex approached statistical significance ($F_{1,20}=3.30$, $p=0.08$), with females having a greater HER endurance time (92.44 ± 27.18s), compared to males (72.41 ± 26.8s). The associated effect size for this relationship was moderate ($d=0.72$; 95%CI: -0.09, 1.53). All other relationships for HER endurance were not statistically significant with effect sizes that were weak.

The means and standard deviations for HABD can be found in Table 3, while the main effect and interaction information can be found in Table 7. There was a nearly significant group by sex interaction ($F_{1,17}=3.44$, $p=0.08$). A strong effect size indicated that for the RRMI group males had greater HABD (45.75 ± 7.06s) compared to the females (38.43 ± 7.06s) ($d=-1.04$; 95% CI: -2.3, 0.46). In contrast, for the healthy group, a moderate effect size indicated that the females had greater HABD (45.34 ± 7.05s) than the males (40.83 ± 7.06s) ($d=0.64$; 95% CI: -0.63, 1.8). All other relationships for HABD
were not statistically significant with effect sizes that were weak with confidence
intervals that crossed zero.

**Trunk endurance measures**

The means and standard deviations for LTF can be found in Table 4, while the
main effect and interaction information can be found in Table 7. A significant side by
group interaction was observed ($F_{1,20} = 3.52, p = 0.01$). Post-hoc testing revealed that the
LTF endurance of the non-injured side of the RRMI group (60.01 ± 22.97s) was
significantly lower than the matched non-injured side of the healthy control group (85.3 ±
22.96s) ($p = 0.03; d = -1.06, 95\% CI: -1.95, -0.16$) and the injured side of the RRMI group
(76.23 ± 31.81s) ($p = 0.02; d = -0.56, 95\% CI: -1.38, 0.25$). Additionally, the sex main effect
for LTF was nearly statistically significant ($F_{1,18} = 3.52, p = 0.08$), with a strong effect size
($d = 0.77$) with 95\% confidence intervals crossing zero (95\% CI: -0.1, 1.64), indicating that
the males displayed greater LTF endurance (84.27 ± 25.41s) compared to the females
(63.94 ± 25.41s). All remaining relationships were not statistically significant with weak
associated effect sizes.

The means and standard deviations for TFX can be found in Table 5, while the
main effect and interaction information can be found in Table 8. There were no
significant main effects or interactions for TFX, with weak associated effect sizes and
95\% CI that crossed zero.

The means and standard deviations for TEX can be found in Table 6, while the
main effect and interaction information can be found in Table 8. A significant main effect
for sex was observed ($F_{1,22} = 4.18, p = 0.05$). The effect size was strong ($d = 0.81$) with 95\%
confidence intervals crossing zero (95\% CI: -0.03, 1.64), indicating that females displayed
greater TEX endurance (169.8 ± 42.2s) compared to males (134.61 ± 42.2s). All other relationships for TEX endurance were not statistically significant with effect sizes that were weak.

Table 1. Demographic information for the running-related musculoskeletal injury (RRMI) and healthy groups (Mean ± SD)

<table>
<thead>
<tr>
<th>Group</th>
<th>Mean ± SD</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Age (years)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RRMI (n=13)</td>
<td>31.78 ± 8.72</td>
<td>0.85</td>
</tr>
<tr>
<td>Healthy (n=12)</td>
<td>30 ± 8.28</td>
<td></td>
</tr>
<tr>
<td><strong>Height (cm)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RRMI (n=13)</td>
<td>174.28 ± 10.02</td>
<td>0.75</td>
</tr>
<tr>
<td>Healthy (n=12)</td>
<td>170.82 ± 8.67</td>
<td></td>
</tr>
<tr>
<td><strong>Mass (kg)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RRMI (n=13)</td>
<td>69.82 ± 11.52</td>
<td>0.38</td>
</tr>
<tr>
<td>Healthy (n=12)</td>
<td>68.34 ± 12.8</td>
<td></td>
</tr>
<tr>
<td>Sex</td>
<td>Group</td>
<td>Time (s)</td>
</tr>
<tr>
<td>-------</td>
<td>-------------------</td>
<td>---------------</td>
</tr>
<tr>
<td></td>
<td>RRMI (n=7)</td>
<td>88.96 ± 43.99</td>
</tr>
<tr>
<td>Female</td>
<td>Healthy (n=5)</td>
<td>112.24 ± 43.25</td>
</tr>
<tr>
<td></td>
<td>Total (n=12)</td>
<td>98.66 ± 43.35</td>
</tr>
<tr>
<td>Injured</td>
<td>RRMI (n=6)</td>
<td>69.97 ± 29.39</td>
</tr>
<tr>
<td>Male</td>
<td>Healthy (n=6)</td>
<td>86.59 ± 18.67</td>
</tr>
<tr>
<td></td>
<td>Total (n=12)</td>
<td>78.28 ± 25.03</td>
</tr>
<tr>
<td>Total</td>
<td>RRMI (n=13)</td>
<td>80.2 ± 37.74</td>
</tr>
<tr>
<td></td>
<td>Healthy (n=11)</td>
<td>98.25 ± 33.2</td>
</tr>
<tr>
<td></td>
<td>Total (n=24)</td>
<td>88.47 ± 36.15</td>
</tr>
<tr>
<td></td>
<td>RRMI (n=7)</td>
<td>75.07 ± 41.59</td>
</tr>
<tr>
<td>Female</td>
<td>Healthy (n=5)</td>
<td>93.49 ± 42.22</td>
</tr>
<tr>
<td></td>
<td>Total (n=12)</td>
<td>82.75 ± 41.01</td>
</tr>
<tr>
<td>Non-Injured</td>
<td>RRMI (n=6)</td>
<td>58.07 ± 30.49</td>
</tr>
<tr>
<td>Male</td>
<td>Healthy (n=6)</td>
<td>75.03 ± 12.92</td>
</tr>
<tr>
<td></td>
<td>Total (n=12)</td>
<td>66.55 ± 24.02</td>
</tr>
<tr>
<td>Total</td>
<td>RRMI (n=13)</td>
<td>67.22 ± 36.47</td>
</tr>
<tr>
<td></td>
<td>Healthy (n=11)</td>
<td>83.42 ± 29.82</td>
</tr>
<tr>
<td></td>
<td>Total (n=24)</td>
<td>74.65 ± 33.89</td>
</tr>
</tbody>
</table>

Female total=92.82 ± 42.51, n=25; Male total=72.41 ± 24.73, n=24
RRMI group total=73.71 ± 36.96, n=26; Healthy group=93.12 ± 32.87, n=23
Table 3. Hip abduction endurance times for the running-related musculoskeletal injury (RRMI) and healthy groups (Mean±SD)

<table>
<thead>
<tr>
<th>Sex</th>
<th>Group</th>
<th>Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Female</td>
<td>RRMI (n=4)</td>
<td>37.22 ± 8.46</td>
</tr>
<tr>
<td></td>
<td>Healthy (n=6)</td>
<td>48.54 ± 10.31</td>
</tr>
<tr>
<td></td>
<td>Total (n=10)</td>
<td>44.01 ± 10.82</td>
</tr>
<tr>
<td>Male</td>
<td>RRMI (n=5)</td>
<td>47.03 ± 8.05</td>
</tr>
<tr>
<td></td>
<td>Healthy (n=5)</td>
<td>41.8 ± 8.46</td>
</tr>
<tr>
<td></td>
<td>Total (n=10)</td>
<td>44.42 ± 8.26</td>
</tr>
<tr>
<td>Total</td>
<td>RRMI (n=9)</td>
<td>42.67 ± 9.27</td>
</tr>
<tr>
<td></td>
<td>Healthy (n=11)</td>
<td>45.48 ± 9.7</td>
</tr>
<tr>
<td></td>
<td>Total (n=20)</td>
<td>44.21 ± 9.37</td>
</tr>
</tbody>
</table>

Female total=43.04 ± 9.99, n=22; Male total=44.37 ± 24.73, n=21
RRMI group total=44.11 ± 8.75, n=21; Healthy group=43.29 ± 10.17, n=22
Table 4. Lateral trunk flexion endurance times for the running-related musculoskeletal injury (RRMI) and healthy groups (Mean±SD)

<table>
<thead>
<tr>
<th>Sex</th>
<th>Group</th>
<th>Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RRMI (n=6)</td>
<td>58.71 ± 20.16</td>
</tr>
<tr>
<td>Female</td>
<td>Healthy (n=5)</td>
<td>72.06 ± 38.31</td>
</tr>
<tr>
<td></td>
<td>Total (n=11)</td>
<td>64.78 ± 28.97</td>
</tr>
<tr>
<td>Injured</td>
<td>RRMI (n=6)</td>
<td>93.75 ± 29.12</td>
</tr>
<tr>
<td>Male</td>
<td>Healthy (n=5)</td>
<td>77.7 ± 38.95</td>
</tr>
<tr>
<td></td>
<td>Total (n=11)</td>
<td>86.45 ± 33.18</td>
</tr>
<tr>
<td></td>
<td>RRMI (n=12)</td>
<td>76.23 ± 30.08</td>
</tr>
<tr>
<td>Total</td>
<td>Healthy (n=10)</td>
<td>74.88 ± 36.54</td>
</tr>
<tr>
<td></td>
<td>Total (n=22)</td>
<td>75.62 ± 32.36</td>
</tr>
<tr>
<td></td>
<td>RRMI (n=6)</td>
<td>45.32 ± 15.74</td>
</tr>
<tr>
<td>Female</td>
<td>Healthy (n=5)</td>
<td>79.68 ± 11.02</td>
</tr>
<tr>
<td></td>
<td>Total (n=11)</td>
<td>60.94 ± 22.24</td>
</tr>
<tr>
<td>Non-Injured</td>
<td>RRMI (n=6)</td>
<td>74.7 ± 23.98</td>
</tr>
<tr>
<td>Male</td>
<td>Healthy (n=5)</td>
<td>90.92 ± 34.97</td>
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<tr>
<td></td>
<td>Total (n=11)</td>
<td>82.07 ± 29.13</td>
</tr>
<tr>
<td></td>
<td>RRMI (n=12)</td>
<td>60.01 ± 24.69</td>
</tr>
<tr>
<td>Total</td>
<td>Healthy (n=10)</td>
<td>85.3 ± 25.15</td>
</tr>
<tr>
<td></td>
<td>Total (n=22)</td>
<td>71.51 ± 27.5</td>
</tr>
</tbody>
</table>

Female total=63.44 ± 24.85, n=23; Male total=87.37 ± 33.36, n=23
RRMI group total=68.45 ± 27.62, n=25; Healthy group=83.69 ± 34.42, n=21
Table 5. Trunk flexion endurance times for the running-related musculoskeletal injury (RRMI) and healthy groups (Mean±SD)

<table>
<thead>
<tr>
<th>Sex</th>
<th>Group</th>
<th>Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Female</td>
<td>RRMI (n=6)</td>
<td>219.77 ± 104.61</td>
</tr>
<tr>
<td></td>
<td>Healthy (n=5)</td>
<td>267.72 ± 84.25</td>
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<tr>
<td></td>
<td>Total (n=11)</td>
<td>241.57 ± 94.54</td>
</tr>
<tr>
<td>Male</td>
<td>RRMI (n=6)</td>
<td>238.93 ± 34.19</td>
</tr>
<tr>
<td></td>
<td>Healthy (n=4)</td>
<td>174.87 ± 38.27</td>
</tr>
<tr>
<td></td>
<td>Total (n=10)</td>
<td>213.31 ± 47.24</td>
</tr>
<tr>
<td>Total</td>
<td>RRMI (n=12)</td>
<td>229.35 ± 74.87</td>
</tr>
<tr>
<td></td>
<td>Healthy (n=9)</td>
<td>226.46 ± 80.58</td>
</tr>
<tr>
<td></td>
<td>Total (n=21)</td>
<td>228.11 ± 75.38</td>
</tr>
</tbody>
</table>

Table 6. Trunk extension endurance times for the running-related musculoskeletal injury (RRMI) and healthy groups (Mean±SD)

<table>
<thead>
<tr>
<th>Sex</th>
<th>Group</th>
<th>Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Female</td>
<td>RRMI (n=6)</td>
<td>157.53 ± 38.43</td>
</tr>
<tr>
<td></td>
<td>Healthy (n=6)</td>
<td>182.14 ± 48.12</td>
</tr>
<tr>
<td></td>
<td>Total (n=12)</td>
<td>169.83 ± 43.46</td>
</tr>
<tr>
<td>Male</td>
<td>RRMI (n=6)</td>
<td>124.59 ± 30.25</td>
</tr>
<tr>
<td></td>
<td>Healthy (n=6)</td>
<td>144.63 ± 49.13</td>
</tr>
<tr>
<td></td>
<td>Total (n=12)</td>
<td>134.61 ± 40.28</td>
</tr>
<tr>
<td>Total</td>
<td>RRMI (n=12)</td>
<td>141.06 ± 37.19</td>
</tr>
<tr>
<td></td>
<td>Healthy (n=12)</td>
<td>163.38 ± 50.33</td>
</tr>
<tr>
<td></td>
<td>Total (n=24)</td>
<td>152.22 ± 44.76</td>
</tr>
</tbody>
</table>
Table 7. Hip external rotation (HER), hip abduction (HABD), and lateral trunk flexion (LTF) endurance main effects and interactions information

<table>
<thead>
<tr>
<th>Variable</th>
<th>Side main effect</th>
<th>Group main effect</th>
<th>Sex main effect</th>
<th>Side x sex interaction</th>
<th>Side x group interaction</th>
<th>Group x sex interaction</th>
<th>Side x sex x group interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>HER</td>
<td>$F_{1,20}$ 2.4</td>
<td>2.92</td>
<td>3.30</td>
<td>0.06</td>
<td>0.02</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>$p$ 0.14</td>
<td>0.10</td>
<td>0.08</td>
<td>0.80</td>
<td>0.90</td>
<td>0.86</td>
<td>0.89</td>
</tr>
<tr>
<td></td>
<td>Power 0.31</td>
<td>0.37</td>
<td>0.41</td>
<td>0.06</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>HABD</td>
<td>$F_{1,16}$ 0.90</td>
<td>1.05</td>
<td>1.24</td>
<td>0</td>
<td>0.67</td>
<td>4.27</td>
<td>0.89</td>
</tr>
<tr>
<td></td>
<td>$p$ 0.36</td>
<td>0.32</td>
<td>0.28</td>
<td>0.99</td>
<td>0.43</td>
<td>0.05*</td>
<td>0.36</td>
</tr>
<tr>
<td></td>
<td>Power 0.13</td>
<td>0.06</td>
<td>0.07</td>
<td>0.05</td>
<td>0.12</td>
<td>0.41</td>
<td>0.14</td>
</tr>
<tr>
<td>LTF</td>
<td>$F_{1,18}$ 0.35</td>
<td>1.22</td>
<td>3.52</td>
<td>0</td>
<td>7.47</td>
<td>1.20</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>$p$ 0.56</td>
<td>0.28</td>
<td>0.08</td>
<td>0.99</td>
<td>0.01*</td>
<td>0.29</td>
<td>0.57</td>
</tr>
<tr>
<td></td>
<td>Power 0.09</td>
<td>0.18</td>
<td>0.43</td>
<td>0.05</td>
<td>0.73</td>
<td>0.18</td>
<td>0.09</td>
</tr>
</tbody>
</table>

A-priori level ≤ 0.05.
Asterisk (*) denotes statistical significance.

Table 8. Trunk flexion (TFX) and trunk extension (TEX) endurance main effects and interactions information

<table>
<thead>
<tr>
<th>Variables</th>
<th>Group main effect</th>
<th>Sex main effect</th>
<th>Group x sex interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>TFX</td>
<td>$F$ 0.6</td>
<td>1.26</td>
<td>2.92</td>
</tr>
<tr>
<td></td>
<td>$p$ 0.81</td>
<td>0.28</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td>Power 0.06</td>
<td>0.19</td>
<td>0.36</td>
</tr>
<tr>
<td>TEX</td>
<td>$F$ 1.68</td>
<td>4.18</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>$p$ 0.21</td>
<td>0.05*</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>Power 0.24</td>
<td>0.5</td>
<td>0.05</td>
</tr>
</tbody>
</table>

A-priori level ≤ 0.05.
Asterisk (*) denotes statistical significance.
Chapter 5

Discussion

The primary purpose of this study was to examine differences in core muscular endurance between runners with a previous history of a RRMI and healthy controls. While previous investigators have targeted muscular strength among injured and healthy runners, to our knowledge this is the first study to analyze core muscular endurance in this population. There were important findings from this study indicating isolated core muscle endurance differences in runners with and without a history of RRMI, as well influences of sex on some of the measures of core and hip muscle endurance.

RRMI versus healthy association

For LTF, a greater endurance time was observed in the RRMI group on the injured side compared to the non-injured side. This difference could be in part explained by the kinematic alterations in running gait demonstrated by runners with PFP compared to healthy runners. It is assumed that a healthy runner, during the stance phase of running, demonstrates a stable, level pelvis from which the lower extremity moves. On the other hand, runners with PFP may demonstrate pelvic drop of the contralateral, non-injured limb during the stance phase of running, which creates a shift in the center of mass (COM) away from the injured/stance limb and the midline of the body. To counteract the shift in COM and maintain balance, one must perform an ipsilateral trunk lean. As running is a repetitive, long distance sport, this compensation mechanism of activating the lateral trunk muscles to maintain pelvic obliquity occurs often. Therefore, after weeks or months of running with an irregular gait pattern the endurance of the lateral trunk flexor muscles, particularly in the injured side of a runner, could increase.
Further research is warranted into the direct relation between lateral trunk flexion endurance and pelvic obliquity during running. In regards to this kinematic compensation, with increased LTF endurance we would expect to also see decreased HABD endurance because of the hip strength deficit that is the start of this faulty running gait. However, no difference in HABD endurance was observed between groups. This could be due to the contribution of other factors such as rehabilitation efforts, especially those focused on increasing HABD and HER strength within the RRMI population. 6 of the 13 runners in the RRMI group underwent rehabilitation to correct his or her RRMI. If these 6 runners underwent a rehabilitation program incorporating hip strengthening exercises, as suggested in the literature, then we could expect to see an increase in HABD endurance as well as strength.

We hypothesized that we would find decreased hip endurance in the RRMI group, similar to findings by researchers who reported hip strength deficits within a variety of injury subgroups from the RRMI population. In particular, these researchers observed hip abductor and hip external rotator weakness in runners with PFP and ITBFS compared to healthy runners. As this was the first study to examine hip endurance differences in runners there were no established protocols to follow for endurance testing procedures. Therefore, testing procedures were selected from studies examining the effects of fatigue within the lower extremity. Jacobs et al. isolated and fatigued the hip abductor muscle group using 50% of maximum isometric HABD strength. This procedure was found to have very high intrasession reliability for testing HABD endurance (ICC=0.99). Unfortunately, as there was no established testing procedure for HER endurance we used the HABD procedure, with altered testing position to isolate the
hip external rotators. Hence, further investigation into alternative testing procedures for hip muscular endurance, for example utilizing a repetitive-movement endurance test instead of an isometric endurance test, is warranted.

For both TFX and TEX there were no differences in endurance performance between RRMI and healthy control groups. The TFX and TEX endurance tests utilized, although reliable, did not identify differences between our injury groups.\textsuperscript{81,97} Since running is a repetitive physical activity, perhaps the use of repetitive concentric tasks in lieu of isometric fatigue tests would better identify differences in endurance between groups. Investigation into the use of tests such as a repetitive curl-up or back extension to fatigue to identify differences between injured and non-injured runners should be considered in future studies.

\textit{Male versus female association}

In general, males are stronger than females due largely in part to muscle mass differences.\textsuperscript{19,100,104-106} Because of this, sex differences in muscle endurance could be theorized to have the same effect; however, we observed the opposite result for HER and TEX with female runners exhibiting greater HER (+20.03 seconds) and TEX (+35.22 seconds) endurance times compared to male runners. The primary muscle contributor to hip external rotation and extension is the gluteus maximus. A possible explanation for these findings could be the differences in upper body mass distribution, with females generally having more body mass distributed anteriorly on their upper body. Although not their primary focus of the study, Ford et al. found that females run with an anterior trunk lean when compared to males.\textsuperscript{107} Owing to the fact that females must constantly account for additional anterior upper body mass, it is likely that the trunk and hip
extensors are constantly activated in order to compensate for the anterior load and to maintain an upright body posture during standing, walking, and running. This constant activation and training of the back and hip extensors may be the reason why females displayed greater HER and TEX endurance compared to males. Additional investigation is needed of the kinematic and muscle activation patterns of the hip and trunk during running gait to explore these theories.

**Injury group and sex interaction**

Females of the RRMI had lower HABD endurance compared to the healthy female runners. It has been previously demonstrated within several subgroups of injured runners that injured, female runners have decreased HABD strength compared to their healthy counterparts.\textsuperscript{19,23,26,31,40,103,104} Therefore, female runners that display either decreased HABD endurance or strength may be unable to maintain a neutral pelvis during running, increasing the risk for a RRMI as we have discussed above. Further investigation into the correlation between HABD endurance and contralateral pelvic drop during running is merited.

Interestingly, the present study found the opposite relation in males, where healthy males displayed lower HABD endurance compared to RRMI males. A possible explanation for this finding could be related to the rehabilitation compensation mentioned earlier. Perhaps the RRMI males have greater HABD endurance due to the rehabilitation efforts to increase HABD strength, since the literature provides clinicians with validation as to why hip strengthening is warranted.\textsuperscript{4,19,23,31,40,103} However, we did not collect data on specific rehabilitation exercises completed by these runners and therefore, we cannot be
certain that rehabilitation played a role in our findings. Continued work is needed to determine what factors that we did not record could be influencing HABD endurance.

In addition, similar to what this study found with HABD endurance, Nakagawa et al. found no statistical differences in HABD strength between injured and non-injured runners, when including both sexes. However, when taking sex into account, Nakagawa et al. found that males exhibited greater eccentric HABD torque, validating the need to analyze HABD and sex separately. For the present study, when analyzing HABD endurance within each sex and between groups, HABD endurance was lower in the injured females and greater in the healthy females, and the opposite relation was observed between the male groups. When collapsing sexes and analyzing between groups, this could mask any true differences between the groups. Therefore, future research that examines HABD endurance should examine the male and female sexes separately.

Limitations

There were several limitations to our study design and methods. Due to a very specific testing population, we were only able to test 25 volunteers, making the power of our analyses very low for some comparisons. Also, during testing for LTF, 72% of participants reported fatigue in the shoulder of the testing side before the lateral trunk; therefore, our results may reflect fatigue in muscle groups other than our intended lateral trunk flexor group. Furthermore, during the endurance tests additional recruitment of surrounding musculature may have occurred, although specific instructions were given prior to testing. For example, the gastrocnemius and hamstring muscles were visibly active and confirmed by participants to be contracting while testing HER endurance. Because we used a subjective analysis of fatigue and did not include electromyography
(EMG) during the endurance testing we cannot state for sure the participants reached a fatigued state. Lastly, the procedures we used were isolated, open kinetic chain endurance tests, which may not be applicable for running. Therefore, future studies should consider what other endurance tests might translate into better insight into running-related musculoskeletal injury development.

**Conclusion and Clinical Relevance**

This study represents the first study to investigate the influence of injury and sex on core and hip muscle endurance differences in runners. The results highlight some of the differences that exist in these populations, but there is a clear need for additional investigation to fully realize the role that endurance of these muscle groups plays in running mechanics and injury development. The information from this study may provide clinicians with evidence that endurance, in addition to strength, need to be the focus of rehabilitation for runners with RRMIs. All of these observations may provide insight for further research on rehabilitation regimens for targeted core muscular endurance with the goal of reducing injury rates and improvement of patient outcomes in the RRMI population.
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Appendix A

Endurance Testing Positions

Figure 1. HABD testing position

Figure 2. HER testing position
Figure 3. TFX starting and testing positions

Starting position:

Testing position:
Figure 4. TEX testing position

Figure 5. LTF testing position