The Relationship Between Hip Strength and Multiplanar Running Kinematics at the Hip and Knee

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This thesis titled
The Relationship Between Hip Strength and Multiplanar Running Kinematics at the Hip
and Knee

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Abstract

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The Relationship Between Hip Strength and Multiplanar Running Kinematics at the Hip and Knee

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Context: Abnormal running kinematics and insufficient hip strength may contribute to LE injury so understanding how these variables are related can assist the development of interventions. Purpose: The purpose of this study is to evaluate the relationship between hip strength and LE running kinematics in the frontal and transverse planes in trained, competitive female runners. Methods: Nineteen healthy female collegiate cross-country XC runners had kinematic data recorded via motion analysis during a running protocol and static strength measured in the laboratory. Main outcome measures: Frontal plane kinematic variables, knee abduction (KABD) excursion, peak KABD angle, and hip adduction (HADD) excursion, were compared to hip abduction (HABD) strength. For the transverse plane, hip internal rotation (HIR) excursion was compared to hip external rotation (HER) strength. Strength was quantified as maximal voluntary isometric contraction (MVIC) and rate of force development (RFD). Results: Weak and non-significant correlations were found between MVIC and LE running kinematics and RFD and LE kinematics (\(P < 0.006\)). Conclusion: Caution should be used when correlating clinical measures of strength and observations of running gait analysis. Additional research is needed to identify the role of RFD on running kinematics.
Preface

In this thesis document, Chapter 3 serves as a prepublication manuscript. This chapter has been formatted to meet the guidelines set forth by the *Journal of Athletic Training* and the document as a whole was prepared in accordance with the guidelines of Thesis and Dissertation Services at Ohio University. The reference citation style follows the guidelines of the AMA Manual of Style (10th ed., 2007).
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# Table of Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abstract</td>
<td>3</td>
</tr>
<tr>
<td>Preface</td>
<td>4</td>
</tr>
<tr>
<td>Acknowledgments</td>
<td>5</td>
</tr>
<tr>
<td>List of Tables</td>
<td>9</td>
</tr>
<tr>
<td>List of Figures</td>
<td>10</td>
</tr>
<tr>
<td>Chapter 1: Introduction</td>
<td>11</td>
</tr>
<tr>
<td>Research Question and Hypotheses</td>
<td>12</td>
</tr>
<tr>
<td>Variables</td>
<td>13</td>
</tr>
<tr>
<td>Assumptions</td>
<td>14</td>
</tr>
<tr>
<td>Limitations</td>
<td>14</td>
</tr>
<tr>
<td>Delimitations</td>
<td>14</td>
</tr>
<tr>
<td>Chapter 2: Review of Literature</td>
<td>15</td>
</tr>
<tr>
<td>Introduction</td>
<td>15</td>
</tr>
<tr>
<td>Relationship of Hip Strength and Running Kinematics</td>
<td>16</td>
</tr>
<tr>
<td>Hip Strengthening Intervention</td>
<td>16</td>
</tr>
<tr>
<td>Comparison of Strong and Weak Hip Strength Groups</td>
<td>17</td>
</tr>
<tr>
<td>Correlations</td>
<td>18</td>
</tr>
<tr>
<td>Testing Hip Strength</td>
<td>18</td>
</tr>
<tr>
<td>Strength Measures</td>
<td>18</td>
</tr>
<tr>
<td>Hip Abduction Strength Methods</td>
<td>19</td>
</tr>
<tr>
<td>Chapter 3: The Relationship Between Hip Strength and Multiplanar Running Kinematics at the Hip and Knee</td>
<td></td>
</tr>
<tr>
<td>--------------------------------------------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>Methods</td>
<td>28</td>
</tr>
<tr>
<td>Participants</td>
<td>28</td>
</tr>
<tr>
<td>Procedures</td>
<td>28</td>
</tr>
<tr>
<td>Statistical Analysis</td>
<td>32</td>
</tr>
<tr>
<td>Results</td>
<td>34</td>
</tr>
<tr>
<td>Discussion</td>
<td>35</td>
</tr>
<tr>
<td>Limitations</td>
<td>38</td>
</tr>
<tr>
<td>Clinical Implications</td>
<td>39</td>
</tr>
<tr>
<td>Conclusion</td>
<td>40</td>
</tr>
<tr>
<td>References</td>
<td>41</td>
</tr>
</tbody>
</table>

Chapter 4: Conclusion................................................................................. 46
References ........................................................................................................................................ 47
Appendix A: Specific Aims ............................................................................................................. 55
Appendix B: Data Procedures Checklist ....................................................................................... 58
Appendix C: Strength Data Collection Form .................................................................................. 59
Appendix D: Power Analysis .......................................................................................................... 60
List of Tables

Table 1. Descriptive Statistics of all Variables .......................................................... 35
Table 2. Correlations Between Hip Strength and Kinematics .................................... 35
List of Figures

Figure 1. Reflective marker set up ................................................................................. 32
Figure 2. Hip strength testing set up .............................................................................. 32
Chapter 1: Introduction

An estimated 20-75% of long distance runners will experience an injury during their career, with about half of these being overuse in nature with a gradual onset.\textsuperscript{1–3} Over 80% of these injuries involve the lower extremity (LE) and occur most commonly at the knee.\textsuperscript{2,4} Females overall have a higher rate of injury than males, with female collegiate cross-country (XC) runners displaying a rate 1.25 times higher than their male counterparts.\textsuperscript{3,5–7} Based on these statistics, the population of female XC runners is likely predisposed to experiencing LE overuse injuries and therefore require additional consideration.

Interpreting the underlying causes of these running-related injuries requires a comprehensive knowledge of running mechanics and associated factors. Hip musculature has been shown to have an impact on kinematic factors during running. Specifically, the hip abduction (HABD) muscles play an important role in pelvic stabilization during the running gait and weakness of this musculature can “correspond to altered transverse and frontal plane kinematics.”\textsuperscript{2(p349)} The HABD muscle group resists femoral adduction while the hip external rotation (HER) muscle group resists femoral internal rotation during gait.\textsuperscript{8} An inability to limit these motions can lead to abnormal movement at the hip and influence the entire LE through the kinetic chain.

The association between these variables has been widely studied in an attempt to improve outcomes for patients and guide treatment approaches for clinicians. Due to the repetitive nature of the high mileage training and competition, it is especially important for XC runners to maintain optimal kinematics to avoid overuse injuries. Although
researchers have observed a correlation between these variables in female recreational runners or non-runners; it is unknown whether the established relationship is generalizable to a highly trained population such as varsity, intercollegiate runners. Basing preventative strategies on previous findings from other populations is not an effective strategy to provide the best evidence-based care to this population. If a relationship is not apparent between strength and running kinematics in female collegiate XC runners, it would be appropriate for clinicians to identify new intervention strategies specific to this population.

Based on the gap in the literature, female collegiate XC runners need to be studied in isolation. Specifically, the aim of this study is to examine the relationship between hip strength and running kinematics at the hip and knee. Hip strength was quantified specifically for HABD and HER. Running kinematics were quantified for the frontal plane as knee abduction (KABD) excursion, peak KABD angle, and peak hip adduction (HADD) angle, and for the transverse plane as hip internal rotation (HIR) excursion. Excursions were measured from initial contact to peak angle. Hip strength was measured as maximal voluntary isometric contraction (MVIC) and rate of force development (RFD) for a complete measure of the subject’s strength.

**RESEARCH QUESTION AND HYPOTHESES**

1. Effect of HABD strength: Does the strength of the HABD muscle group correlate with frontal plane lower extremity kinematics during running?
   a. Reduced HABD strength will be associated with increased peak KABD angle, peak HADD angle, and KABD excursion.
2. Effect of HER strength: Does the strength of the HER muscle group correlate with transverse plane lower extremity kinematics during running?
   a. Reduced HER strength will be associated with increased HIR excursion during running.

3. The impact of RFD on lower extremity motion: Will RFD have stronger correlations with LE kinematics than MVIC?
   a. RFD will display stronger relationships with LE kinematics than MVIC because it is a more functional measure.

VARIABLES

1. Maximal isometric hip strength (% BW • m)
   a. Hip abduction MVIC
   b. Hip external rotation MVIC

2. Rate of force development ((% BW • m) / s)
   a. Hip abduction RFD
   b. Hip external rotation RFD

3. Frontal plane running kinematics (degrees)
   a. Knee abduction excursion (during stance phase, measured from angle at initial contact to peak angle)
   b. Knee abduction peak angle during the stance phase
   c. Hip adduction peak angle during the stance phase

4. Transverse plane running kinematics (degrees)
a. Hip internal rotation excursion (during stance phase, measured from angle at initial contact to peak angle)

ASSUMPTIONS

1. Running during Trial 3 is indicative of running speed for the subject during a typical training session.
   a. Subjects do not alter their running form due to clinic environment.

2. All participants give full effort.
   a. Subjects respond immediately to auditory cue when testing strength to achieve an accurate RFD value.

LIMITATIONS

1. Isometric strength testing may not represent the dynamic hip strength of the subject.

2. Running testing took place in a controlled laboratory setting, unlike the typical training setting for this population.

DELIMITATIONS

1. Subjects are all student-athletes at Ohio University.

2. Both testing protocols were completed during the same session.
Chapter 2: Review of Literature

INTRODUCTION

High rates of lower extremity (LE) injuries in distance runners lead to increased demands on healthcare providers and time lost for the athletes. As a result, researchers continually attempt to identify measurable risk factors for clinicians to target prophylactically. Abnormal biomechanics, commonly measured by increased joint angles and motion, is a modifiable risk factor that can be examined retrospectively\(^\text{10}\) and prospectively\(^\text{11}\) in both clinical and laboratory settings. The irregular repetitive stresses to the joint that result from increased joint motion can lead to overuse pathologies, with the most common being patellofemoral pain (PFP).\(^\text{12}\) Although correcting gait could help reduce joint motion, it is difficult for clinicians to successfully modify the individual’s gait pattern through feedback or gait retraining programs.

Therefore, researchers have explored other factors affecting running kinematics that are easier to target. A potential contributor to LE joint motion during running is the strength of the hip musculature. Specifically, the hip abduction (HABD) and hip external rotation (HER) muscle groups eccentrically activate during the first half of the stance phase to control both hip adduction (HADD) and hip internal rotation (HIR).\(^\text{2,8}\) Lack of control of these hip motions can lead to knee abduction and segmental rotation, which has been shown to increase lateral forces and pressure on the patella. Injury can occur when these forces are repeated continually, as is case during running.\(^\text{8}\) Therefore it has been suggested that weakness or inhibition of these muscle groups may contribute to the LE joint angles and motions that are seen in overuse running injuries such as PFP and
iliotibial band friction syndrome (ITBS). Understanding the interaction of these variables and how to modify them could assist clinicians in identifying high-risk individuals prior to the injury event and provide a guide for preventative interventions.

**RELATIONSHIP OF HIP STRENGTH AND RUNNING KINEMATICS**

The association between hip strength and LE running kinematics has been widely studied because of the proposed contribution of these variables to injury. It has been examined in healthy subjects and subjects with PFP in terms of group differences or correlations. The group differences have varied findings and have been measured using a repeated measures design following a hip strengthening protocol or by comparison of strong and weak hip strength groups.

**Hip Strengthening Intervention**

Several studies compare the changes to LE kinematics following a hip strengthening protocol. Subjects are included if they had decreased hip strength and/or excessive motion in one of the kinematic variables during baseline data collection. Participants completed a hip strengthening protocol to the hip abductors and occasionally the hip external rotators. In a study conducted by Willy and Davis, subjects with excessive HADD motion at the baseline kinematic analysis were recruited and participated in a 6-week hip strengthening protocol focused on HABD and HER strength. There were no significant differences in HADD and HIR motion when subjects were tested again following the protocol. Ferber et al used a 3 week HABD strengthening program with patients experiencing PFP and found no change in genu valgum angle despite an increase in HABD strength. Snyder et al used a strengthening
protocol with healthy subjects, finding increased HADD range of motion and decreased HIR range of motion with the increase in hip strength.¹⁶

The contradictory results of these studies could be attributed to the use of healthy subjects and subjects with abnormalities at baseline. Due to lack of evidence, implementing a strengthening protocol in isolation may not be an effective strategy to affect change in LE kinematics. These findings do not challenge the proposed relationship between hip strength and kinematics at the hip and knee, but rather states that the kinematic variables do not respond to changes from a short-term hip strengthening intervention.

Comparison of Strong and Weak Hip Strength Groups

Another method used to analyze group differences is dividing subjects into strong and weak hip strength groups then comparing the kinematics between groups. Heinert et al divided subjects based on baseline data, enrolling the subjects from the bottom quartile of HABD strength values in the weak group and the top quartile of subjects in the strong group. KABD angle was the only kinematic variable significantly different between the strength groups.⁵ Lawrence et al also divided subjects into weak and strong HABD strength groups but compared LE kinematics during a single leg drop-landing task rather than during running and found no differences for the kinematic variables.¹⁷ Limited research exists to justify the comparison of kinematic variables between weak and strong HABD strength groups, suggesting that comparing these variables on a continuum may be better suited.
Correlations

Generally, hip strength and LE kinematics are compared in cross-sectional study designs, assessing correlations. The majority of these studies examine kinematics in a drop-landing, single leg hop, or other functional tasks, with fewer studies evaluating during running. Data from studies using a walking protocol may offer similar findings to running studies but are not generalizable to trained runners and the task is arguably not challenging enough to identify differences and were therefore not evaluated. In a study with healthy female runners, Baggaley et al found no correlations between HABD strength and peak HADD angle and HADD excursion during gait. Another study considered the association between HABD and HER strength with a variety of kinematic variables following a fatiguing run to reduce hip strength. The only association occurred between peak HADD angle and HABD strength. Although useful findings, the presence of a correlation can only provide insight into how these variables are associated and cannot imply causation.

TESTING HIP STRENGTH

Strength Measures

The literature shows hip strength quantified using various measures, most commonly maximal voluntary isometric contraction (MVIC). It has recently been proposed that a maximal strength value may not be relevant when compared to running kinematics because the subject’s maximum force production may not be required during running and will not be in an isometric state. In attempt to evaluate a more functional measure of hip strength, several studies also collect rate of force development
(RFD) during the peak contraction. Other similar studies evaluate hip strength using concentric isokinetic strength, eccentric strength, and endurance strength measures but also have inconsistent results. To increase validity, the majority of studies normalize the strength data to body weight and lever arm length, defined as the distance from a consistent distal landmark to the location of the force applied.

MVIC testing is fairly standard among the literature. First, the subject’s testing limb is placed in the appropriate testing position by the examiner. Then the subject is instructed to hold the position while the tester applies resistance, or the subject applies their maximum capable force against the clinician. Both methods test isometric strength but differ in the specific instructions from the examiner. From the maximal strength data, researchers can also collect the RFD measure to gain a more functional understanding of the subject’s strength capability. The ability of the hip musculature to control LE motion is dependent on quantity of force production and the time period in which it is achieved. The RFD value may relate to injury in terms of the muscle’s capacity to respond to and correct an injurious mechanism.

**Hip Abduction Strength Methods**

The protocol for assessing HABD strength is consistent within the literature. The subject is tested in a side-lying position on the non-testing side. The testing limb is placed in a neutral hip position, supplemented by the use of pillows, and the knee is extended to ensure the entire limb is parallel with the table. The non-testing limb is placed in 90 degrees of hip flexion and knee flexion and a stabilization strap was placed around the pelvis to reduce the contribution from the musculature on the contralateral side.
resistance is applied at the site of the dynamometer secured by a stabilization strap proximal to the lateral knee joint line to isolate testing to the hip. One study proposed testing the subject in a standing position to gain a more functional assessment of hip strength but identified challenges in isolating the muscle of interest and the associated fatigue of the stance leg when tested. HABD strength can also be tested with the subject in a supine position, exerting force laterally against resistance. This testing position eliminates the influence of limb weight on strength and may be beneficial when testing subjects of a wide range of sizes.

**Hip External Rotation Strength Methods**

HER strength is traditionally assessed with the subject in a seated position with the subject’s hips and knees at 90 degrees of flexion. The thigh is secured to the table using a stabilization strap. The resistance is applied to the distal leg and the subject applies or resists force in a medial direction at the dynamometer, approximately 5 cm proximal to the medial malleolus. Stabilization of the pelvis or femurs bilaterally with a strap limits frontal plane motion.

Willy and Davis used a different approach by testing HER strength with the subject prone and the knee flexed to 90 degrees. The authors stated that placing the hip in a neutral position obtains a measure that is most representative of the contribution of the external rotators during running. The resistance is still applied 5 cm proximal to the medial malleolus, with the subject pushing the distal segment in a medial direction.

**Reliability**

The use of a handheld dynamometer (HHD) has demonstrated high reliability
values when testing a variety of subjects. Kelln et al reported high intra-rater and inter-rater reliability for three testers measuring the strength of several LE muscle groups on a young, healthy, athletic population.\textsuperscript{35} When specifically testing HABD strength with a HHD, Fenter et al found high test-retest reliability but a high variance in the range of scores.\textsuperscript{33} Similar findings were observed by Snyder et al with respect to the assessment of HER strength.\textsuperscript{16} Overall the use of a HHD for assessment of LE strength is a highly reliable tool. However, caution to HHD use include the inability to stabilize the dynamometer, discrepancies in tester strength,\textsuperscript{35,36} and reluctance from the subject to apply full force against the tester. Stabilization straps can reduce the influence from the contralateral limb and secure the placement of the device, increasing the reliability of the measure.\textsuperscript{15}

**Testing Protocol**

In addition to the different protocols mentioned, other factors may have an impact on the generalizability of the strength measure. Practice trials can be completed at a submaximal level to avoid fatigue prior to data collection and help ensure the subject is completing the correct action.\textsuperscript{37} An average or peak value of several trials should be collected. A test should be redone if maximal contraction is not reached or in the event of improper equipment placement or stabilization.\textsuperscript{37,38} The length of rest time between attempts varies between studies, ranging from 30 seconds to 1 minute, with preference towards longer rest times because of the increased ability to sustain the contraction in the next trial.\textsuperscript{39}
MEASURING 3D RUNNING KINEMATIC VARIABLES

Methods

Much of the current research uses the same protocol for kinematic data collection, as follows. Various retro-reflective markers are placed on the subject to indicate key LE anatomical landmarks. The orientation of the markers is recorded by a multi-camera system during a static calibration trial with the subject in a neutral stance. This calibration allows the software to estimate a 3D global coordinate system from the 2D camera input\textsuperscript{40} to identify the subject’s normative data and calculate the joint centers.\textsuperscript{5,13} Joint centers are defined as the halfway distance between two markers.\textsuperscript{5} Several studies controlled for effects on alignment from footwear by supplying all subjects with the same shoes upon enrollment of the study.\textsuperscript{8,15,41}

The running protocol varies slightly across the literature but typically the subject completes a warm-up, the selected running protocol, and then a cool-down. The majority of studies completed the running portion of testing on a treadmill. The use of an instrumented treadmill can also calculate ground reaction forces and assist in the identification of the phases of gait. One study collected kinematic data while subjects ran down a 25-m runway, ensuring one foot strike was recorded by the force plate.\textsuperscript{41} In most studies, the pace is self-selected by the subject to ensure comfort and to individualize the protocol to a speed typical of the subject’s regular training. Using a predetermined pace when not on a treadmill included the use of photocells to direct the subjects.\textsuperscript{16} Motion analysis processing software is used to analyze the kinematic data.
Reliability

Based on a systematic review, 3D analysis has been determined to be the best tool for accurately identifying hip and knee kinematics.\textsuperscript{23,42} Barriers to the reliability of the 3D kinematic analysis include errors in marker placement due to movement of the markers on the skin or clothing surface, improper identification of anatomical landmarks, and variation during the static posture assessment.\textsuperscript{42,43}

Rationale for Further Research

Population Selection

The literature is scarce regarding the relationship between hip strength and running kinematics in highly trained, competitive runners. Collegiate XC runners may respond differently to prevention or treatment interventions based on the training loads and demands of the sport. The currently established rehabilitation protocols are based on literature that examines these variables in high school runners, recreational adult runners, and non-runners, and therefore may not be applicable.\textsuperscript{23} The mileages and time spent running per week is very structured for cross-country athletes, particularly at the collegiate level, resulting in different effects on the body when compared to untrained runners. As a result, XC runners may be at a higher risk of injury due to higher training mileage\textsuperscript{1,3} Some literature argues that increased mileage per week can act as a protective mechanism for knee injuries, indicating that recreational runners have a higher risk of injury despite fewer exposures.\textsuperscript{1} Regardless of the effect, these studies provide a rationale to study highly trained runners separately from recreational runners or non-runners.
Additionally female XC runners should be studied separately from males due to their higher rates of injury, typically greater joint angles and excursions, and typically lower strength than their male counterparts. Therefore, it is necessary to consider prevention and management of injuries in female runners independently of male runners and evaluate relationships for this population separately.

**Variable Selection**

It is reasonable to deduce that a relationship between the strength of the muscles surrounding a joint and the motion of that joint would be related. In the LE this occurs because of the role of the lateral hip musculature in stabilizing the hip and pelvis. The concept of the kinetic chain in the LE explains how joint motion at the hip can impact the knee at both the tibiofemoral and patellofemoral joints through changes in the relative position of the femur. For example, greater HADD angles and HIR excursion can influence knee mechanics and potentially cause knee valgus, a highly studied risk factor for knee injuries. Therefore, these kinematic variables are predicted to correlate with HABD and HER strength and may contribute to future studies to help understand the role of these variables in LE injury.
Chapter 3: The Relationship Between Hip Strength and Multiplanar Running Kinematics at the Hip and Knee

Context: Female runners display high rates of lower extremity (LE) overuse injuries. Studies to identify risk factors and interventions are common for recreational runners but are lacking for competitive and trained runners, specifically collegiate XC runners.

Purpose: The purpose of this study is to evaluate the relationship between hip strength and LE running kinematics in the frontal and transverse planes in collegiate XC runners.

Methods: Nineteen female collegiate XC runners with no current LE injury (age = 19.5 ± 1.17 years, height = 163.3 ± 6.57 cm, mass = 53.3 ± 6.23 kg) had kinematic data recorded via motion analysis while completing a treadmill running protocol. Hip strength was measured by maximal voluntary isometric contraction (MVIC) and rate of force development (RFD). Main outcome measures: Knee abduction (KABD) excursion, peak KABD angle, and hip adduction (HADD) excursion were compared to the MVIC and RFD for hip abduction (HABD) strength for the frontal plane. Hip internal rotation (HIR) excursion was compared to the MVIC and RFD for hip external rotation (HER) strength for the transverse plane. Results: Weak and non-significant correlations were found between MVIC and LE running kinematics and between RFD and LE kinematics ($P < 0.006$).

1 This chapter represents a prepublication manuscript to be submitted to the Journal of Athletic Training (May 2018). Authors are: Victoria C. Holmes, AT (School of Applied Health Sciences and Wellness, Ohio University, Athens); Janet E. Simon, PhD, AT, CSCS (School of Applied Health Sciences and Wellness, Ohio University, Athens); Jae Yom, PhD (School of Applied Health Sciences and Wellness, Ohio University, Athens); and Robert Wayner, PT, DPT (School of Rehabilitation and Communication Sciences, Ohio University, Athens).
**Conclusion:** Due to the lack of significant correlations, caution should be used when correlating clinical measures of strength and observations of running gait analysis. Additional research is needed to identify the role of RFD on running kinematics.

**Key Words:** Cross-country, female, runners

**Key Points**

- No relationship was found between MVIC and LE running kinematics.
- RFD may be related to LE running kinematics.

An estimated 20-75% of long distance runners will experience an injury during their career, with about half of these described as an overuse injury with gradual onset.\(^1\text{–}\text{3}\) Over 80% of these injuries involve the lower extremity (LE) and occur most commonly at the knee.\(^2,\text{4}\) Females overall have a higher rate of injury than males, with female collegiate cross-country (XC) runners specifically displaying a rate 1.25 times higher than their male counterparts.\(^3,\text{5}\text{–}\text{7}\) Based on these statistics, the population of female XC runners is likely predisposed to experiencing LE overuse injuries and therefore require additional consideration.

Interpreting the underlying causes of these running-related injuries requires a comprehensive knowledge of running mechanics and associated factors. Hip musculature has been shown to have an impact on kinematic factors during running. Specifically, the hip abductors play an important role in pelvic stabilization during the running gait and weakness of this musculature can “correspond to altered transverse and frontal plane kinematics.”\(^2(p349)\) The hip abductor muscle group resists femoral adduction while the hip external rotator muscle group resists femoral internal rotation during gait.\(^8\) An inability to
limit these motions can lead to increased movement at the hip and influence the entire LE through the kinetic chain.

The association between these variables has been widely studied in an attempt to improve outcomes for patients and guide treatment approaches for clinicians. Due to the repetitive nature of the high mileage training and competition, it is especially important for XC runners to maintain optimal kinematics to avoid overuse injuries. Although researchers have observed a correlation between these variables in female recreational runners or non-runners, it is unknown whether the established relationship is generalizable to a highly trained population like collegiate athletes. Basing preventative strategies on previous findings from other populations is not an effective strategy to provide the best evidence-based care. If this relationship is not present between strength and running kinematics in female collegiate XC runners, it would be more appropriate for clinicians to identify new intervention strategies specific for this population.

Based on the gap in the literature, female collegiate XC runners need to be studied in isolation. Specifically, the aim of this study was to examine the relationship between hip strength and running kinematics at the hip and knee. Hip strength was quantified specifically for hip abduction (HABD) and hip external rotation (HER). Running kinematics were quantified for the frontal plane as knee abduction (KABD) excursion, collected from initial contact to peak angle, peak KABD angle, peak hip adduction (HADD) angle, and for the transverse plane as hip internal rotation (HIR) excursion, measured from initial contact to peak angle.
METHODS

Participants

Nineteen members of the university’s women’s XC team (age = 19.5 ± 1.17 years, height = 163.3 ± 6.57 cm, mass = 53.3 ± 6.23 kg) that were presently enrolled in an IRB-approved (#16-X-201) multidisciplinary performance and health evaluation were recruited for this study based on a priori power analysis, with a power set at 0.8 and a correlation coefficient set at > 0.6. Testing for this study occurred concurrently with data collection for the already approved study. Participation was not required as part of membership to the team. Participants experiencing a LE injury at the time of data collection were excluded from this study.

Procedures

Upon enrollment in the larger study, the subjects were screened for eligibility based on the inclusion and exclusion criterion. Informed consent was collected from all eligible participants during their visit the Gait lab for their single testing session. The lab is housed in the Division of Physical Therapy, Grover Center W265, under the direction of Robert Wayner, PT, DPT. Demographic data of the participants, including height, weight, and age to describe the target population was collected from the initial intake questionnaire.

Runners completed a 4-trial running protocol as defined by IRB approved study 16-X 201. Static postural measurements, height and weight were taken using an internal gait data collection form for normalization of 3D gait data.
Thirty retroreflective markers arranged in clusters on plastic sensor plates were affixed to each participant on the trunk and LE using a non-adhesive fabric wrap to analyze the running mechanics and to measure 3D running motion (see Figure 1). Major anatomical landmarks on the trunk and LE were identified for assistance in motion analysis by the same researcher. These landmarks are spine (C7/T1, T12/L1, L5/S1), and bilaterally: ASIS, medial and lateral femoral epicondyles, medial and lateral malleoli, and tip of the second phalanx. Where skin was exposed, non-toxic washable marker was used to identify the landmark. In areas where skin was not exposed, athletic tape was used to mark the landmark. A standing calibration trial was conducted with the subject standing in the center of the camera volume on an instrumented treadmill (Bertec, Worthington, OH), to create a subject model in the data collection software (The Motion Monitor, Chicago, IL).

Subjects completed a 3-5 minute walking warm up on the treadmill. Then they ran for 2 minutes to acclimate to the treadmill at a pace that was established by asking each subject what pace she would select for an easy 20-minute run, as done in Ford et al.11 After the walking warm up and 2 minute run was completed, subjects completed the 4-trial running protocol, each trial lasting 2 minutes. Due to the homogeneity in running performance of the sample, using a standardized speed for all subjects was appropriate to achieve the desired level of exertion. The running trials completed were as follows: Trial 1: A pace that corresponds to a light to moderate pace in normal training (6 miles/hour), Trial 2: A pace that corresponds to a moderate pace in normal training (7 miles/hour), Trial 3: A pace that corresponds to a moderate to hard pace in normal training (8
miles/hour), Trial 4: A pace that corresponds to race pace for these collegiate athletes (9 miles/hour). Subjects were given a 2-minute cool-down to transition from running to walking. This completes subject testing for running biomechanics.

3D analysis was recorded using a 10-camera infrared motion capture system (VICON, Oxford, UK) recording at 240 Hz. 5 strides were collected from the stance phase during the conclusion of each running trial. Stance phase was determined as the time between initial contact and toe-off, assessed by the instrumented treadmill. For analysis, 3D gait data was taken from Trial 3 as this most accurately depicts the subjects’ typical training load, which is the unique characteristic of this subject population. KABD excursion, peak KABD angle, peak HADD angle, and HIR excursion were collected from the recorded strides and processed using The Motion Monitor Software. Excursion is defined as the difference between the angle at initial contact and the peak angle.¹²

Hip strength was measured immediately after the non-fatiguing running protocol to control for the interference from muscle fatigue on the maximal effort needed for the maximal voluntary isometric contraction (MVIC) strength assessment. The primary investigator tested all subjects for MVIC strength bilaterally using a handheld dynamometer (HHD) (Lafayette instrument 01165 MMT). Previous uses of HHDs reported high intra-rater and inter-rater reliability and high consistency in same-day repeated measures protocols.¹³,¹⁴ The strength testing protocol followed the procedure outlined by Willy and Davis¹⁵ due to the reported high intra-rater reliability for HABD and HER strength, 0.96 and 0.91 respectively. Each subject completed one submaximal practice trial to ensure correct muscle action and one maximal practice trial to practice
timing with the auditory cues. To control for learning effects, strength was measured three times with each trial lasting 3 seconds in duration\textsuperscript{16} and 1 minute of rest between trials.\textsuperscript{17} All subjects were told to contract as hard and as quickly as they can when they heard the second beep from the HHD. Once the subject began the contraction, the examiner provided verbal encouragement to “push” for the HABD strength measure and to “pull” for the HER strength measure. The patient was instructed to relax when they heard the double beep from the HHD, signaling the end of the contraction. Peak force was collected from the device and the highest of the three trials was used for analysis.

Rate of force development (RFD) was calculated from the force versus time curve from the MVIC trial with the greatest force value.

HABD strength was measured with the subject side lying on the contralateral side on a fixed height treatment table as seen in Figure 2A. The HHD was placed proximal to the lateral femoral epicondyle and stabilized against the testing limb with a strap. Pillows were placed between the subject’s legs to ensure the direction of the force was perpendicular to the dynamometer, which was confirmed by an inclinometer. Transverse plane movement of the pelvis was minimized with a stabilization strap secured around the pelvis. HER strength was measured with the subject prone on the treatment table to place the hip in a position similar to the position during running (Figure 2B). The pelvis was stabilized with a strap and the subject was able to further stabilize the trunk by holding onto the table. The patient was positioned on a fixed height table with the knee of the testing limb at a premeasured location, to maintain consistency. The dynamometer was placed 6 cm proximal to the medial malleolus and secured with a belt. The
stabilization belt was secured to the wall by a chain and placed at a measured height to ensure consistent tension and direction of pull. Subjects were instructed to pull their lower leg away from the wall to correctly complete the muscle action.

**Figure 1.** Reflective marker set up.

**Figure 2.** (A) Hip abduction strength set up; (B) Hip external rotation strength set up.

The peak value of the 3 MVIC trials was used for analysis. RFD was calculated using the Lafayette Instruments MMT Download tool and was defined as the average slope of the force-time curve after the onset of the maximal contraction. The average RFD was calculated from the middle 60% of the data, from the onset of the contraction.
and the peak force value before plateau. MVIC and RFD were normalized to body weight and lever arm length as was standard in the literature.\textsuperscript{15,20} Most studies normalized force to body weight, but force was also normalized to lever arm as was used by Willy and Davis to reduce the effects of limb leverage.\textsuperscript{15} The lever arm for the HABD strength assessment was defined as the greater trochanter to the lateral femoral condyle. The lever arm for the HER strength assessment was defined as the distance from the femoral condyle to the site of resistance applied by the dynamometer at the tibia.\textsuperscript{15} All strength data was recorded on the Strength Testing Data Collection form included in Appendix C.

**Statistical Analysis**

Means and standard deviations were calculated for all variables for the dominant leg. Leg dominance was defined as the foot the subject would use to kick a ball.\textsuperscript{15,21} One outlier was found for HABD MVIC assessed by a boxplot (z = -2.86) but was not removed from the data as it was within 3 SD of the mean and therefore considered normal. For the main analysis, three correlations were calculated for HABD strength (MVIC) and the three frontal plane kinematic variables (KABD excursion, peak KABD angle, peak HADD angle), and one correlation was calculated between HER strength (MVIC) and the single transverse plane kinematic variable (HIR excursion) for the dominant leg. A sub-analysis included three correlations for HABD strength (RFD) and the three frontal plane kinematic variables (KABD excursion, peak KABD angle, peak HADD angle) for the dominant leg, and one correlation for HER strength (RFD) and the single transverse plane kinematic variable (HIR excursion) for the dominant leg. All
correlations were run as a Pearson Product Moment with an Alpha level adjusted using a Bonferroni correction to reduce Type I error ($P < 0.006$ for all correlations).

RESULTS

Table 1 contains the descriptive statistics for all variables. All correlations are located in Table 2. There were weak and non-significant correlations between the MVIC strength measures and the LE kinematic variables ($P > 0.006$). RFD data was calculated for only seven subjects as the data was lost from the HHD. For the included participants, the correlations between the RFD and kinematic variables were weak to moderate and non-significant ($P > 0.006$). As hypothesized, correlations between HABD strength and frontal plane kinematics were slightly stronger when using RFD rather than MVIC, but this was not seen for the HER correlations.
Table 1. Descriptive Statistics of all Variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean ± SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hip External Rotation MVIC (n = 19) (% BW · m)</td>
<td>6.228 ± 1.133</td>
</tr>
<tr>
<td>Hip Abduction MVIC (n = 19) (% BW · m)</td>
<td>14.550 ± 2.757</td>
</tr>
<tr>
<td>Knee Abduction Excursion (n = 19)*+ (degrees)</td>
<td>2.074 ± 3.281</td>
</tr>
<tr>
<td>Peak Knee Abduction Angle (n = 19)*+ (degrees)</td>
<td>2.308 ± 3.011</td>
</tr>
<tr>
<td>Hip Internal Rotation Excursion (n = 19)*+ (degrees)</td>
<td>-2.390 ± 5.946</td>
</tr>
<tr>
<td>Peak Hip Adduction Angle (n = 19)*+ (degrees)</td>
<td>13.003 ± 2.575</td>
</tr>
<tr>
<td>Hip External Rotation RFD (n = 7) (% BW · m / s)</td>
<td>8.770 ± 2.102</td>
</tr>
<tr>
<td>Hip Abduction RFD (n = 7) (% BW · m / s)</td>
<td>23.69 ± 8.979</td>
</tr>
</tbody>
</table>

*KABD is positive whereas knee adduction is negative.
† HIR is positive, whereas hip external rotation is negative.
*HADD is positive whereas hip abduction is negative.

Table 2. Correlations Between Hip Strength and Kinematics

<table>
<thead>
<tr>
<th></th>
<th>HABD MVIC (n = 19)</th>
<th>HER MVIC (n = 19)</th>
<th>HABD RFD (n = 7)</th>
<th>HER RFD (n = 7)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KABD EXC</td>
<td>-0.031</td>
<td>-</td>
<td>-0.093</td>
<td>-</td>
</tr>
<tr>
<td>KABD PEAK</td>
<td>-0.112</td>
<td>-</td>
<td>-0.378</td>
<td>-</td>
</tr>
<tr>
<td>HADD PEAK</td>
<td>0.067</td>
<td>-</td>
<td>0.409</td>
<td>-</td>
</tr>
<tr>
<td>HIP IR EXC</td>
<td>-</td>
<td>0.167</td>
<td>-</td>
<td>-0.033</td>
</tr>
</tbody>
</table>

DISCUSSION

The purpose of this study was to examine the relationship between hip strength and running kinematics of the LE in female collegiate XC runners. The methodology was
based on the recommendations from previous literature\textsuperscript{15,20} and it was hypothesized that hip strength would influence hip and knee kinematics.\textsuperscript{8,20,22–24} Since the hip is the proximal segment, movement at this joint may influence the entire LE through the kinetic chain. Based on the knowledge of overuse and non-contact injuries, these mechanisms are relevant to study in female XC runners.\textsuperscript{2,7,25,26}

Numerous measures were taken to increase the reliability and validity of this study to improve the chance that these results are representative of the population. Our strength testing methods were highly reliable and consistent by using only tester for every subject and standardized verbal cues. Stabilization belts successfully reduced compensation from other muscles, prevented slippage of the HHD, and ensured proper and consistent procedures. Normalizing strength to limb length and body weight allowed for proportional strength and reduced the effects of leverage.\textsuperscript{15,20} Patient positioning was chosen to be functional and to test the muscles in a position similar to the position during gait. Running kinematics were assessed for both the hip and knee using 3D motion analysis, which is the gold standard for biomechanical analysis.\textsuperscript{20,27} Standardized set-up and cues were also used during the running protocol.

From the descriptive statistics it was noted that this sample had higher strength values and lesser joint angles and motions when compared to other studies. The majority of studies measured these variables in recreational or moderately active female runners. The subjects in this study had greater maximal strength values for both HABD and HER strength than the samples of recreational athletes from other studies.\textsuperscript{15,28} When compared to studies that used a strengthening intervention, the strength values from the strong
group or the post-intervention group were more similar to the values from the sample of this study.\cite{15,28} This indicates that these individuals likely do not have a strength deficit, which may influence the relationship with running mechanics. Therefore, strength may not be a beneficial intervention strategy for subjects within this population because they already have high strength values. Due to the variability of methodology of RFD collection in the literature, it was not feasible to compare RFD data from this study to other studies. Most studies examined maximal strength only and did not include RFD information. When RFD was included, it was not normalized to body weight so comparison to our study was challenging.

Kinematic variables were also noticeably different from the values from recreational runners in other studies. In most cases, these studies found greater peak joint angles and joint motions. Most commonly KABD peak angle\cite{5,10,23,29} and HADD peak angle\cite{12,23,29} were calculated in other studies and were generally larger than the angles for subjects in this study. Snyder et al reported KABD excursion and HIR excursion values that were higher than those of this study.\cite{28} Identifying these differences reinforces the rationale to consider trained runners separately from recreational runners as they may have different injury mechanisms.

Additionally, the variances of all the variables were relatively small, indicating that this is a highly homogenous sample. The assumption that this population tends to exhibit higher strength, lesser joint angles and motion, and is relatively uniform can contribute to how the results of this study are interpreted. No significant findings were identified when testing for an association between hip strength and running kinematics,
but this could be attributed to the clustered nature of the data. This population likely will need to implement more specific and specialized interventions to target these injurious mechanisms as they do not have clear deficiencies.

**Limitations**

RFD was included as a supplemental analysis to provide a more comprehensive and dynamic view of HABD and HER muscle function. We hypothesized that RFD would display a greater relationship with LE kinematics than the correlation between MVIC and LE kinematics. Although weak to moderate correlations were found between RFD and running kinematics, these findings were not significant and were underpowered. Due to equipment malfunction, RFD data was lost from the HHD, so this relationship was only assessed for 7 subjects. As these findings are unpowered, future studies should continue to include RFD in addition to MVIC when assessing the correlation between strength and running kinematics. Many other studies have examined this relationship using only MVIC with contradictory results, so the RFD data would have provided a more functional quantification of hip strength and strengthened our study.

Furthermore, the HHD collected data at 40 Hz compared to 1000 Hz of higher capacity equipment from other studies. To control for delayed reaction from the subject, RFD data was calculated from the middle 60% of the rise in the force curve and quantified as average RFD. Being able to collect data at a faster rate would improve the RFD analysis by allowing for differentiation between the contributors of muscle contraction, muscle fiber type (onset to 75-100 ms) or neural drive (>100 ms).
Overall a larger sample size would have increased the power of the study. By selecting a specific population, the sample was narrow and limited in analysis methods. With a larger sample, subjects could have been divided into quartiles by either strength or kinematics and analyzed the differences in variables between the extreme groups. The homogeneity of all the variables may have decreased the likelihood of finding a significant correlation between hip strength and the kinematic variables. Additional statistical analyses should be considered for this population.

**Clinical Implications**

Based on the findings from this study, we are unable to draw any conclusions regarding an association between the variables. Caution should be used when assuming a relationship between hip strength and LE kinematics. Future research should examine the effect of RFD and other contributing neuromuscular variables on LE kinematics. Comparison of these variables between a recreational population and a highly trained population may produce interesting findings regarding the effects of training on kinematics. Prospective studies linking strength and kinematic abnormalities to injury may more appropriately guide interventions regarding these variables. Treatment plans may consider directly addressing the kinematics rather than manipulating strength as there is insufficient evidence to support a correlation between the variables. As always injury rehabilitation should be individualized and use outcome measures to determine the interventions that will be most successful for the patient.
CONCLUSION

This study aimed to evaluate the relationship between hip strength and LE kinematics in female collegiate XC runners. There were no significant correlations between HABD strength measures (MVIC and RFD) and the frontal plane LE kinematic variables or HER strength measures (MVIC and RFD) and the transverse plane kinematic variable. These results suggest that caution should be used when correlating clinical measures of strength and observations of running gait analysis, especially when quantifying strength using MVIC. RFD may have more association with joint motion and angles during gait than maximal strength, but additional research is needed. We cannot make recommendations for interventions related to these variables, but skepticism should be used for practices that are based on an association between these variables. Further research should be conducted in order to provide strong clinical recommendations.
REFERENCES


Chapter 4: Conclusion

This study aimed to evaluate the relationship between hip strength and LE kinematics in female collegiate XC runners. There were no significant correlations between HABD strength (MVIC and RFD) and the frontal plane LE kinematic variables or HER strength (MVIC and RFD) and the transverse plane kinematic variable. These results suggest that caution should be used when correlating clinical measures of strength and observations of running gait analysis, especially when quantifying strength using MVIC. RFD may be correlated to LE kinematics and may be beneficial for researchers and clinicians to identify functional muscle capability and identifying areas of limitation. We cannot draw any conclusions about the effect of hip strength on running kinematics, but clinicians should evaluate their current treatment practices. Further research is needed before we can provide strong clinical recommendations.
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Appendix A: Specific Aims

The prevalence of lower extremity (LE) injury is considerable in runners, with an estimated 20-75% of runners experiencing at least one injury during their career.\(^1\text{--}^3\) Females report noticeably higher injury rates than matched males,\(^3\) potentially due to different kinematics during gait\(^4^7\) and decreased strength.\(^2^7\) Overuse mechanisms are responsible for over half of running-related injuries.\(^3\) XC runners may have a higher risk of injury resulting from high training mileage and demands of competition. Without proper intervention the stresses of training could exacerbate injury agents.

Deviations from proper running kinematics, such as increased knee abduction angle during gait, can be attributed to a number of factors including LE anatomical alignment and insufficient strength at the hip.\(^2^3\) Decreased strength as measured by maximal voluntary isometric contraction (MVIC) at the hip can lead to an inability to control motion of the distal segments.\(^6^,7\) Similarly delayed force production of the hip musculature, as measured by rate of force development (RFD), can influence the runner’s capacity to resist injurious mechanisms.\(^4^8\) Hip strength may be more modifiable than running kinematics, so for clinicians to develop appropriate injury prevention interventions, the relationship between hip strength and running kinematics must be clearly identified.

Previous research primarily examines this relationship in female recreational runners or in subjects performing other functional tasks. This leaves a gap in the literature regarding trained female XC runners. To appropriately treat this population, it is crucial
to analyze how hip strength and LE running kinematics relate in collegiate female XC runners specifically.

The overall objective of this study is to identify the relationship between hip strength and running kinematics at the hip and knee in female collegiate XC runners. If the central hypothesis of an inverse relationship between hip strength and kinematics at the hip and knee is true, then clinicians can implement preventative and rehabilitative hip strengthening protocols accordingly. Employing evidence-based interventions specific to the population may improve outcomes for patients.

**Aim 1:** Determine the relationship between HABD and frontal plane kinematics at the hip and knee during running.

- A correlation will be run between HABD strength (MVIC and RFD) and peak HADD angle, peak KABD angle, and KABD excursion.

**Aim 2:** Determine the relationship between HER strength and transverse plane kinematics at the hip and knee during running.

- A correlation will be run between HER strength (MVIC and RFD) and HIR excursion during running.

**Aim 3:** Determine if RFD will produce more significant associations with running kinematics than MVIC.

- Evaluate correlations between MVIC and kinematics as well as RFD and kinematics.

We propose to identify correlations between hip strength measures and same plane LE running kinematics in healthy subjects from this population of collegiate female
XC runners. RFD will display stronger correlations with running kinematics than MVIC because it is a more functional descriptor of strength. Defining these relationships and understanding the interactions between strength and kinematics may help to guide prevention and treatment strategies.
## Appendix B: Data Procedures Checklist

<table>
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<tr>
<th>Part One</th>
<th>Time</th>
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<td>Informed Consent</td>
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<thead>
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<tr>
<td>Standing Calibration Test</td>
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<tr>
<td>Walking Warm-up</td>
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<td>Running Warm-up</td>
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<td>4 Trial Running Protocol</td>
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<tr>
<td>Cool-Down</td>
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<table>
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<td>Hip External Rotation Strength Assessment</td>
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<tr>
<td>• Set up</td>
<td>2 minutes</td>
</tr>
<tr>
<td>• Bilateral</td>
<td>5 minutes each side</td>
</tr>
</tbody>
</table>
Appendix C: Strength Data Collection Form

**Hip Strength Data Collection Form**

Subject # ________

Tibia Lever Arm (medial epicondyle to 6 cm proximal to medial malleolus):
R:______________, L:______________

Femur Lever Arm (greater trochanter to lateral femoral epicondyle):
R:______________, L:______________

Chain Height: __________

<table>
<thead>
<tr>
<th>Trial</th>
<th>R Hip ER</th>
<th>L Hip EXT</th>
<th>R Hip EXT</th>
<th>L Hip ER</th>
<th>R Hip ABD</th>
<th>L Hip ABD</th>
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<tbody>
<tr>
<td>50% Effort Practice Trial</td>
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<td></td>
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<td></td>
<td>Instruct patient to lift leg to ensure level before beginning contraction</td>
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</table>

Notes
Appendix D: Power Analysis

A power analysis was conducted to determine sample size. The type one error rate was set at 0.006 with power set at (1-β = 0.8). With an expected large correlation coefficient > 0.6 the sample size needed is 14.