ASSOCIATION BETWEEN OVERUSE INJURY AND BIOMECHANICS IN DISTANCE RUNNERS

BY

JOHN KING

A Thesis Submitted to the Graduate Faculty of

WAKE FOREST UNIVERSITY GRADUATE SCHOOL OF ARTS AND SCIENCES

in Partial Fulfillment of the Requirements

for the Degree of

MASTER OF SCIENCE

Health and Exercise Science

May 2013

Winston-Salem, North Carolina

Approved By:

Stephen Messier, Ph.D., Advisor
Shannon Mihalko, Ph.D., Chair
Paul DeVita, Ph.D.
Joseph Seay, Ph.D.
ACKNOWLEDGEMENTS

Special thanks to…

My family and friends who have provided unwavering support, love, and companionship throughout this important chapter in my life.

My classmates and fellow graduate students.

My committee members, Dr. Seay, Dr. DeVita, and Dr. Mihalko.

My advisor, Dr. Messier, for teaching me about quality and responsibility in both work and life as well as the value in taking care of those close to you.

My statisticians, Santiago and Dr. Ip for their patience and expertise.

All of the biomechanics staff for teaching me not just about research but more importantly, about being a part of team and the value in supporting those on it.

And finally, the rest of the HES faculty and staff for giving me this unforgettable experience and the lessons I will take with me after I leave.
# TABLE OF CONTENTS

LIST OF TABLES ........................................................................................................ vi

LIST OF FIGURES ...................................................................................................... vii

ABSTRACT ................................................................................................................... viii

INTRODUCTION .......................................................................................................... 1

REVIEW OF THE LITERATURE ................................................................................. 4

Incidence ..................................................................................................................... 5

Risk Factors ............................................................................................................... 6

Biomechanical ........................................................................................................... 9

Rearfoot Biomechanics ............................................................................................. 9

Lower Extremity Joint Kinematics and Kinetics ....................................................... 9

Physiological ............................................................................................................. 11

Anthropometric ....................................................................................................... 11

Strength .................................................................................................................... 12

Behavioral ............................................................................................................... 12

Training History ...................................................................................................... 12

Injury History .......................................................................................................... 14

Gait ............................................................................................................................ 15

Gait Cycle ............................................................................................................... 15

Kinematics .............................................................................................................. 17

Ankle ....................................................................................................................... 18

Knee ......................................................................................................................... 19

Hip ........................................................................................................................... 19
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinetics</td>
<td>20</td>
</tr>
<tr>
<td>Vertical Ground Reaction Force</td>
<td>20</td>
</tr>
<tr>
<td>Hip</td>
<td>21</td>
</tr>
<tr>
<td>Knee</td>
<td>22</td>
</tr>
<tr>
<td>Ankle</td>
<td>23</td>
</tr>
<tr>
<td>Muscle Modeling</td>
<td>24</td>
</tr>
<tr>
<td>Anthropometrics</td>
<td>26</td>
</tr>
<tr>
<td>Q-angle</td>
<td>26</td>
</tr>
<tr>
<td>Arch-Index</td>
<td>26</td>
</tr>
<tr>
<td>Isokinetic Strength Testing</td>
<td>27</td>
</tr>
<tr>
<td>METHODS</td>
<td>29</td>
</tr>
<tr>
<td>Study Design</td>
<td>29</td>
</tr>
<tr>
<td>Participants</td>
<td>30</td>
</tr>
<tr>
<td>Participant Visits</td>
<td>34</td>
</tr>
<tr>
<td>Prescreening Visit</td>
<td>34</td>
</tr>
<tr>
<td>Screening Visit 1</td>
<td>34</td>
</tr>
<tr>
<td>Screening Visit 2</td>
<td>34</td>
</tr>
<tr>
<td>Knee Model</td>
<td>37</td>
</tr>
<tr>
<td>Anthropometric Evaluation</td>
<td>43</td>
</tr>
<tr>
<td>Strength Evaluation</td>
<td>45</td>
</tr>
<tr>
<td>Statistical Analysis</td>
<td>50</td>
</tr>
<tr>
<td>RESULTS</td>
<td>53</td>
</tr>
<tr>
<td>DISCUSSION</td>
<td>62</td>
</tr>
</tbody>
</table>
Demographical Analysis ................................................................. 62
Kinematic Analysis ........................................................................ 63
Kinetic Analysis ........................................................................... 64
Anthropometric Analysis ............................................................... 65
Strength Analysis ......................................................................... 65
Limitations .................................................................................... 67
Conclusions .................................................................................. 68
REFERENCES ................................................................................ 69
APPENDIX A: INFORMED CONSENT ........................................... 75
APPENDIX B: PARTICIPANT FLOW ............................................ 86
APPENDIX C: TESTING ................................................................. 88
Anthropometrics ......................................................................... 91
Strength ....................................................................................... 95
Gait ............................................................................................. 106
APPENDIX D: TESTING QUESTIONNAIRES ............................. 129
Demographics Form ..................................................................... 129
Injury History Form ..................................................................... 137
Training History Form .................................................................. 146
CURRICULUM VITAE ................................................................. 152
LIST OF TABLES

Table I. Incidence of common runners’ overuse injuries reported..................................5
Table II. Inclusion and exclusion criteria ........................................................................32
Table III. Two year plan based on 12-month follow up .................................................48
Table IV. Data collection visits ....................................................................................49
Table V. Cross-classification of injury status by self-report and actual observation
...........................................................................................................................................50
Table VI. Descriptive statistics (Mean ± SE) of the never injured (Never), injured in
study or in past (Occasionally), and the injured in study and in past groups
(Frequently)......................................................................................................................54
Table VII. Comparison of kinematic variables (Mean ± SE) of the Never Injured,
Occasionally Injured, and Frequently Injured groups.................................................56
Table VIII. Comparison of the kinetic variables (Mean ± SE) of the Never Injured,
Occasionally Injured, and Frequently Injured groups.................................................58
Table IX. Comparison of loads at the knee (Mean ± SE) of the Never Injured,
Occasionally Injured, and Frequently Injured groups.................................................59
Table X. Comparison of anthropometric variables (Mean ± SE) of the Never
Injured, Occasionally Injured, and the Frequently Injured groups .........................60
Table XI. Comparison of lower extremity strength variables (Mean ± SE) of the
Never Injured, Occasionally Injured, and the Frequently Injured groups .61
LIST OF FIGURES

Figure 1. Joint range of motion of the hip, knee, and ankle during running ..........20
Figure 2. Ground Reaction Force during running ..................................................21
Figure 3. External joint moments (Nm/kg) of the hip during gait ..........................22
Figure 4. External joint moments (Nm/kg) of the knee during gait .........................23
Figure 5. Joint moments of the ankle during gait ..................................................24
Figure 6. Schematic of study design .................................................................29
Figure 7. Structure of partially ordered set of injury status. An arrow pointing from x to y indicates that x dominates y .................................................................51
Figure 8. Model 1. (b) and (c) are considered as one single category of Occasionally Injured .................................................................52
Figure 9. Model 2 for the Occasionally Injured. Categories (b) and (c) within the Occasionally Injured are compared using the subsample of respondents whose responses are (b) or (c) .............................................52
Figure 10. Age (years) for the never injured (Never), injured in study or in past (Occasionally), and injured in study and in past (Frequently) group ........55
Figure 11. Knee peak flexion angle (degrees) at heel-strike for the Never, Occasionally, and Frequently Injured groups .............................................57
Figure 12. Knee peak flexion angle (degrees) in stance for the Never, Occasionally, and Frequently Injured groups .............................................57
Figure 13. Ankle peak dorsiflexion moment during stance (Nm/kg) for the Never Injured, Occasionally injured, and Frequently Injured groups ..........59
Figure 14. Q-angle (degrees) for the Never Injured, Occasionally Injured, and Frequently Injured groups .........................................................60
ABSTRACT

PURPOSE: The purpose of this investigation was to determine the association of gait kinematic and kinetic, anthropometric and muscular strength variables with injury frequency in distance runners. We hypothesize that frequency of injury will influence a discrete set of kinematic, kinetic, anthropometric, and strength variables. Specifically, increased injury frequency will be associated with greater joint motion and joint loads, a lower arch-index and Q-angle, as well as inferior lower extremity strength variables.

METHODS: Data from a subset of participants (159 out of 184) enrolled in The Runners and Injury Longitudinal Study (TRAILS) were used for this study. Runners between the ages of 18 and 60 years who had been running at least 5 mi/wk for a minimum of six months without developing an overuse injury were recruited and their training history, gait, anthropometrics, and lower extremity strength were assessed. Joint kinematics and kinetics were assessed using a 3-D gait analysis with a 37-reflective marker set arranged in a modified Cleveland Clinic full-body configuration, a 6-Camera Motion Analysis System set to sample data at 200 Hz, and a torque-driven musculoskeletal model (DeVita and Hortobagyi). Q-angle was measured using digital photographs, a technique developed by Herrington and Nester (2004). Arch-index was measured at half bodyweight stance using a method by Cavanagh et al (1987). Knee and ankle concentric strength were measured using a Kin-Com 125E isokinetic dynamometer set at an angular velocity of 60°/sec, while hip isometric and concentric strength were measured with the dynamometer set at an angular velocity of 30°/sec. Participants were then followed for 12-24 months and sorted into Never, Occasionally, and Frequently Injured groups.
Regression equations were calculated for age, weekly mileage, training frequency, training pace, peak hip, knee and ankle joint angles and relative moments as well as knee compressive and A-P shear force at heel-strike and during stance, Q-angle, arch-index, and isokinetic concentric strength of the hip abductors, knee flexors and extensors, and ankle dorsiflexors and plantar flexors.

RESULTS: After controlling for gender and total years running, significant associations were found for age (p = 0.002), peak knee flexion angle at heel-strike (p = 0.042), peak knee flexion angle during stance (p = 0.015), peak relative ankle plantar flexion moment during stance (p = 0.032), and Q-angle (p = 0.03). Increased injury frequency was associated with lower age, increased peak knee flexion angle at heel-strike and during stance, greater peak ankle plantar flexion moment, and a greater Q-angle.

CONCLUSIONS: The significance of these results is tempered by the lack of corroborating evidence on the contralateral side, the relatively weakness of significant associations, and the many associations that did not reach statistical significance. While there is some evidence that less frequently injured runners have characteristics that may lead to reduce stress on lower extremity joints, taken together, the body of the evidence suggests that there are few, if any, significant associations between gait, strength, and anthropometrics and injury frequency. Our results also suggest that running may be a safer activity for older individuals as frequency of injury seems to be attenuated in this population.
INTRODUCTION

Epidemiologic studies show that running reduces the risk of developing many chronic diseases, decreases pain and disability, and diminishes the burden on the health care system\(^1\). Latest estimates place the number of Americans who run each year at 36 million, with approximately 10.5 million running over 100 days/yr\(^2\). The overuse injuries commonly developed in runners, however, are a significant burden, as up to 45-76% of all runners stop running to seek medical treatment each year\(^1,3-5\). Rest is the first line of defense for combating these injuries. Other treatments include injections, such as cortisone shots, oral pain killers and anti-inflammatories, or various surgeries, all of which treat the symptoms while ignoring the cause, leading to poor medical outcomes\(^6\).

The most common injuries associated with running are classified as overuse syndromes\(^7\). Several studies have examined the various aspects of running, including running history, biomechanical factors, and physiological factors in order to determine the mechanism of injury. To date, there have been no randomized clinical trials conducted to examine these variables on a civilian population, partly because of a lack of consistent evidence upon which to base an intervention. Hreljac\(^8\) stated that although the causes of overuse injuries in runners remains unknown, it is clear that they are multifactorial and diverse. The majority of studies on running injuries have been retrospective in design and many lack control groups. Those that have a control typically compare an uninjured group to a currently injured group.

Several studies have compared never injured controls to previously injured groups. The currently injured design is problematic because the injured subjects may be compensating for the injury, altering their normal gait. The assumption in studies using currently uninjured groups is
that although the clinical symptoms have been resolved, the risk factors that caused the injury are still present and can be determined. Milner et al. studied tibial stress fractures in female runners and found the injury was associated with increased tibial forces and free moment\textsuperscript{9,10}. Studies by Pohl et al. found a different set of variables were associated with tibial stress fractures in the same population\textsuperscript{11}, while Zifchock\textsuperscript{12,13} and Creaby\textsuperscript{14} found no significant differences between groups. Only three studies using this design have examined other injuries, and the results are just as equivocal\textsuperscript{15–17}. All of the studies examined biomechanical factors and their link to certain injuries, with only one study assessing anthropometric data\textsuperscript{12}. There have been no studies using this design which have included behavioral variables, and no studies looking at anterior knee pain, the most common overuse running injury. In all studies that specified, participants averaged 20+ miles/week\textsuperscript{9,10,12,13,17}.

It is unknown whether a return to pre-injury weekly mileage following an overuse injury that resulted in a period of reduced or complete absence of running also means that the potential risk factors have returned to normal. Studies like this one assume that although the clinical factors have been resolved, the risk factors are still present, predisposing those individuals to another injury. It is also unclear whether the differences in the risk factor variables are because the injury has altered the runner’s mechanics or if the altered mechanics are responsible for the injury. What is clear, however, is the need for consistency in the literature on the etiology of running injuries. This study hopes to improve on many of the shortcomings of previous research by enrolling many more participants, including all of the most common injuries in the analysis, as well as measuring biomechanical, behavioral, and physiologic variables, many of which have gone completely unexamined in similar studies. Importantly, this study will examine previously injured runners who have returned to running rather than currently injured runners. These data
could be used to intervene in a clinical trial to prevent these injuries, and will also allow clinicians to better treat this frequently injured population by providing a link with relatively easily measured and modified physiological and behavior variables, rather than biomechanical factors alone.

The purpose of this investigation was to determine the association of gait kinematic and kinetic, anthropometric and muscular strength variables with injury frequency in distance runners. We hypothesize that frequency of injury will influence a discrete set of kinematic, kinetic, anthropometric, and strength variables. Specifically, increased injury frequency will be associated with greater joint motion and joint loads, a lower arch-index and Q-angle, as well as inferior lower extremity strength variables.
**REVIEW OF THE LITERATURE**

**Overuse Injuries in Runners**

To date there has only been one randomized clinical trial (RTC) that has tested the efficacy of various interventions to reduce the risk of overuse running injuries\(^\text{18}\). This 8 week intervention placed 2,777 midshipmen through one of 5 conditions during basic training: foam heel pad, heel stretching, heel pad and stretching, graduated running, or no intervention. Andrish et al. found that the graduated running group had the highest incidence of shin splints, 6%. Although running is the primary form of conditioning during basic training, the plethora of other physical demands placed on military personnel during basic training limits the generalizability of the results.

One reason for the lack of randomized clinical trials that examined overuse injuries in runners is the absence of evidence on which to select potentially beneficial interventions. Currently, physicians treating runners rely on expert opinion, observational studies, and surveys for treatment options. These studies typically examine a select number of potential risk factors but their conclusions are limited. None of the studies examined any behavior risk factors and few even examine physiological variables, making rehabilitation of injured runners mostly guesswork. The exact causes of overuse injuries in runners are still uncertain though they are most likely numerous and diverse\(^\text{8}\).

There are two primary designs for retrospective studies examining overuse injuries in runners. One design compares currently injured runners to non-injured runners\(^\text{7,19–32}\). A second design compares a currently uninjured group of runners that has sustained an overuse running injury in the past to a group of runners that have never sustained an overuse injury\(^\text{9–17}\). The
assumption made in the currently uninjured versus never injured studies is that although the clinical factors have been resolved the risk factors are still present, predisposing individuals to another injury. Five prominent studies, however, used neither of these two designs and instead used questionnaires and no control group\textsuperscript{3,33–37}.

Incidence.

Several studies have determined incidence rates for many overuse injuries in runners\textsuperscript{4,21,34,38–42}. Anterior knee pain, also known as patellofemoral pain or runners’ knee is the most common overuse injury at a mean prevalence of 23% across studies. Other common injuries include medial tibial stress syndrome, or shin splints, Achilles tendinitis, Iliotibial band friction syndrome, and plantar fasciitis, ranging from a mean prevalence of 7% to 11%. The most commonly studied injury is medial tibial stress syndrome\textsuperscript{7,9–12,14,17,20,21,28}. Table I shows the mean incidence rate of common injuries as well as the range reported across studies.

**Table I.** Incidence of common runners’ overuse injuries reported\textsuperscript{4,21,34,38–42}

<table>
<thead>
<tr>
<th>Injury</th>
<th>Incidence Range (%)</th>
<th>Mean Incidence (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anterior Knee Pain</td>
<td>12-36</td>
<td>23</td>
</tr>
<tr>
<td>Medial Tibial Stress</td>
<td>6-16</td>
<td>11</td>
</tr>
<tr>
<td>Achilles Tendinitis</td>
<td>5-18</td>
<td>11</td>
</tr>
<tr>
<td>Iliotibial Band Friction Syndrome</td>
<td>4-12</td>
<td>9</td>
</tr>
<tr>
<td>Plantar Fasciitis</td>
<td>4-13</td>
<td>7</td>
</tr>
<tr>
<td>Hamstring Strain</td>
<td>4-7</td>
<td>5</td>
</tr>
</tbody>
</table>
Risk Factors for Running Injuries

Generalized Running Injury Risk Factors.

A few studies examine overuse running injuries as a whole using a retrospective design rather than focusing on individual injuries. James et al. studied 180 injured runners in their clinical practice. Patients presented with 232 overuse injuries, 60% of which were attributed to training errors. Janis used a survey of 358 runners to examine overuse injuries. They found that as training mileage increased, so did the incidence of injury. The study also showed that most injuries were attributed to long-distance training, with less than 5% resulting from speed work. A large study of 3,702 recreational, 378 marathon, and 93 elite middle distance runners diagnosed with an injury at the same sports medicine clinic found that the only significant differences between groups was in the type of injury. Recreational runners most commonly presented with anterior knee pain; marathon runners developed iliotibial band friction syndrome; and middle distance runners commonly had medial tibial stress syndrome.

Taunton et al. also studied injured runners diagnosed at a clinic, but unlike the other studies of this nature, he compared injured runners with different injuries. In men, he found age to be a significant risk factor for certain injuries, though he did not have a control group for comparison. Men over 34 years old had a higher rate of anterior knee pain, while men under 34 had higher rates of iliotibial stress syndrome, patellar tendinopathy, and medial tibial stress syndrome. In women, BMI was a significant discriminator; women with a BMI over 21 kg/m² had higher rates of medial tibial stress syndrome.

In 2008, Messier et al. conducted a retrospective study examining training, biomechanical, and physiological variables. This study of 20 uninjured runners determined the
forces on the knee with a gait analysis and strength with an isokinetic dynamometer. Although this study did not assess knee injury, it did find that increased mileage, body weight, lower limb strength, and hamstring flexibility were all significantly correlated with higher loads on the knee, possible mechanisms for injury.

Jacobs et al\textsuperscript{34} gave questionnaires to entrants to a 10,000 meter race. Of the 451 who filled out the questionnaire, 355 were men and 96 were women. This study examined demographics, training history, and injury history, and found that as pace, training frequency, training mileage, stretching, and participation in races increased, frequency of injury increased. Lack of participation in other sports was also identified as a risk factor for injury in this study.

Warren et al, analyzed 134 currently injured runners at a clinic\textsuperscript{32}. They found no significant difference in any variables when attempting to discriminate between the groups arranged by pain.

The major limitation of all of these studies is the retrospective design. They also lack control groups and most lack data on anthropometrics and running mechanics. There is also a heavy reliance on recall in the survey and questionnaire studies that also threatens validity as participants may have inaccurate recollections of variables assessed.

Two studies examined generalized lower extremity overuse injuries in runners using a prospective design\textsuperscript{3,35}. Macera et al\textsuperscript{3} questioned 583 habitual runners from a mailing list on their training history and followed up on the group 12-months later. Over half of those questioned developed an overuse injury during the study and weekly mileage was the most important risk factor. Running more than 40 miles/wk had an odds ratio (OR) of 2.9, followed by previous injury (OR=2.7) and less than 3 years running experience (OR=2.2). Walter et al\textsuperscript{35} used a similar
design. They questioned runners from 2 community running events (10 mile and 3.5 mile races) and followed up 1-year later. Training history and anthropometric variables were assessed, including patella alignment and rear foot valgus. Almost half of these participants developed an overuse injury (48%), and about half of those were new injuries (54%). Increased mileage and a history of injury were positively correlated with injury incidence. While these studies have the benefit of being prospective in nature, they also have some of the same limitations as the retrospective studies: no control group, reliance on recall, and they failed to test the multifactorial nature of overuse injuries.

All of the studies on generalized lower extremity overuse running injuries, both retrospective and prospective, examine training history’s influence on injury. While results differed from study to study, one common finding was that injury and mileage are linked, with an increase in mileage correlated with an increased risk of injury. No such trend existed for any of the other variables measured.

**Risk Factors by Category**

Studies have examined three general categories of potential injury risk factors: biomechanical, consisting primarily of running mechanics; physiological, including strength and anthropometric variables; and the most studied category, behavioral risk factors, including training history variables. Studies have also studies injury history extensively.
Biomechanics of Injury

Rearfoot Biomechanics

When analyzing the gait of injured runners, biomechanical analysis typically focused on measuring rearfoot motion with the corresponding impact forces. Certain rearfoot motion patterns were found to be potential mechanisms for certain overuse injuries. Compensatory overpronation, caused by a larger inversion angle at heel strike, was linked to excessive stress on the Achilles tendon and the development of Achilles tendinitis. Overpronation, or excessive rearfoot motion, was also linked to plantar fasciitis. The chief hypothesis linking overpronation and injury was that excessive rearfoot motion causes a mistiming of lower extremity segment movements. This may or may not increase the forces placed on the joints and other structures of the lower body, but by altering the forces on the segments, the structures of the lower extremity are unable to adequately repair. Duffey et al. believed that this mistiming of segments results in a twisting action at the knee during the latter half of the support phase. Hamill proposed that analyzing maximum pronation values without measuring intersegmental timing may account for the lack of significant associations found by other studies between rearfoot motion and anterior knee pain. Greater pronation had also been linked with posterior tibial tendon dysfunction (PTTD) in a 2011 study comparing 12 healthy runner and 12 runners currently with PTTD.

Lower Extremity forces and joint moments

Running can be viewed as a series of collisions with the ground. Impact forces at touchdown range from 1.5 to 3 times bodyweight and vary with running speed. Internal forces have been estimated between 5 times body weight at the ankle and 14 times body weight at the
Kinetic factors thought to cause overuse injuries in runners include ground reaction vertical impact forces, vertical loading rate, anteroposterior propulsive forces, and knee-joint forces and moments, though few studies have examined these parameters and results have been mixed.

In a study examining kinetic variables in runners with previous lower extremity stress fractures, Ferber et al. found greater ground reaction forces in runners with stress fractures than healthy runners. A study by Grimston et al. also supported these findings.

In 2006, Milner et al. investigated several kinetic variables and their effects on tibial stress fractures in female runners. Twenty uninjured female runners averaging 32+ km/wk was compared to 20 female runners with a history of tibial stress fractures (TSF). Results showed that females with a history of TSF had a higher tibial loading rate and greater tibial shock than the uninjured females and that tibial shock alone was 70% predictive of history of TSF. Interestingly, the following year a similar study comparing uninjured males to males with a history of TSF found no significant differences between the groups in any kinematic variables. Creaby et al. hypothesized this may have been due to the much larger mass of men’s segments, increased kinetic forces pose less of an injury risk than in women, who’s bones are smaller. Creaby et al. propose that the mechanism of injury for TSF may be different in men and women.

Messier et al., in a comprehensive retrospective study analyzing both anthropometric and biomechanical variables, used 20 noninjured runners and 16 runners with anterior knee pain to investigate the etiologic factors associated with knee pain in runners. They found that vertical impact and propulsive forces were greater in injured runners, but vertical peak forces and loading rates were lower in the injured groups. Kinetic variables are important to analyze when
attempting to determine mechanism for injury because repeated application of relatively high impact forces without sufficient time between them for remodeling to occur ultimately results in an overuse injury.8.

Physiological Risk Factors

Anthropometrics

Messier et al. found that a Q-angle over 16 degrees and a high arch were risk factors for anterior knee pain.24 Decreased joint range of motion is also linked to increased risk of developing an overuse injury. Hartig et al. studied 298 young men in basic training, half of which regularly stretched their hamstrings.46 Increased flexibility of the hamstrings was linked to fewer overuse injuries compared to the control group. Hamstring inflexibility was also correlated with increased knee joint loads in another study by Messier et al.27 Being too flexible could also lead to injury as shown in a study by Warren et al.25 In this study plantar fasciitis was linked to excessive plantar flexion range of motion.

Arch height has been investigated by multiple researchers.7,13,17,20,22–26,32 Pohl et al. searched for biomechanical factors associated with plantar fasciitis by comparing 25 uninjured female runners with 25 female runners with a history of plantar fasciitis.17 They found that the group with a history of plantar fasciitis had a lower arch index (higher arch) than the uninjured group. Duffey et al. also found that a lower arch index was associated with anterior knee pain in runners,26 although none of the other studies investigating this risk factor found significant results. Discrepancies in methodology and results make it difficult to form any firm conclusions on anthropometric risk factors for overuse running injuries.
Strength

Studies have also investigated strength variables and running injuries. As with the anthropometric variables, results were mixed. Two studies with sample sizes of 36 and 169 found that runners with knee pain were deficient in knee flexor and extensor strength compared to uninjured control groups. Increased knee flexor and extensor strength was correlated with increased loads on the knee in a separate study, however. McCrory et al found that weak ankle musculature was a possible risk factor for Achilles tendinitis. In other studies by the same research group, muscle weakness was the most consistent discriminating factor between injured and uninjured runners.

One prospective study has investigated hip strength and knee pain in high school runners. In 2011, Finnoff et al. tested the hip strength of 98 male and female high school running athletes using a handheld dynamometer and followed them for one year. This study found that knee pain was associated with increased hip adductor strength, increased hip adduction to abduction strength ratio, and decreased hip external to internal rotation strength ratio. Lack of muscle strength and improper strength ratios appear to be important etiologic factors in many runners’ overuse injuries.

Behavioral Risk Factors

Training History

A runner’s history questionnaire typically informs on weekly mileage, training surfaces, and years running. Most studies, particularly the earlier ones, focus on training history when investigating potential risk factors for overuse injuries. Some researchers suggest
that most overuse injuries are due to training errors, such as excessive mileage. Just as it is hypothesized with injuries due to alterations in the forces on certain segments of the lower extremity due to mistiming, injuries attributed to excessive mileage are believed to develop when runners exceed their individual distance and intensity limits, so the repair process cannot keep pace with tissue damage.

Results of studies on training history are as varied as any of the other tested variables. Studies from the Wake Forest research group found no significant differences in weekly mileage between runners with anterior knee pain, Achilles tendinitis, medial tibial stress syndrome, or plantar fasciitis and healthy controls. High weekly mileage was related to iliotibial band friction syndrome and another study found that non-injured runners ran significantly more miles than runners with anterior knee pain.

A study by Macera et al suggests that there is also a period during a running career where running injuries are more likely to develop. The study found that runners who had been running less than 3 years and more than 40 miles per week were more likely to have had a history of overuse injury. The 1984 Bern Grand Prix study, however, found that high mileage was an independent predictor of overuse injuries and the main reason for seeking medical care related to injury. In contrast, many studies found no significant correlations between training history and injury, though this may be due to variations in the depth of the training history, or more likely, the injury(s) being investigated as certain injuries may not be prevalent enough to find correlations unless very large samples are used or all injuries are analyzed together.

Training and racing pace as well as stretching habits are related to overuse injuries in some studies. In Jacobs and Berson’s study on 451 runners from a 10k race, they found that
stretches were related to overuse injuries as those who had a history of injury tended to stretch more often before their training. McCrory et al, however, found that injured runners were less likely to stretch than non-injured runners. One probable reason for the lack of consistent findings on this topic is because very few runners stretch regularly, whether injured or uninjured, so sample sizes may be too small for stretching’s effect to be observed. Additionally, the quality of the stretch is generally unknown leading to a potential discrepancy between those who report that they stretch and those who are actually stretching in an efficacious manner.

Walter et al. surveyed 1680 runners and found that training pace did not predict injury potential. These findings of this large, prospective study were in stark contrast to the strong correlation shown previously that has been attributed to the increased knee loads from the faster pace. Faster training pace and more years running were also found to discriminate between runners with Achilles tendinitis and the un-injured control group. Also concerning running experience, Taunton et al. observed that those who were active for less than 8.5 years were more likely to have had medial tibial stress syndrome.

In summary, faster training and racing paces and a lack of stretching have been found to predict injury in runners as well as experience running. Contradictory findings do exist, however, making firm conclusions difficult to draw.

**Injury History**

Runners that have developed an overuse running injury in the past are more likely to develop one in the future when compared to runners who have never been injured. However, two other retrospective studies failed to show similar connections.
Gait

Gait Cycle

A gait cycle lasts from heel strike to the subsequent heel strike of the same foot. During running, the gait cycle is dividing into three phases, stance phase, when both feet are in contact with the ground, swing phase, when only the opposite foot is in contact with the ground, and flight phase, when neither foot is in contact with the ground. During the first half of stance force absorption (pronation) occurs, while during the second half the body is being propelled forward and supination is occurring at the subtalar joint. Stance phase can be further divided into three major components: initial contact to foot flat, foot flat to heel-off, and heel-off to toe off. Swing phase is divided into initial swing and terminal swing. Flight phase occurs twice, at the beginning of initial swing phase and at the end of terminal swing phase.

Initial contact to foot flat

At initial contact, the heel contacts the ground slightly supinated as the leg swings toward the midline of the body along the line of progression. The calcaneus is inverted 4 degrees on average and the leg exhibits a functional varus of 8 to 14 degrees. Unlike during walking, there is no period of brief plantar flexion after heel strike as the foot actually progresses into dorsiflexion, causing increased pronation and less supination.

Vertical ground reaction forces may reach a magnitude of up to 4 times body weight while running, making energy absorption a key function of the lower extremity during this phase. Dorsiflexion at the ankle joint as well as flexion of the hip and knee help dissipate these forces. Other factors contributing to this process include eccentric muscle contraction,
aricular cartilage compression, and importantly pronation of the subtalar joint\textsuperscript{56,57}. The majority of subtalar joint pronation occurs during the initial 20\% of stance, allowing the foot to contact solidly with the ground and adjust to uneven terrain while dissipating energy\textsuperscript{57}. Pronation of the joint includes rearfoot eversion and tibial internal rotation.

**Foot flat to heel-off**

As the gait cycle continues, maximum pronation is reached just as the body center of gravity passes anteriorly to the base of support, marking the end of the absorptive phase of stance. Maximum dorsiflexion (20 degrees) occurs immediately after, in the middle of stance phase, due to forward progression of the tibia\textsuperscript{51,58,59}.

Supination of the subtalar joint follows maximal pronation and begins the propulsive component of the stance phase\textsuperscript{60}. Pelvic rotation coincides with supination as the opposite limb swings forward resulting in an external rotation torque of the stance limb and corresponding inversion at the calcaneus. Initiation of subtalar supination also marks the end of this phase and the beginning of heel-off\textsuperscript{47}.

**Heel-off to toe-off**

This phase of the gait cycle begins with plantar flexion, which initiates acceleration of the stance limb\textsuperscript{61}. Supination is also initiated at heel-off, and continues for the rest of stance phase. While pronation results in a flexible foot, supination results in a rigid foot configuration and increase the stability of the foot as it prepares to push off of the ground\textsuperscript{62}. 

16
During this portion of stance phase the body is thrust forward, resulting in maximal ground reaction forces, up to 4 times body weight\textsuperscript{54,55}. Hip and knee extension also aid in propulsion, though neither joint extends past neutral\textsuperscript{59}.

**Initial swing**

Initial swing marks the beginning of the first flight phase, as the body is propelled into the air and the line of the ground reaction force passes posterior to the knee joint\textsuperscript{63}. The hip adducts relative to the opposite side during initial swing as the pelvis rotates and places the stance limb in external rotation. Dorsiflexion also occurs at the ankle to clear the foot as the limb advances, though this is less important than in walking due to the increase in knee flexion\textsuperscript{63}.

**Terminal Swing**

Terminal swing begins after the contralateral limb has undergone toe-off and marks the beginning of the second and final flight phase. During this phase, the swing limb prepares for heel-strike by terminating knee and hip flexion and rapidly extending these joints\textsuperscript{63}. The hips also adduct to bring the swing limb back towards the midline before ground contact, resulting in the completion of one gait cycle and the start of another.

**Kinematics**

A popular method for determining the kinematics of gait can involve 3D motion analysis systems that digitally recreates a runner’s body as a multisegment system\textsuperscript{64}. Infrared markers are used to map specific anatomical landmarks, the position of which can be determined and recorded by infrared cameras. Measurements for each joint are collected in all three cardinal
planes of motion and allow the calculation of joint angles of the proximal and distal segment, joint angular velocity, and joint acceleration.

**Kinetic chain**

The actions of pronation and supination cause several changes throughout the kinetic chain of the lower extremity during running gait. During pronation, the subtalar joint everts while the forefoot abducts and the talocrural joint dorsiflexes and internally rotates the tibia. Internal rotation of the tibia forces the knee to follow in a flexed and valgus position, causing hip flexion, adduction, and internal rotation\(^ {47,64}\). During supination, the subtalar joint inverts while the forefoot adducts. The talocrural joint plantarflexes and the tibia externally rotates while the knee extends into a varus position causing hip extension, abduction, and external rotation\(^ {47,64}\). Figure 1 shows joint range of motion at the hip, knee, and ankle over one gait cycle.

**Foot and ankle**

Dorsiflexion, plantar flexion, pronation, and supination all occur at the foot and ankle during stance phase and act to both absorb and produce force\(^ {47,65}\). The subtalar joint axis follow a 23° (4°-47°) medially directed and 41° (21°-69°) superiorly directed posterior-to-anterior rotational axis, allowing it to move through abduction, adduction, inversion, and eversion which is required for pronation and supination\(^ {47}\). At heel-strike, the calcaneus is inverted 6°-8° and moves to 6°-8° of eversion during the remainder of stance\(^ {64}\). The ankle joint is ideally 90° at heel-strike and progresses to 20° of dorsiflexion from neutral during midstance as the knee flexes and the tibia translates forward\(^ {47}\). The foot is maximally pronated about halfway through stance, before it begins to supinate for toe-off. Individuals exhibit varying degrees of pronation and
supination during heel-strike and toe-off, however, because of varying degrees of hindfoot varus/valgus and forefoot varus/valgus.\textsuperscript{66}

**Knee**

During the start of the gait cycle, when pronation occurs, the knee is in valgus position and flexes. During supination, however, the knee is in varus and extends\textsuperscript{43,60}. At footstrike, the knee is flexed 20° to 25° and continues to 45° by midstance, providing shock absorption\textsuperscript{64}. Following midstance, the knee extends for toe-off before maximally flexing to 90°-130° during the swing phase\textsuperscript{64}. At late swing phase, the knee will extend to within 10° to 20° of full extension, allowing for maximum stride length and flight phase before preparing for heel-strike\textsuperscript{67}.

**Hip**

During stance, the hip extends and adducts, while it flexes and abducts during swing\textsuperscript{64}. At heel-strike, the hip in swing phase is flexed up to 65° depending on speed, and extends to 11° at toe-off\textsuperscript{68}. The hip also extends during late swing phase so that heel-strike occurs under the center of gravity\textsuperscript{64}. The range of motion at the hip, from full flexion to full extension is between 40° and 60° depending on the speed\textsuperscript{47}. The hip abduction-adduction arc can be as large as 15° from 10° adduction during stance to 5° abduction during early swing\textsuperscript{64}. 

19
Kinetics

Kinetics describes forces acting on the lower extremity during gait in an attempt to define the forces that cause movement. When the foot comes into contact with the ground during running a vertical vector is created that creates torque about the hip, knee, and ankle. To balance this external torque, muscles create an equal and opposite internal torque. A net moment includes all forces, both internal and external, acting on a joint and reflects which one is greater.

Vertical Ground Reaction Force (GRF)

During a normal running gait, two peaks are present for the vertical ground reaction force, one during heel-strike, and another at toe-off. The first peak, the impact peak, occurs during the first 10% of stance, while the second, or active peak, occurs approximately during midstance. The impact peak is typically the smaller of the two, and dividing this peak by the
time it takes to reach the impact peak is known as the loading rate. Although the magnitude of the forces vary with speed, the impact peak is approximately 1.9 times BW and the active peak is approximately 2.7 times BW\(^{70,71}\). Compared with the vertical ground reaction force, the magnitudes of the anterior-posterior and medio-lateral forces are small\(^{72}\). Figure 2 shows the ground reaction forces during running in the vertical, antero-posterior, and medial-lateral direction.

Figure 2. Ground Reaction Force during running\(^{64}\).

**Internal moments at the hip**

Along the sagittal-plane at the hip joint, a small flexion torque develops immediately after heel-strike, which quickly transitions into an extension torque during the first half of stance with a magnitude of approximately 3 times body weight depending on the velocity of the runner\(^{73}\). The hip experiences a flexion torque again during the latter half of stance and continues during the first half of swing before a second and third extension torque peak develops at the end of swing\(^{73}\). Figure 3 shows the external moment at the hip over one gait cycle.
Internal moments at the knee

During stance, a peak extension torque develops at the knee with a magnitude of approximately 3.5 times bodyweight. A small flexion torque is then seen immediately prior to toe-off. A smaller extension torque (up to 1 times BW) develops during the first half of swing before another flexion torque (up to 2 times BW) prior to heel-strike. Figure 4 shows the external moment at the knee over one gait cycle.

Figure 3. External joint moments (Nm/kg) of the hip during gait.
Figure 4. External joint moments (Nm/kg) of the knee during gait.\textsuperscript{73}

**Internal moments at the ankle**

At the ankle, a large plantar flexion torque of approximately 3-4 Nm develops and peaks during midstance\textsuperscript{73}. By toe-off this torque has decreased to a small dorsiflexion torque which persists until the following heel-strike\textsuperscript{73}. Figure 5 shows the external moment at the ankle over one gait cycle.
Figure 5. Joint moments of the ankle during gait\textsuperscript{23}.

**Muscle Modeling**

Biomechanical models have been developed to estimate muscle and joint forces non-invasively to combat the impracticality of in vivo measurements. One type of model to estimate these forces uses inverse dynamics, or static optimization\textsuperscript{74}. This “torque-driven” model uses external moments to calculate internal forces. The model uses position, acceleration, and velocity data for each segment from a gait analysis as well as the external forces measured from a force plate to calculate joint torques and muscle forces from this general equation:

\[
TMT = M(q)q_1 + G(q) + E
\]

Where TMT are the muscle joint torques, \(q\) and \(q_1\) are vectors of the generalized coordinates, velocities and accelerations respectively, \(G(q)\) is gravitational loading, and \(E\) is the external force\textsuperscript{74}. Once the joint torque are calculated using this equation, the forces for the corresponding
muscles can then be determined. The validity of these calculations depend primarily on the accuracy of the kinematic data gathered in a gait analysis\textsuperscript{74}.

An inverse dynamics model to calculate forces of the quadriceps, hamstrings, gastrocnemius, and lateral collateral ligament was developed by DeVita and Hortobagyi in 2001\textsuperscript{75}. This knee model uses those forces to then calculate compressive and anterioposterior shear forces at the joint. This model has been validated against other inverse dynamics models and has been shown to produce similar results\textsuperscript{76}, though it is not without limitations. The primary limitation is that it is a lumped muscle model and groups muscles as quadriceps, hamstrings, and gastrocnemius, and does not account for individual muscle units\textsuperscript{76}. This model also does not account for co-contraction of the rectus femoris, a quadriceps muscle, at the hip during initial stance and can lead to an underestimation of forces at the knee of up to 5\%\textsuperscript{76}. Additionally, the only knee ligament present in this model is the lateral collateral ligament. Other knee ligaments that may contribute to knee forces are not included\textsuperscript{76}.

The other type of model uses forward dynamics and is also called dynamic optimization\textsuperscript{74}. This model calculates movements and external forces based on known internal forces and is used when muscle forces and joint torques are available to calculate the corresponding movements. The neural command is first measured using an EMG or a mathematical model. The command is then transformed into muscle forces using values known for the musculotendon length, shortening velocity, and muscular activation. Equations of skeletal dynamics are then used with these forces to calculate corresponding body movement.

Forward dynamics solves one optimization problem for each complete cycle of movement rather than solving an optimization problem at each instant of the movement like inverse dynamics, making forward dynamics computationally expensive and involve complex
nonlinear relationships\textsuperscript{77}. Other limitations include variability in tendons and muscles between individuals which makes accurate calculations difficult if the individual differs in these areas from the assumed values. Additionally, converting from muscle activation to muscle forces is difficult to measure and is not entirely understood\textsuperscript{74,77}.

**Anthropometrics**

**Q-angle**

The Q-angle (i.e., quadriceps angle) measures the angle that a line from the anterior superior iliac spine to the midpoint of the patella forms with the projection of a line from the middle of the patella to the tibial tuberosity. Typical Q-angles are 10°-14° in males and 15°-17° in females. Smaller than normal Q-angles create the condition genu varum, where the knees align more laterally. Larger Q-angles create genu varus, where the knees cave in medially towards each other\textsuperscript{78}.

**Arch Index**

The Arch index is a measurement of the height of the medial longitudinal arch about the ground during weight bearing activities. A static arch index is determined by taking a footprint during half body weight stance. This is achieved by having an individual stand on a scale and lower one foot onto a sheet of paper that will pick up the print until half of their body weight is transferred from the scale to the other foot. Once the footprint is determined, a line is drawn from the center of the heel to the tip of the second toe. Two other lines are drawn perpendicular to the first to divide the foot into equal thirds. The area of the middle third is then divided by the area of the entire foot, not including the toes, to give the arch index. An index at or below 0.21 is
classified as a high arch. An index between 0.21 and 0.26 indicates a normal arch. An index equal to or above 0.26 is characteristic of flat arch. Low arch indexes have been correlated with increased risk of both plantar fasciitis as well as anterior knee pain.

Isokinetic strength testing

Isokinetic strength testing, or isokinetic dynamometry, is a method of determining muscular strength using hydraulic- or motor-driven instruments to impose constant velocity movements at predetermined velocities. The limb of the subject is attached to the lever arm of the dynamometer and the subject’s joint is aligned with the dynamometer’s axis of rotation. In order to maintain constant velocity, the dynamometer resists the subject’s movement just enough to maintain the preset velocity of movement and records this force as a torque measure. With proper joint alignment, the torque measured by the dynamometer will approximate the torque of the anatomical torque very closely, and if the subject exerts maximal effort against the lever arm throughout the entire range of motion, maximal strength of the muscles responsible for the movement can be quantitatively measured.

Rationale, Purpose, and Hypothesis

There is a clear need for consistency in the literature on the etiology of running injuries. This study hopes to improve on many of the shortcomings of previous research by enrolling many more participants, including all of the most common injuries in the analysis, as well as measuring biomechanical, behavioral, and physiologic variables, many of which have gone completely unexamined in similar studies. Importantly, this study will examine previously injured runners who have returned to running rather than currently injured runners. These data
could be used to intervene in a clinical trial to prevent these injuries, and will also allow clinicians to better treat this frequently injured population by providing a link with relatively easily measured and modified physiological and behavior variables, rather than biomechanical factors alone.

The purpose of this investigation was to determine the association of gait kinematic and kinetic, anthropometric and muscular strength variables with injury frequency in distance runners. We hypothesize that frequency of injury will influence a discrete set of kinematic, kinetic, anthropometric, and strength variables. Specifically, increased injury frequency will be associated with greater joint motion and joint loads, a lower arch-index and Q-angle, as well as inferior lower extremity strength variables.
METHODS

Study Design

This study analyzed data collected from The Runners and Injury Longitudinal Study (TRAILS), a large observational trial that examined the biomechanical, behavioral, physiologic, psychological, and clinical risk factors for runners who sustain an anterior knee pain (AKP) overuse running injury. A secondary purpose was to determine the shared risk factors among runners who sustained any of the common overuse running injuries: AKP, iliotibial band friction syndrome, medial tibial stress syndrome, Achilles tendinitis, or plantar fasciitis. Figure 6 shows a schematic of the study design. TRAILS followed 184 runners who were injury-free for the past 6 months and ran a minimum of 5 or more miles/week. The observation period ranged from a minimum of 12 months to a maximum of 24 months.

*NOTE: The most common overuse running injuries include AKP, IT band friction syndrome, medial tibial stress syndrome, Achilles tendinitis, and plantar fasciitis

Figure 6. Schematic of study design
Prior to being enrolled in TRAILS, people who responded to recruiting efforts completed an eligibility questionnaire during a pre-screening visit (PSV). Study personnel then gave participants an overview of the study, obtained a signed informed consent from the participants, and collected baseline behavioral, biomechanical, and physiologic data during two screening visits (SV1 and SV2). TRAILS collected follow-up data on all runners during a 6-month, 12-month, and 24-month visits, as well as during an additional visit in the event of an overuse injury. For this study, baseline kinematic, kinetic, anthropometric, and strength data and follow-up data on injury status were used to compare selected biomechanical, physiological, and behavioral variables of runners who had a history of overuse injury but with no current injury (i.e., ever injured) to runners who had never sustained an overuse injury (i.e., never injured) to determine if these variables are associated with injury frequency.

**Participants**

184 distance runners between the ages of 18 and 60 years old were recruited to TRAILS during a 6-month period. Male and female runners were enrolled who have been running injury free for the past 6 months. For this analysis, 159 TRAILS participants, whose gait, strength, and anthropometric data were available, were split into a Never Injured (N = 49), Occasionally Injured (N = 36), and Frequently Injured group (N = 74). The Never Injured group had not experienced an overuse running injury prior to the study and had remained injury free over the course of the study. The Occasionally Injured group had either 1) been injured prior to the study but not during the study, or 2) had been injured during the study, but not prior to the study. The Frequently Injured group had been injured prior to the study and during the study.

**Inclusion and Exclusion Criteria**
Male and female distance runners who had been running a minimum of 5 miles per week for at least 6 months without an overuse running injury that, due to pain and discomfort, caused them to reduce or to stop running or to seek medical attention were eligible for participation in this study. Our sample included some who had never been injured and previously injured runners who had been free of pain and discomfort attributable to the injury for 6 months. Table II summarizes inclusion/exclusion criteria and the proposed method of determination for this study.
<table>
<thead>
<tr>
<th>Inclusion Criteria</th>
<th>Method of Determination</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>No younger than 18 yrs; no older than 60</td>
</tr>
<tr>
<td></td>
<td>Phone or face-to-face Prescreen</td>
</tr>
<tr>
<td>Injury Status</td>
<td>Injury-free for at least 6 mos with current training unaffected by any previous injury</td>
</tr>
<tr>
<td></td>
<td>Phone or face-to-face Prescreen</td>
</tr>
<tr>
<td>Weekly Mileage</td>
<td>≥ 5 miles . wk⁻¹ for at least 6 mos and intend to maintain at least this mileage for the next 2 years</td>
</tr>
<tr>
<td></td>
<td>Phone or face-to-face Prescreen</td>
</tr>
<tr>
<td>Living Radius</td>
<td>Within 200 miles (roundtrip) of WFU</td>
</tr>
<tr>
<td></td>
<td>Phone or face-to-face Prescreen</td>
</tr>
<tr>
<td>Residency</td>
<td>Planning to stay in area for at least 2 yrs from study enrollment</td>
</tr>
<tr>
<td></td>
<td>Phone or face-to-face Prescreen</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Exclusion Criteria</th>
<th>Method of Determination</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chronic Disease</td>
<td>Diagnosed chronic muscular or skeletal disease including arthritis, osteoporosis, and multiple sclerosis; diagnosed heart disease or actively seeking treatment for cancer, other than skin cancer, surgical menopause, oophorectomy</td>
</tr>
<tr>
<td></td>
<td>Medical history</td>
</tr>
<tr>
<td>Orthopaedic Conditions</td>
<td>ACL tears, reconstructive joint surgery, joint replacement, acute musculoskeletal injury that affects running, overuse running injury during the past 6 months</td>
</tr>
<tr>
<td></td>
<td>Medical history</td>
</tr>
<tr>
<td>Pregnancy</td>
<td>Currently pregnant or planning on conceiving within the next 2 years</td>
</tr>
<tr>
<td></td>
<td>Questionnaire</td>
</tr>
<tr>
<td>Unwillingness to attend sessions and unlikely to be compliant</td>
<td>Unwillingness to attend testing and follow-up clinical session (in the case of injury) at WFU, to complete brief training logs, and to communicate via telephone or email at regular intervals with study personnel</td>
</tr>
<tr>
<td></td>
<td>Assessment by study Personnel</td>
</tr>
</tbody>
</table>
All levels of running experience were included because experience may be an important etiologic factor. The upper age limit of 60 years for study inclusion was designed to limit the influence of age, independent of running experience, on our outcome variables. The lower age boundary of 18 years limited the subject population to adults.

Recruitment

Subjects recruited for this study were male and female runners from the community, aged 18-60 who run 5+ miles/wk. Runners were recruited via advertisements in local and regional media (Winston-Salem, NC area newspapers, running journals, radio, running club newsletters, etc), flyers at running stores and workout facilities, and recruiting stations at local road races.

Informed Consent

The informed consent was signed after a brief screening visit during which eligibility was determined. It was signed during the first screening visit after all study-related procedures and time commitments had been explained. No study procedures occurred, and no identifiable data was collected prior to the participant giving informed consent.

Screening Procedures

A brief screening visit took place, either in person or over the phone, to determine the participant’s eligibility for the study. The potential participants were asked how many miles per week they currently ran, whether or not they were currently injured, and how much time had passed since they were affected by an overuse injury. Subjects were excluded if they did not
meet entrance criteria, had a medical condition that might have interfered with training, or were unwilling or unable to attend follow-up sessions.

**Participant Compensation**

Participants received a gift certificate for $100 toward a new pair of running shoes at a local sporting goods store at completion of TRAILS.

**Participant Visits**

**Prescreening Visit (PSV)**

A brief questionnaire on major eligibility criteria was given to those who contacted our recruitment office seeking to participate in the study. No personally identifying information (PII) or personal health information (PHI) was collected until the pre-screening form was completed satisfactorily and the individual was deemed eligible and willing to participate. After the first screening visit was scheduled, the contact form was completed. If the individual decided not to participate after reading the informed consent, the contact form was destroyed.

**Screening Visit (SV1)**

The study was explained and informed consent was obtained during participants’ first visit to Wake Forest University. Medical history, runners’ history, injury history, demographics, and medication use were assessed with questionnaires. Anthropometric measurements were taken, and isokinetic knee and ankle strength were assessed using an isokinetic dynamometer.

**Screening Visit (SV2)**
A health status questionnaire was completed as well as isokinetic hip strength measurement and a three-dimensional gait analysis at the runner's training pace.

Data and Specimen Collection and Analysis

Screening Measurements

The Eligibility Questionnaire addressed injury status (injury free past 6 months), willingness to participate in a year-long study, average weekly mileage over the past 6 months (5+ miles/wk), age (18-60yrs), living radius (within 200 miles round trip to Winston Salem), and residency over the duration of the study (not planning moving out of the area).

Information collected during the study

Demographics

Information was gathered on occupation, income, and education using standard techniques.

Medical History, Medication Use, Runners’ Training History, and Runners’ Injury History

Forms used in our previous injury studies were modified to assess past and current health status as well as training and overuse injury history. Participants’ self-reported medications were placed into major therapeutic categories for analysis. The forms were reviewed by a physician prior to the second screening visit.

Definition of Injury
In this study, an overuse running injury was defined as trauma to a lower extremity not caused by an external event, such as a fall, that produced pain or discomfort and caused (a) reduced weekly mileage and/or training intensity (number of days/wk, time per session, or pace); (b) cessation of running for at least one week; or (c) needed to seek medical attention. The latter category included runners who may not have altered their training in response to the injury but, due to pain, sought medical help. Marti et al. defined 3 grades of injury that were used in this study: Grade 1, maintains full activity in spite of symptoms; Grade 2, reduces weekly mileage; and Grade 3, interrupts all training for at least 2 weeks. We defined our injured group as having sustained either a Grade 2 or Grade 3 injury during the course of the 24 month observation period and/or reported a previous injury on the Runners’ Injury history form at the first screening visit.

Biomechanics of Injury

Overview

During SV2, three-dimensional kinematic and kinetic data were used to analyze all runners’ lower extremity mechanics. A 6-camera motion capture system (Motion Analysis Corporation, Santa Rosa, CA) was synchronized with a strain-gauge force platform (Advanced Mechanical Technology, Inc., Watertown, MA) mounted into the floor. Motion and force data were analyzed to determine lower extremity and motion parameters, and used as input into a musculoskeletal model to calculate knee joint forces.

Running mechanics included examination of rearfoot biomechanics (including touchdown angle, maximum pronation angle, total rearfoot motion, velocity of pronation) and knee-joint loads. Subjects ran in their normal training shoes at their average (± 3.5%) training
speed on a 22.5 m runway while motion and force data was captured. Running speed was recorded and monitored with a Lafayette Model 63501 photoelectric control system interfaced with a digital timer with photocells positioned 7.3 m apart. A set of 37 passive reflective markers arranged in the Cleveland Clinic full-body configuration was attached to the runners. Markers were placed on the rearfoot and shank to calculate 3D rearfoot motion (shank - lateral knee, anterior tibia, and lateral ankle markers; rearfoot - heel, lower heel, and lateral calcaneal markers). Three acceptable trials for each side were averaged to yield representative values. An acceptable trial was defined as running within a normal training pace and contacting the force platform with the appropriate foot in normal stride.

Raw coordinate data from the 3D system were smoothed using a Butterworth low-pass digital filter with a cut-off frequency of 6 Hz. The smoothed video-coordinate data, ground-reaction, gravitational, and inertial forces provided input to calculate temporal and lower extremity kinematic and kinetic variables using Orthotrac and Visual3D software. Outcome variables included rearfoot motion parameters (subtalar inversion-eversion, time to maximum eversion and inversion, total eversion range of motion, and maximum eversion and inversion velocity), tibial medial/lateral rotation, knee flexion/extension, timing between lower extremity segments, and vertical and anteroposterior ground-reaction forces.

Knee-Joint Forces

The lower extremity was modeled as a rigid linked segment system. Magnitude and location of the segmental masses, mass centers, and segmental moments of inertia were estimated from position data using a previously published mathematical model, relative segmental masses reported by Dempster, and the subject’s anthropometric data. Inverse
dynamics using linear and angular Newtonian equations of motion were used to calculate the joint reaction forces and moments at each joint. These data were used to determine hamstring, quadriceps, and gastrocnemius muscle forces, and lateral collateral ligament force, which were then used to determine bone-on-bone tibiofemoral and patellofemoral compressive forces and tibiofemoral shear force. The model is torque-driven in that it uses the joint torques from the inverse dynamic analysis to determine the muscle forces.

A 2D inverse dynamics model developed by DeVita and Hortobagyi was modified to a 3D model that incorporated frontal plane knee forces and torques and was used to calculate tibiofemoral compressive, anteroposterior shear, and resultant joint forces, and patellofemoral compressive force. A 3D inverse dynamics analysis was used to obtain the joint torques and reaction forces at the hip, knee, and ankle. Those results, along with the kinematic description of the lower extremity and related anatomical and physiologic characteristics, were used to calculate knee muscle, lateral collateral ligament, and joint forces during the stance phase of running.

In applying the ground reaction forces to the foot at the center of pressure and calculating the vertical and horizontal joint reaction forces at the ankle as well as the joint torque at the ankle, the following linear and angular Newtonian equations were used:

\[ F_z = ma_z + mg - GRF_z \]  \hspace{1cm} (1)

\[ F_y = ma_y - GRF_y \]  \hspace{1cm} (2)

\[ T = I \alpha - GRF_x(d1) - GRF_y(d2) - F_x(d3) - F_y(d4) \]  \hspace{1cm} (3)
Horizontal ($F_y$) and vertical ($F_z$) directions are derived from the ankle GRF. $T$ is the Ankle joint torque and is expressed as a reaction torque to the calculated external torque, giving an internal moment that reflects the force produced by muscles and tissues across the joint. $I$ is the moment of inertia of the foot, $m$ is the mass of the foot, $a$ is the linear acceleration of the foot, $\alpha$ is the angular acceleration of the foot, and $d_1$, $d_2$, $d_3$, and $d_4$ are the lever arms between the ankle and the vertical ground reaction force and the center of mass of the foot. The torques are then reversed and applied to the rest of the leg. Forces and torques at the knee are calculated using the same three equations, whose results are then used in calculating forces and torques at the hip.

In order to calculate the bone-on-bone forces at the knee, the muscular and lateral collateral ligament forces must then be calculated and combined with the joint reaction forces. The three basic steps of this process are 1) calculate the forces of the gastrocnemius, hamstring, and quadriceps muscles and lateral support tissue of the knee, namely the lateral collateral ligament, 2) apply these forces along with the joint reaction forces to the tibia, and 3) determine knee joint forces.

Muscle forces are determined as a proportion of the total torque produced about a joint. Gastrocnemius force calculations use the plantar flexor moment at the ankle joint, which is assumed to be produced by the triceps surae (gastrocnemius and soleus) and that the tibialis anterior is co-active during the first 25% of stance, increasing the gastrocnemius force by 10% in the initial part of stance\textsuperscript{83}. The force of the triceps surae was calculated as the quotient of the ankle joint torque and the moment arm (obtained from the literature\textsuperscript{84,85}) for the triceps surae at the observed angular position of the ankle joint plus the 10% increase in force due to co-activation of the tibialis anterior. To determine gastrocnemius force, the proportion of the
physiological cross section area of the gastrocnemius out of the total physiological cross section area of the triceps surae from the literature, 0.319\textsuperscript{86}, was used to set up an equal proportion using muscle force.

The gastrocnemius force direction is based on the marker position of the heel and knee and is expressed as $\alpha$ (the angle between the gastrocnemius force and the tibia). The heel marker represents the distal muscle end and the proximal end is assumed to be 0.020 m superior and 0.023 m posterior to the knee joint, along the line of the femur\textsuperscript{87}, a position which accounts for the gastrocnemius wrapping around the femoral condyles. Average resultant direction of the gastrocnemius force is at $\alpha = 3^\circ$ from parallel with the leg, leading to a large compressive force and small shear force on the knee.

The force of the hamstring is calculated during the first half of stance from the hip extensor torque, where there is a strong association between EMG hamstring activity and hip extensor torque\textsuperscript{87,88}. This model assumes no co-contraction of the hip flexors during the first half of stance and that hip extension torque is produced by the hamstrings and gluteus maximus\textsuperscript{89}. In order to calculate hip extensor torque, equation 4 is used, which accounts for both the hamstring and gluteus maximus physiological cross sectional area and moment arms. Then the hamstring force is portioned out based on their proportion of the hip extensors physiological cross sectional area using equation 5. The values for physiological cross sectional area, moment arms and hamstring proportion of the hip extensors (Hp) were obtained from the literature and are as follows: Ham PCA = 42.4mm\textsuperscript{2}; GM PCA = 17.39mm\textsuperscript{2}; Hd = 0.042m; GMd = 0.047m; and Hp = 0.63\textsuperscript{90}. Hamstring force is assumed to be parallel with the femur and creates angle $\beta$ with the tibia.

$$Hp = \left[\frac{\text{Ham PCA}}{\text{Ham PCA} + \text{GM PCA}}\right] \left(\text{Hm} \times \text{GMd}\right)$$

(4)
\[ H = \frac{H_p(H_{et})}{H_d} \quad (5) \]

Quadriceps force was calculated from the observed knee joint torque that was determined by inverse dynamics and the calculated hamstring and gastrocnemius force. Knee torque \((K_t)\) is calculated using the equation:

\[ K_t = Q(Q_d) - H(H_d) - G(G_d) \quad (6) \]

Where \(K_t\) is the knee torque from inverse dynamics, \(Q\) and \(Q_d\) are the quadriceps force and moment arm, respectively, \(H\) and \(H_d\) are the hamstring force and moment arm, respectively, and \(G\) and \(G_d\) are the gastrocnemius force and moment arm, respectively. Values for the moment arms throughout the knee range of motion were obtained from the literature and determined to be \(Q_d = 0.035m, H_d = 0.032m,\) and \(G_d = 0.018m\). Since all of the muscles crossing the knee joint are accounted for in this equation, it does account for co-contraction at the knee. The direction of \(Q\) is determined from the literature as well and the angle \(\phi\) it creates with the tibia. Quadriceps force can be calculated by rearranging the equation to:

\[ Q = \frac{[K_t + H(H_d) + G(G_d)]}{Q_d} \quad (7) \]

A method developed by Schipplein et al., in 1991 was used to determine frontal plane loads of the lateral collateral ligament. The external loads place and adductor torque on the knee that is resisted by a combination of abductor torques from the quadriceps and the lateral structures of the knee. The quadriceps exerts a small abductor torque, which is a product of the quadriceps force and its frontal plane lever arm. This torque is subtracted from the observed net internal abductor torque calculated by the inverse dynamic analysis. The remaining torque is then
distributed over the lateral support structures. The force from these structures is assumed to act parallel to the line of the tibia and is calculated as the quotient of this torque and the lever arm.

Finally, the knee joint forces are calculated. After all the muscle forces, forces in the lateral support structures, and joint reaction forces are obtained, they are partitioned into their compressive (Kc) and anterio-posterior shear (Ks) components and summed using this equation below. Compressive components are those parallel with the tibia while AP shear are those perpendicular to the frontal plane.

\[ K_c = G \sin \alpha - H \sin \beta + Q \sin \phi - K_z \sin \lambda + K_y \cos \lambda \] (8)

\[ K_s = G \cos \alpha - H \cos \beta + Q \cos \phi - K_z \cos \lambda + K_y \sin \lambda + L_{ss} \] (9)

Where \( K_z \) and \( K_y \) are the vertical and horizontal knee joint reaction forces and \( L_{ss} \) is the force exerted by the lateral support structures. A positive \( K_s \) indicates an anterior load on the tibia. A positive \( K_c \) indicates a compressive force pushing into the tibia.

**Behavioral Risk Factors**

**Runners’ Training History**

This questionnaire gathered information about weekly mileage, years running, average training pace, and mileage in shoes before discarding. It was used during the first screening visit (SV1) to determine current training status and running history.

**Runners’ Injury History**
This questionnaire requested information about past injuries and was used to determine whether participants had any current running-related problems.

Physiological Risk Factors

Anthropometric Evaluation

Quadriiceps, hamstring, and ankle flexibility, Q-angle, and arch height were measured during SV1. Retrospective studies implicate these variables in overuse running injuries. Flexibility measurements have often been criticized for poor reliability. Following Herrington and Nester’s recent use of digital photographs to measure Q-angles, we have used a similar technique to measure flexibility and have found high ICCs between 0.87-0.99.

Hamstring flexibility was measured with the subject supine, and the hip and knee flexed to 90°. Marks were made over the lateral malleolus, lateral femoral condyle, and greater trochanter. Two vertical rods were secured to each side of the examining table equidistant from its head with a rod between them 1 ft. above its surface, so when the hip was flexed 90°, the thigh touched the rod, helping the subject maintain the 90° flexed position. A strap over the contralateral thigh secured the subject to the table. While maintaining the 90° flexed hip, the subject extended the knee as far as possible. With a digital camera (Nikon Coolpix L22, 12.0 Megapixels) leveled perpendicular to the sagittal plane, the maximum extension position was photographed.

Quadriiceps flexibility was measured with the subject lying prone with both legs strapped to the examining table. The subject flexed the knee until resistance was met, or the hip began to
Maximum knee flexion was measured using the same camera and landmarks as for the hamstring flexibility test. Three consecutive trials were averaged to yield a representative value for each limb. Using a similar technique, Eckstrand et al.\textsuperscript{96} had an intratester CV of 0.5%.

Ankle flexibility was measured by first obtaining the subject’s neutral angle. The subject sat with legs fully extended and markers placed on the lateral malleolus, lateral femoral condyle, and the 5\textsuperscript{th} metatarsal head. The participant’s foot was placed in, and then removed from, a box set at 90 degrees of flexion. The participant was asked to maintain the angle imposed by the box 3 times for each side while a photograph was taken. Plantar flexion and dorsiflexion were calculated from the neutral angle and the average of 3 trials of maximum flexion of the subject. It was measured with the same marker set-up and camera placement. The subject lay supine with knees fully extended and ankles off the table. Three trials were photographed on each side.

Q-angle was measured with the subject standing, feet standardized by a template on the ground. Markers were placed on the anterior superior iliac spine (ASIS), the midpoint of the patella, and the tibial tuberosity. The same digital camera described above was placed 1.5 meters from the participant at a height of 0.6 meters so it was centered at mid-thigh. A level was used to ensure horizontal alignment of the lens both superiorly and inferiorly. One picture was taken ensuring all makers on both legs were visible. The angle of each limb was measured using the technique of Roush et al.\textsuperscript{97}.

Body weight, height, and Body Mass Index (BMI) were measured using standard techniques. Body weight was obtained without shoes or jackets. Instruments were calibrated weekly. BMI was calculated using the formula BMI = weight (kg)/height\textsuperscript{2} (m).
Arch height was measured using the technique of Cavanagh et al. The subject stepped off a scale with one foot and onto a Harris mat until ½ of total bodyweight was on the mat. Once the footprint was determined, a line was drawn from the center of the heel to the tip of the second toe. Two other lines were drawn perpendicular to the first to divide the foot into equal thirds. The area of the middle third was then divided by the area of the entire foot, not including the toes, to give the arch index.

**Strength Measurements**

Knee and ankle concentric strength were measured using a Kin-Com 125E isokinetic dynamometer set at an angular velocity of 60°/sec, while hip isometric and concentric strength were measured with the dynamometer set at an angular velocity of 30°/sec. Each subject was secured, with torso and contralateral limb strapped to the testing chair, hands across the chest, dynamometer axis aligned with the greater trochanter, and resistance pad attached to the lower leg distal to the knee joint. Both legs were tested, with the order of testing (right vs. left) alternated to limit any practice or fatigue effects. The first joint evaluated (knee or ankle) was alternated for each successive subject. Two maximal reproducible trials were averaged, with no more than 6 trials for each test condition. Prior to testing, a warm-up habituated subjects to the equipment.

The order of knee strength tests for all subjects was (1) knee extension (concentric protocol at 60°/sec); and (2) knee flexion (concentric protocol at 60°/sec). Ankle plantar flexion and dorsiflexion were tested using a similar protocol at an angular velocity of 60°/sec. Hip strength testing was performed during the SV2 visit, since the protocol was slightly different than that of knee/ankle.
Knee Strength.

Knee extensor strength and quadriceps insufficiency, measured as the ratio of knee flexor strength to knee extensor strength, were outcome measures for aims 1 and 3. Both were significant discriminators in our previous retrospective studies. Each subject was secured, with torso and tested leg strapped to the testing chair, hands across the chest, dynamometer axis aligned with the knee, and resistance pad attached to the lower leg proximal to the ankle joint. Gravity-effect torque was calculated based on leg weight at a 45° angle. The activation force for each muscle group was set at 50% of maximal voluntary isometric contraction. Knee extensors were tested through a joint arc from 90° to 30° (0° = full extension). The first and last 10° were deleted to account for the dynamometer’s acceleration and deceleration at the ends of the range-of-motion and possibly inconsistent effort. Hence, average force was calculated between joint angles of 40-80°. Trials were spaced by rest periods of 30-60 s. Subjects were asked to give maximal effort. Two maximal reproducible trials were averaged from, at most, 6 trials for each test. Knee concentric flexion tests were then conducted through the same range of motion used for the extension tests.

Ankle Strength

Ankle isometric strength was measured for 3 seconds at 0° of ankle plantar flexion. The activation force for each group was set at 50% of maximal voluntary isometric contraction. Ankle plantar flexors and dorsiflexors were tested through a joint arc from 15° dorsiflexion to 15° plantar flexion. The first and last 5° were then deleted to account for the dynamometer’s acceleration and deceleration at the ends of the range-of-motion and possibly inconsistent effort.
Trials were spaced by a rest period of 30s. Subjects were asked to give maximal effort. Two maximal reproducible trials were averaged from, at most, 6 trials for each test.

**Hip Strength**

Isometric strength was measured for 3sec at 0° of hip abduction. The activation force for each muscle group was set at 50% of maximal voluntary isometric contraction. Hip abductors were tested through a joint arc from 0° to 30° (0° = anatomical position). The first and last 5° were then deleted to account for the dynamometer’s acceleration and deceleration at the ends of the range-of-motion and possibly inconsistent effort. Hence, average force will be calculated between joint angles of 5-25°. Trials were spaced by rest periods of 30-60 s. Subjects were asked to give maximal effort. Two maximal reproducible trials were averaged from, at most, 6 trials for each test.

**Study Timeline**

Table III provides a general overview of the study timetable for TRAILS with activities pertinent to this study highlighted. Table IV provides the sequence of events that occurred for each subject as they progressed through TRAILS. Only data collected from the first three events (PSV, SV1, SV2) were used for this study.
Table III. Two year plan based on 12-month follow-up.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Year 1 (1-month intervals)</th>
<th>Year 2 (3-month intervals)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Planning</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recruitment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baseline Testing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scheduled follow-ups (FU6, FU12)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Injury Follow-up (FU_{injury})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data Analysis</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table IV. Data Collection Visits. Column headers are defined in the text and “X” indicates data that were collected during specific visits.

<table>
<thead>
<tr>
<th>Measurements</th>
<th>PSV</th>
<th>SV1</th>
<th>SV2</th>
<th>FU_{injury}^+</th>
<th>FU6</th>
<th>FU12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eligibility and Descriptive Measurements</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eligibility Questionnaire</td>
<td>Xc</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medical History</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Informed Consent</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Demographics</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medication Use</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Injury Measurements</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Physician Injury Evaluation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Injury Status (Phone Call)</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>MRI/X-ray (as necessary, to confirm diagnosis of anterior knee pain.)</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Primary and Secondary Outcomes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biomechanical Factors</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rearfoot Biomechanics</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knee Joint Loads</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Behavioral Factors</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Runner’s Training History</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Injury History</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Physiological Factors</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Statistical Analysis

The goal of the statistical analysis was to delineate factors that contributed to the injury of runners. The outcome variable involved two measurements of injury: self-reported injury (ever been injured) at baseline, and observed injury status over the course of the study. Thus, the cross-classification of these two measures resulted in 4 categories, which are depicted in Table V.

<table>
<thead>
<tr>
<th></th>
<th>Injured during the course of the study</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td>Ever-injured (self-report at baseline)</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>No</td>
</tr>
</tbody>
</table>

The 4 categories of injury status, labeled (a) through (d) in Table V, formed a partially ordered set. Category (d), which we called the Never Injured, “dominated” (ranked superior to) the other three categories, category (a), which we called Frequently Injured, was being dominated by all other categories, and categories (b) and (c), which as a group we called Occasionally Injured, were not ordered. Figure 7 shows the partial order relationship between the categories.
Figure 7. Structure of partially ordered set of injury status. An arrow pointing from x to y indicates that x dominates y.

The analysis of partial ordered set followed the conditional approach described in Zhang and Ip (2012)\(^9^8\), which comprised two models. Model 1 treated the Never Injured, Occasionally Injured, and Frequently Injured as ordinal categories. Figure 8 schematically depicts the ordered categories for Model 1. Ordinal logistic regression was applied to the outcome of the 3 ordered categories with relevant predictors that were included in the model. We tested the hypotheses that the slopes of individual variables were zero on the log odds scale, with the assumption that the slopes were uniform across the categories. Thus, a significant p-value for a predictor variable would indicate that there is a statistically significant general trend from the Never to Frequently Injured as a function of increasing value of the predictor variable.
Figure 8. Model 1. (b) and (c) are considered as one single category of Occasionally Injured.

Model 2 (Figure 9), which was a conditional model, only considered the respondents that belonged to categories (b) or (c). Subsequently, logistic regression was applied to this subgroup of respondents, with the same set of predictor variables as in Model 1. Under model 2, we tested the hypotheses that the odds ratios of individual predictor variables were 1.0.

Figure 9. Model 2 for the Occasionally Injured. Categories (b) and (c) within the Occasionally Injured are compared using the subsample of respondents whose responses are (b) or (c).
RESULTS

The purpose of this investigation was to determine the association of gait kinematics and kinetics as well as anthropometric and muscular strength variables with the frequency of overuse injury development in distance runners. We hypothesized that increased injury frequency will influence a discrete set of kinematic, kinetic, anthropometric, and strength variables. Specifically, an increased frequency of injury will be associated with greater joint angles and moments of the hip, knee, and ankle in addition to greater knee compressive and shear forces, a greater Q-angle, a smaller arch-index, and attenuated lower extremity strength measures.

A total of 159 participants from the TRAILS cohort (N = 184) were analyzed. Although our analyses are correlational, to enhance the clinical interpretation of the data the cohort was also divided into three groups based on the self-reported injury history as well as whether or not they were diagnosed with an injury over the course of the study. One group (Never) consisted of 49 participants who had never been injured. The second group (Occasionally) consisted of 36 participants who had either been injured prior to the study or developed a grade 2 or grade 3 injury during the study. The final group (Frequently) consisted of 74 participants who had sustained an overuse injury at least 6 months prior to study enrollment and also sustained a grade 2 or 3 injury over the course of the study. Subjects were matched on gender and total months running for all analyses. Although mean values are presented for each group, a significant p-value indicates that the slope of the regression line for the variable of interest is not equal to zero (for the entire cohort); it does not indicate that the groups are significantly different from each other. Mean values and standard errors of the demographic variables for each group are summarized in Table VI. Figure 10 graphically depicts the significant association between age and injury frequency (p = 0.002), showing increases in age were associated with a decrease in the
frequency of injury. A $\beta$ value of 0.0567 indicated that the odds of being in the Never Injured group vs Occasionally Injured and Frequently Injured groups was $1.06 (e^{0.0567} = 1.06)$, or 6% higher for every 1 year increase in age. This odds ratio also applied to the Never and Occasionally Injured groups vs the Frequently Injured group as well.

Table VI. Descriptive statistics (Mean ± SE) of the never injured (Never), injured in study or in past (Occasionally), and the injured in study and in past groups (Frequently). Significant p values indicate the regression slope is significantly different from zero.

<table>
<thead>
<tr>
<th>Injury History</th>
<th>Never</th>
<th>Occasionally</th>
<th>Frequently</th>
<th>$\beta$, P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gender (% female)</td>
<td>49</td>
<td>44</td>
<td>38</td>
<td>0.46</td>
</tr>
<tr>
<td>Race (% white)</td>
<td>96</td>
<td>97</td>
<td>93</td>
<td>0.63</td>
</tr>
<tr>
<td>Age (years)</td>
<td>44.1 ± 0.6</td>
<td>40.8 ± 0.7</td>
<td>39.8 ± 0.9</td>
<td>0.0567, 0.002*</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>72.0 ± 1.1</td>
<td>72.9 ± 1.2</td>
<td>73.5 ± 0.9</td>
<td>0.001, 0.95</td>
</tr>
<tr>
<td>Avg. Pace (min/mi)</td>
<td>9.3 ± 0.09</td>
<td>9.0 ± 0.09</td>
<td>8.8 ± 0.09</td>
<td>0.258, 0.07</td>
</tr>
<tr>
<td>Average weekly miles (mi)</td>
<td>17.3 ± 0.7</td>
<td>20.3 ± 1.1</td>
<td>21.3 ± 1.1</td>
<td>-0.018, 0.18</td>
</tr>
</tbody>
</table>
Figure 10. Age (years) for the never injured (Never), injured in study or in past (Occasionally), and injured in study and in past (Frequently) groups. Significant p values indicate the regression slope is significantly different from zero.

All kinematic, kinetic, anthropometric, and strength variables were analyzed for both the dominant and non-dominant leg. With few exceptions, there were no differences between the dominant and non-dominant sides; hence, unless otherwise noted, results are shown for the dominant side only. Kinematic variables included sagittal plane (flexion/extension) angles of the hip, knee, and ankle during the gait cycle. These results are summarized in Table VII. A significant association was found for knee peak flexion angle at heel-strike and knee peak flexion angle during stance for the non-dominant leg, but not for the dominant side. In both instances, increases in peak knee flexion angle were associated with an increase in the frequency of injury (p = 0.04 and p = 0.015 for knee peak flexion angle at heel-strike and knee peak flexion angle during stance respectively). Beta coefficients of -0.044 (odds ratio: e^{-0.044} = 0.96) for heel-strike and -0.052 (odds ratio: e^{-0.052} = 0.95) during stance indicated that for every degree increase in knee flexion angle the odds of being in a lower injured group decreased by 4% and 5% respectively for heel-strike and stance. Figure 11 graphically depicts changes in knee peak
flexion angle at heel-strike and Figure 12 shows the same information for knee angle during stance for the three groups analyzed. No other kinematic variables were significantly related to injury frequency.

**Table VII.** Comparison of kinematic variables (Mean ± SE) of the Never Injured, Occasionally Injured, and Frequently Injured groups. Significant p values indicate the regression slope is significantly different from zero.

<table>
<thead>
<tr>
<th></th>
<th>Injury History</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Never</td>
</tr>
<tr>
<td><strong>Hip Angle (°)</strong></td>
<td></td>
</tr>
<tr>
<td>Flexion at heel-strike</td>
<td>27.52 ± 0.50</td>
</tr>
<tr>
<td>Peak extension</td>
<td>16.68 ± 0.54</td>
</tr>
<tr>
<td>Peak flexion</td>
<td>36.13 ± 0.59</td>
</tr>
<tr>
<td><strong>Knee Angle (°)</strong></td>
<td></td>
</tr>
<tr>
<td>Flexion at heel-strike*</td>
<td>7.18 ± 0.49</td>
</tr>
<tr>
<td>Peak flexion in stance*</td>
<td>41.09 ± 0.56</td>
</tr>
<tr>
<td><strong>Ankle Angle (°)</strong></td>
<td></td>
</tr>
<tr>
<td>Peak dorsiflexion</td>
<td>7.18 ± 0.47</td>
</tr>
<tr>
<td>Peak plantar flexion</td>
<td>40.68 ± 0.52</td>
</tr>
</tbody>
</table>

*results for non-dominant leg, there was no significant difference in the dominant leg
**Figure 11.** Knee peak flexion angle (degrees) at heel-strike for the Never, Occasionally, and Frequently Injured groups. Significant p values indicate the regression slope is significantly different from zero.

**Figure 12.** Knee peak flexion angle (degrees) in stance for the Never, Occasionally, and Frequently Injured groups. Significant p values indicate the regression slope is significantly different from zero.
Data for the kinetic variables included peak joint flexion/extension moments (Nm/kg) for the hip, knee, and ankle during the gait cycle as well as peak knee compressive and A-P shear forces. The joint moment data are summarized in Table VIII. With the exception of ankle peak plantar flexion moment during stance, there were no significant associations with injury frequency. For every 1 Nm/kg increase in ankle peak plantar flexion moment the odds of being in a less frequently injured group decreased by 65% ($\beta = -1.043$, odds ratio: $e^{-1.043} = 0.35$, $p = 0.032$) (Figure 13).

Table IX summarizes the knee joint loads on the knee. No significant associations were observed for either compressive ($p = 0.253$) or A-P shear force ($p = 0.306$).

**Table VIII.** Comparison of the kinetic variables (Mean ± SE) of the Never Injured, Occasionally Injured, and Frequently Injured groups. Significant $p$ values indicate the regression slope is significantly different from zero.

<table>
<thead>
<tr>
<th>Injury History</th>
<th>Never</th>
<th>Occasionally</th>
<th>Frequently</th>
<th>$\beta$, $P$ value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hip Joint Moments (Nm/kg)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak extension during stance</td>
<td>1.21 ± 0.02</td>
<td>1.23 ± 0.03</td>
<td>1.24 ± 0.03</td>
<td>-0.018, 0.97</td>
</tr>
<tr>
<td>Peak flexion during stance</td>
<td>0.85 ± 0.02</td>
<td>0.87 ± 0.02</td>
<td>0.89 ± 0.02</td>
<td>0.684, 0.39</td>
</tr>
<tr>
<td><strong>Knee Joint Moments (Nm/kg)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak flexion at heel-strike</td>
<td>0.43 ± 0.01</td>
<td>0.42 ± 0.01</td>
<td>0.43 ± 0.01</td>
<td>-0.658, 0.64</td>
</tr>
<tr>
<td>Peak extension during stance</td>
<td>1.79 ± 0.04</td>
<td>1.85 ± 0.04</td>
<td>1.90 ± 0.03</td>
<td>-0.325, 0.35</td>
</tr>
<tr>
<td><strong>Ankle Joint Moments (Nm/kg)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak dorsiflexion during stance</td>
<td>0.04 ± 0.01</td>
<td>0.02 ± 0.01</td>
<td>0.01 ± 0.01</td>
<td>-1.793, 0.20</td>
</tr>
<tr>
<td>Peak plantar flexion during stance</td>
<td>2.00 ± 0.02</td>
<td>2.03 ± 0.03</td>
<td>2.17 ± 0.03</td>
<td>-1.043, 0.032*</td>
</tr>
</tbody>
</table>
Figure 13. Ankle peak plantar flexion moment during stance (Nm/kg) for the Never Injured, Occasionally Injured, and Frequently Injured groups. Significant p values indicate the regression slope is significantly different from zero.

Table IX. Comparison of loads at the knee (Mean ± SE) of the Never Injured, Occasionally Injured, and Frequently Injured groups. Significant p values indicate the regression slope is significantly different from zero.

<table>
<thead>
<tr>
<th>Injury History</th>
<th>Never</th>
<th>Occasionally</th>
<th>Frequently</th>
<th>β, P value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Peak Knee Forces (N)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compressive</td>
<td>6272.90 ± 128.50</td>
<td>6623.80 ± 172.38</td>
<td>6815.51 ± 115.00</td>
<td>-0.0002, 0.253</td>
</tr>
<tr>
<td>A-P shear</td>
<td>1125.96 ± 26.94</td>
<td>1171.87 ± 30.46</td>
<td>1218.51 ± 22.77</td>
<td>-0.0006, 0.306</td>
</tr>
</tbody>
</table>

Anthropometric variables included arch index and Q-angle and are summarized in Table X. A significant association was observed for Q-angle where decreased angles were associated with decreased frequency of injury ($\beta = -0.054$; odds ratio: $e^{-0.054} = 0.95$, $p = 0.034$). For every 1 degree increase in Q angle the odds of being in a less frequently injured group decreased by 5%.

59
There was no significant association between injury frequency and arch index ($p = 0.799$) (Figure 14).

**Table X.** Comparison of anthropometric variables (Mean ± SE) of the Never Injured, Occasionally Injured, and the Frequently Injured groups. Significant p values indicate the regression slope is significantly different from zero.

<table>
<thead>
<tr>
<th>Injury History</th>
<th>Never</th>
<th>Occasionally</th>
<th>Frequently</th>
<th>$\beta$, P value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Anthropometrics</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arch Index</td>
<td>0.23 ± 0.004</td>
<td>0.23 ± 0.003</td>
<td>0.22 ± 0.005</td>
<td>0.749, 0.80</td>
</tr>
<tr>
<td>Q-Angle (°)</td>
<td>14.1 ± 0.6</td>
<td>14.0 ± 0.5</td>
<td>15.4 ± 0.6</td>
<td>-0.054, 0.03*</td>
</tr>
</tbody>
</table>

* $p = 0.03$ for slope

**Figure 14.** Q-angle (degrees) for the Never Injured, Occasionally Injured, and Frequently Injured groups. Significant p values indicate the regression slope is significantly different from zero.
Strength variables included average force production during isokinetic testing for the ankle plantar flexors and dorsiflexors, knee extensors and flexors, and hip abductors and are summarized in Table XI. No significant associations were found for any of the strength variables.

**Table XI.** Comparison of lower extremity strength variables (Mean ± SE) of the Never Injured, Occasionally Injured, and the Frequently Injured groups. Significant p values indicate the regression slope is significantly different from zero.

<table>
<thead>
<tr>
<th></th>
<th>Injury History</th>
<th>β, P value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Never</td>
<td>Occasionally</td>
</tr>
<tr>
<td><strong>Strength (Nm)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ankle Dorsiflexors</td>
<td>27.98 ± 0.73</td>
<td>29.99 ± 0.81</td>
</tr>
<tr>
<td>Ankle Plantar Flexors</td>
<td>79.87 ± 2.52</td>
<td>79.82 ± 2.48</td>
</tr>
<tr>
<td>Knee Extensors</td>
<td>97.23 ± 2.38</td>
<td>87.20 ± 2.51</td>
</tr>
<tr>
<td>Knee Flexors</td>
<td>48.92 ± 1.19</td>
<td>45.77 ± 1.35</td>
</tr>
<tr>
<td>Hip Abductors</td>
<td>69.86 ± 1.78</td>
<td>68.01 ± 2.52</td>
</tr>
</tbody>
</table>
DISCUSSION

Numerous studies on runners have found links between overuse injuries and a variety of risk factors including kinematic, kinetic, anthropometric, and strength variables. Although results have been mixed, the general trend is that those who develop overuse injuries less frequently have mechanics and values that decrease loads on the lower extremity. Five of 46 measured variables, combined dominant and non-dominant sides, revealed significant associations with injury frequency that would tend to support these findings. After adjusting for gender and running experience (i.e., years running), increased frequency of injury was associated with lower age, higher knee flexion angle at heel-strike and during stance for the non-dominant side, greater peak ankle plantar flexion moment, and greater Q-angle for the dominant side. Overall, the limited number of significant relationships suggest that there are few, if any, statistically significant and clinically meaningful associations between gait kinetics and kinematics, anthropometric and strength variables and injury frequency.

Demographic analysis

An analysis of the demographic variables indicated that age was associated with frequency of injury. For every 1 year increase in age, the chance of a runner belonging to the Never Injured group compared to the Occasionally Injured and Frequently Injured groups or the odds of belonging to the Never and Occasionally injured groups versus the Frequently Injured group increased by 6%. These results are partially supported by Taunton et al (2002) who showed age was a discriminating factor between types of injuries, with men older than 34 years having a higher prevalence of anterior knee pain and men younger than 34 years having higher prevalence of medial tibial stress syndrome, iliotibial band friction syndrome, and patellar...
tendinopathy\textsuperscript{21}. Based on the incidence rates of the most common overuse injuries\textsuperscript{4,21,34,38–42} our results and those of Taunton would suggest that more injuries occur in younger runners, independent of gender and running experience.

It is also important to note that age is a discriminating variable even after adjusting for total months running. Had no adjustment for experience been made, it would have been impossible to discern if trends observed in age could have explained the differences in injury rate or if the difference was due to the two injured groups having more years of running experience, hence a greater chance of injury.

**Kinematic analysis**

Our kinematic data support the results of Dicharry (2010)\textsuperscript{64}, who defined the joint motion of runners over the entire gait cycle; the values and movement patterns for each joint were similar between the two studies. When comparing joint kinematics in the Never, Occasionally, and Frequently Injured groups, we found that an increase in peak knee flexion angle at heel strike and during stance was associated with greater frequency of injury. At heel-strike the knee is flexed and continues to flex through mid-stance. During this time the quadriceps must eccentrically contract to control motion at the knee, as flexion continues and body weight is lowered on to the supporting limb. This eccentric contraction of the quadriceps produces a large force at the knee joint. By flexing less at heel-strike through stance (sometimes termed quadriceps avoidance\textsuperscript{99}), we suggest that the runners who are injured less frequently place smaller loads on their knee, potentially reducing their risk of developing an overuse injury. Impact forces on the tibia have been shown to increase with knee flexion angle, which have been linked to increased risk of tibial stress fractures\textsuperscript{9,10,101,102}. The lack of a discernable trend in the
hip and ankle kinematics also suggests that the focal point for kinematic risk factors for overuse injuries lies principally with the knee, though this association was found only in the non-dominant leg.

Alternatively, it has been proposed that increasing knee flexion angle is a shock-absorbing mechanism that serves to reduce loads on the lower extremity\textsuperscript{100–102}. By increasing knee flexion, peak vertical ground reaction impact force is reduced, potentially reducing the risk of injury. It is also possible that there is no association between injury frequency and knee flexion angle as a significant association was only found for the non-dominant leg in this study.

**Kinetic analysis**

Our kinetic analysis revealed only one variable that was associated with frequency of injury, peak ankle plantar flexion moment during stance. Greater plantar flexion moments were associated with greater injury frequency. This finding supports our hypothesis that those injured less frequently place smaller loads on their joints than those injured more frequently. As the heel strikes the ground and moves through stance, tibial advancement over the fixed foot (i.e., ankle dorsiflexion) must be controlled eccentrically by a large plantar flexion torque, thus loading both the knee and ankle joints (the triceps surae is a two joint muscle acting to flex the knee and plantar flex the ankle). Over thousands of steps per day, placing additional loads on the joints may contribute to an increased risk of injury. Milner et al (2006) also found that higher loads on the tibia were related to increased risk of injury to the area\textsuperscript{9}. The rest of the kinetic data analyzed including plantar flexion moment on the non-dominant side, however, showed no significant associations. Also, the lack of significant associations with bone-on-bone knee joint forces
suggests that there may be little or no association between lower extremity kinetic variables and an individual’s frequency of injury.

**Anthropometric analysis**

When comparing the anthropometric variables Q-angle and arch-index for the Frequently, Occasionally, and Never-injured groups, we found a significant association between Q-angle and injury history but no association with arch-index. As expected, greater frequency of injury in our participants was associated with greater Q-angles. In 1991, Messier et al. also found Q-angles over 16° to be associated with greater risk of injury in runners. Supporting our hypothesis, greater Q-angles have been hypothesized to place greater loads on the knee joint by predisposing the patella to a lateral deviation as the quadriceps contract, pressing the patella against the lateral femoral condyle instead of moving in the femoral trochlear groove as it does in individuals with a normal Q-angle. Mean Q-angle of the Frequently Injured group closely approached this threshold for injury of 16° proposed by Messier et al. adding additional evidence to support the importance of Q-angle in determining risk factors for overuse injury. This significant association is somewhat tempered by the strength of the relationship; each 1 degree increase in Q angle only increased the odds of being in the lower injured group by 5%.

Results for the arch-index were surprising and do not support our hypothesis that those injured more frequently would have lower arch-indices (higher arch) than those injured less frequently as the literature suggests. The potential mechanism posited in the literature is that a lower arch-index increases the pressure on the foot by reducing the surface area in contact with the ground. These higher pressures, or loads on specific areas, increase the risk of injury to the
lower extremity. Our results are supported, however, by other researchers who found no significant link between arch-index and overuse injury risk\textsuperscript{7,13,20,22–24,32}.

Strength analysis

An analysis of the knee flexors and extensors, ankle dorsiflexors and plantar flexors, as well as hip abductor strength showed no significant associations with injury history. These results do not support our hypothesis that the higher frequency of injury would be associated with less strength. These results also do not support the results of other studies that showed that muscular weakness of the knees, hips, and ankles were risk factors for the development of an overuse injury\textsuperscript{7,22–24,26}. It is important to note, however, that each of these studies that showed a link between injury and strength were retrospective in design and participants were injured at the time of testing. In our study, participants had been free of injury for at least six months prior to testing, which may account for lack of differences in these strength variables. Due to the design of the other studies, it was impossible for them to determine if the muscular weaknesses were the cause of the injury, or if the muscular weaknesses were present as a result of the injury. We speculate that 6 months without any injuries and pain was sufficient time to overcome any muscular deficiencies brought about by previous injury, and highlights the importance of prospective designs when examining the risk factors for overuse injuries. Indeed, our study was unique in that we compared injury incidence over 24 months prospectively with baseline characteristics and previous injury history.

Another plausible reason for the lack of significance in our strength measurements is that the strength ratios between the lower body musculature may be more important than the absolute or relative (to the body) strength of the individual muscles. A study by Finnoff et al. (2011)
found that a greater hip adductor to abductor ratio and hip internal to external rotator ratio was associated with increased risk of overuse injury in high school athletes\textsuperscript{36}. Significant results may have been found in our study by including hip adductor strength in the analysis to determine the strength ratios around the hip, knee, and ankle joint in addition to the individual muscle strength measurement that we have analyzed.

Limitations

The primary limitation of our study was that the analysis was not adjusted for multiple comparisons, increasing our odds of finding significant differences in some of the variables due to random chance alone. This was especially problematic in our study considering the large number of variables that were included in the analysis, taking away from our ability to make firm conclusions.

We did not include rearfoot motion variables in this analysis. Research suggests that rearfoot motion is linked to injury risk in runners and should be included in a study such as this one\textsuperscript{7,15,22,78}. Rearfoot motion variables were collected for the study, however, and results for those variables will be included in the final analysis.

Finally, our study assumes 6 months after clinical symptoms of injury have resolved and the runner is back to running pre-injury mileage, all kinematic, kinetic, anthropometric, and strength variables have returned to pre-injury values, though this may not be the case. It is possible that a previous injury will permanently alter these values, however, our strength data would suggest otherwise.
Our results provide some evidence that less frequently injured runners have characteristics that may lead to reduce stress on lower extremity joints. Alternatively, the relatively weak significant associations and the large number of non-significant relationships could indicate that there are few if any differences that distinguish more and less frequently injured runners. Our analysis could be enhanced by controlling for leg dominance, effectively reducing the number of variables by half, and adding rearfoot motion to list of potential risk factors.

Conclusions

Within the limitations of our study, increased frequency of injury was associated with younger age, greater knee angle at heel-strike and during stance, greater peak ankle plantar flexion torque, and a greater Q-angle. The significance of these results is tempered by the lack of corroborating evidence on the contralateral side, the relative weakness of significant associations, and the many associations that did not reach statistical significance. While there is some evidence that less frequently injured runners have characteristics that may lead to reduce stress on lower extremity joints, taken together, the body of evidence suggests that there are few, if any, significant associations between gait, strength, and anthropometrics and injury frequency. Our results also suggest that running may be a safer activity for older individuals as frequency of injury seems to be attenuated in this population.
References

78. Hamill, J. & Kathleen, K. *Biomechanical basis of human movement.* (Lippincott Williams & Wilkins, 2009).
APPENDIX A: INFORMED CONSENT

The Runners And Injury Longitudinal Study

Stephen Messier, Ph.D., Principal Investigator

INTRODUCTION

You are being asked to take part in this study because you are a runner. The purpose of the study is to determine the differences between runners who sustain any overuse running injury and runners who remain injury-free. This study is being conducted with researchers from Wake Forest University and the United States Army Research Institute of Environmental Medicine (USARIEM). You can expect to be in the study for a minimum of 2 years. Your participation is voluntary. Please take your time to make your decision, and ask the study staff or the study doctor to explain any words or information that you do not understand. You may also discuss the study with your friends and family.

WHY IS THIS STUDY BEING DONE?

Approximately 36 million Americans incorporate running into their exercise routine each year, with 10.5 million running at least 100 days per year. Research has shown that running reduces the threat of some chronic diseases, decreases disability and pain, and lowers healthcare costs. Unfortunately, these benefits can be offset by overuse injuries. Our goal is to determine the differences between runners who sustain any overuse running injury and runners who remain injury-free.

HOW MANY PEOPLE WILL TAKE PART IN THE STUDY?

180 men and women will take part in the study. You may participate in this study if you are a male or female distance runner who has been running a minimum of 5 miles per week for at least 6 months without an overuse running injury that has caused you to reduce or to stop running or to seek medical attention.
You cannot participate in this research if you are currently injured, or have been injured within the last 6 months, run less than five miles per week, or are planning on moving from the area within the next three years.

**WHAT IS INVOLVED IN THE STUDY?**

If you agree to be in the study, the following procedures and tests will be performed:

**Screening Visit One (SV1):** You have come to Reynolds Gymnasium at Wake Forest University for your first screening visit. The study will be described in detail and you will be asked to sign this consent form. You will be given questionnaires to complete including medication use, medical history, injury and training details, and demographics. Your height and weight, and knee and ankle flexibility will be measured. This visit will last approximately 1 hour.

**Screening Visit Two (SV2):** Your medical history and medication usage will be reviewed by the study staff. Your completed questionnaires will be reviewed by the study coordinator. You will perform tests so we can determine your running mechanics and knee strength. The testing session will last approximately 1-1.5 hours and will be performed in the JB Snow Biomechanics Lab in Reynolds Gymnasium of Wake Forest University.

After entrance into the program, you will be asked to notify the study staff of your injury status (injured or not injured) via email every two weeks in the case of no injuries, and within 24 hours if an injury occurs. The study staff will contact you if an injury-positive email is received and will determine whether a medical exam is necessary.

**Follow-up Injury Visit (FUinjury):** If a medical exam is deemed necessary, you will be asked to meet with the study physician, Dr. David Martin, for an assessment. This visit will last approximately 1 hour. Completion of an interim training history form which will document training since the last evaluation will be completed. All runners who sustain an injury will continue to attend follow-up appointments and receive regular follow-up phone calls to assess...
their rehabilitation. Additionally, injured runners will receive one physical therapy visit for running related injury. Further evaluation and treatment must be arranged through your own physician and health insurance provider.

6-month Follow-up Visit (FU6): This visit includes completion of an interim training history, summarizing the runner’s training during the past 6 months, and an appointment with the study coordinator to discuss any training, injury, or potential retention concerns. This visit will last approximately 1 hour.

12-month Follow-up Visit (FU12): This visit is similar to the FU6 visit with the addition of a final training history, final medication use form, and a close-out visit with the study coordinator. All participants will complete this visit which will last approximately 1 hour.

It will be your responsibility to provide or arrange for your own transportation to study visits at your own expense. You will only be asked to come to Wake Forest for the visits previously described. If, at anytime, you wish to discontinue your participation please notify the study coordinator via telephone or in writing.

As part of this research study, you will be videotaped during the walking test. The videotape only records markers that will be placed on your body and does not show a person’s actual face or body.

**HOW LONG WILL I BE IN THE STUDY?**

You will be in the study for about 2 years.

You can stop participating at any time. If you decide to stop participating in the study we encourage you to talk to the investigators or study staff first to learn about any potential health or safety consequences.
**WHAT ARE THE RISKS OF THE STUDY?**

Being in this study involves some risk to you. You should discuss the risk of being in this study with the study staff. The risk of harm or discomfort that may happen as a result of taking part in this research study is not expected to be more than in daily life or from routine physical or psychological examinations or tests. There may be muscle or joint soreness following the physical performance. These symptoms usually subside quickly and are usually not serious. It is possible to have a more serious injury, such as a torn ligament or sprain from these tests. However, these tests will be monitored very closely to provide a high degree of safety for you.

The greatest risk to you is the release of information about your health and private information. Stephen Messier, PhD and his research staff will protect your records so that all your identifying information (name, address, phone number, information in your health record) is kept private. Sometimes, however, sponsors, funders, inspectors from the Army Human Research Protections Office and other government regulatory agencies, and the USARIEM Human Use Review Committee may have to review the research records to make sure that this study is being done correctly and that your rights and welfare are being protected. The chance that this information will be found out by someone else is very small.

You should understand that this is not a waiver or release of your legal rights. You should discuss this issue thoroughly with the principal investigator before you agree to be in this study.

Should any further questions arise concerning your rights on study related injury you may contact the Center Judge Advocate at US Army Medical Research and Materiel Command, (301) 619-7663/2221. Should any study concerns arise you may contact the WFUHS Institutional Review Board 716-4542.
ARE THERE BENEFITS TO TAKING PART IN THE STUDY?

There may or may not be any direct benefit to our participants. We hope the information learned from this study will benefit other people in the future. Participation in this study will provide our participants with close medical attention at no cost. There is no charge for any of the tests included in this study. In addition, each participant will contribute to our knowledge about running injuries and may aid in our attempt to reduce or eliminate the causes associated with them.

WHAT OTHER CHOICES ARE THERE?

You do not have to be in this study to receive treatment. You should talk to your doctor about all the choices you have. The tests and medications provided are available in the community; these usually involve a charge to participants. Instead of being in this study, you have the option of being treated with conventional medical therapy.

WHAT ABOUT THE USE, DISCLOSURE AND CONFIDENTIALITY OF HEALTH INFORMATION?

By taking part in this research study, your personal health information, as well as information that directly identifies you, may be used and disclosed. Information that identifies you includes, but is not limited to, such things as your name, address, telephone number, and date of birth. Your personal health information includes all information about you which is collected or created during the study for research purposes. It also includes your personal health information that is related to this study and that is maintained in your medical records at this institution and at other places such as other hospitals and clinics where you may have received medical care. Examples of your personal health information include your health history, your family health history, how you respond to study activities or procedures, laboratory and other test results, medical images, photographs/videotapes/audiotapes and information from study visits, phone calls, surveys, and physical examinations.
Your personal health information and information that identifies you (“your health information”) may be given to others during and after the study. This is for reasons such as to carry out the study, to determine the results of the study, to make sure the study is being done correctly, to provide required reports and to get approval for new products.

Some of the people, agencies and businesses that may receive and use your health information are the research sponsor; representatives of the sponsor assisting with the research; investigators at other sites who are assisting with the research; central laboratories, reading centers or analysis centers; the Institutional Review Board; representatives of Wake Forest University Health Sciences and North Carolina Baptist Hospital; representatives from government agencies such as the Food and Drug Administration (FDA), the Department of Health and Human Services (DHHS), US Army Medical Research and Materiel Command, and similar agencies in other countries.

Some of these people, agencies and businesses may further disclose your health information. If disclosed by them, your health information may no longer be covered by federal or state privacy regulations. Your health information may be disclosed if required by law. Your health information may be used to create information that does not directly identify you. This information may be used by other researchers. You will not be directly identified in any publication or presentation that may result from this study unless there are photographs or recorded media which are identifiable.

If this research study involves the treatment or diagnosis of a medical condition, then information collected or created as part of the study may be placed in your medical record and discussed with individuals caring for you who are not part of the study. This will help in providing you with appropriate medical care. In addition, all or part of your research related health information may be used or disclosed for treatment, payment, or healthcare operations purposes related to providing you with medical care.

When you sign this consent and authorization form you authorize or give permission for the use of your health information as described in the consent form. You can revoke or take away your
authorization to use and disclose your health information at any time. You do this by sending a written notice to the investigator in charge of the study at the following address:

Stephen P. Messier  
Wake Forest University  
PO Box 7868  
Winston-Salem, NC 27109

If you withdraw your authorization you will not be able to be in this study. If you withdraw your authorization, no new health information that identifies you will be gathered after that date. Your health information that has already been gathered may still be used and disclosed to others. This would be done if it were necessary for the research to be reliable. You will not have access to your health information that is included in the research study records until the end of the study. Laboratory test results and other medical reports created as a result of your participation in the research study may be entered into the computer systems of Wake Forest University Health Sciences and North Carolina Baptist Hospital. These will be kept secure, with access to this information limited to individuals with proper authority, but who may not be directly involved with this research study.

This authorization is valid for five years after the completion of the study.

WHAT ARE THE COSTS?

There are no costs to you for taking part in this study. All study costs, including any study medications and procedures related directly to the study, will be paid for by the study. Costs for your regular medical care, which are not related to this study, will be your own responsibility.
WILL YOU BE PAID FOR PARTICIPATING?

Participants will receive a gift certificate for $50 toward a new pair of running shoes at a local sporting goods store upon completion of the study (i.e., after the FU12 follow-up visit). Also, one treatment session with the study physical therapist will be available as a service to injured participants. The therapist will provide you with a suggested treatment plan. Further care of your injury if you choose to do so will be with a doctor or therapist of your choice and will be your responsibility. The study staff will perform a follow-up call to you monthly to receive an updated on your injury status.

Other than the gift certificate mentioned above, you will receive no payment or other compensation, including reimbursement for gas and/or other travel related expenses, for taking part in this study. The findings from this research may result in the future development of products that are of commercial value. There are no plans to provide you with financial compensation or for you to share in any profits if this should occur.

WHO IS SPONSORING THIS STUDY?

This study is being sponsored by Wake Forest University, Wake Forest University Health Sciences, and US Army Medical Research and Materiel Command. The sponsors are providing money or other support to Wake Forest University Health Sciences to help conduct this study. The researchers do not, however, hold a direct financial interest in the sponsor or the product being studied.

WHAT ARE MY RIGHTS AS A RESEARCH STUDY PARTICIPANT?
Your participation in these procedures is voluntary. You may discontinue participation at any time without penalty. You may choose not to answer any question(s) you do not wish to for any reason. If you have questions now or at any time, you should ask them. If you receive an unsatisfactory answer, you should speak to the Principal Investigator, Dr. Stephen Messier, (336) 758-5849.

If you decide not to participate, this will not influence your opportunities for employment by any branch of Wake Forest University, your future medical care by the staff or Wake Forest University/Baptist Medical Center, or any other relationship(s) you may have with the university. Your decision not to participate or to withdraw will also not affect your current or future relations with the US Army, and you will not be penalized or lose any benefits to which you are otherwise entitled.

**Significant New Findings**

You will be told in a timely manner of any significant new information that might affect your willingness to stay in this study.

**Withdrawal**

- We ask that you follow the directions to the best of your ability.
- If you are unable to do so, or the researchers feel it is best for you to leave the study, the researchers may end your participation in the study even though you might like to continue.
- The researchers may have to withdraw you from the study if you become ill or injured during the research.
- The decision may be made either to protect your health and safety, or because it is part of the research plan that people who develop certain conditions may not continue to participate. The investigator will make the decision and let you know if it is not possible for you to continue.
- If you choose to withdraw from the study before you have completed the study, you will be asked to notify the study staff via phone or e-mail. Once a participant has withdrawn from the study, you will no longer receive study correspondence, and you will no longer be eligible to receive the gift certificate.
WHOM DO I CALL IF I HAVE QUESTIONS OR PROBLEMS?

You have had the opportunity to ask, and have had answered, all of your questions about this research. If you have questions after you have signed this consent, or if you experience a research-related injury or illness, you may contact either Dr. Stephen Messier, the study Principal Investigator at (336) 758-5849, or Jovita Newman, the study coordinator, at (336) 758-3969. In case of an emergency, you should call 911. If you have questions related to research or about your legal rights as a participant please contact the Wake Forest University Health Sciences Institutional Review Board at (336) 716-4542. You may also contact the US Army Research Institute of Environmental Medicine (USARIEM) Office of Research Quality & Compliance (508-233-4803).

You will be given a copy of this signed form to keep for your records and future reference.

YOUR SIGNATURE

We can send copies of your test results to your personal physician. Even if you do not wish to have any of your medical information sent to your physician, you can still participate in this research study.

Do you request that we send important medical findings from your study tests/exams to your personal physician?
[ ] Yes    [ ] No    ___________ Initials

By signing below, you indicate that you are willing to participate in this research project.

___________________________________________________
Subject Name (Printed)

___________________________________________________   ____________________
Subject Signature  Date

___________________________________________________   ____________________
Person Obtaining Consent  Date

______________________
Time
APPENDIX B: PARTICIPANT FLOW

Participant Arrival
- Obtain Informed Consent
  - Participant changes into appropriate clothing
    - Obtain Arch Index
      - Flexibility Testing
        - Obtain Q-angle
          - Strength Testing of Knee
            - Questionnaires
              - Strength Testing of Ankle
                - End Session

Participant Arrival
- Questionnaires
  - Participant changes into appropriate clothing
    - Record Height and Weight
      - Motion Capture of Gait
        - Strength Testing of Hip
          - End Session

Record on Gait Analysis Form
Record on Hip Strength Analysis Form
Record on Strength Analysis Form
### Data Collection and Study Form

<table>
<thead>
<tr>
<th>Measurements (Location if other than HES Dept)</th>
<th>PSV (over phone)</th>
<th>SV1 (WFU)</th>
<th>SV2 (WFU)</th>
<th>EU6 (WFU)</th>
<th>EUinjury (WFU/WFUBMC)</th>
<th>EU12 (WFU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eligibility Questionnaire (f1)</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Contact Form (f2)</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Informed Consent (f12)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Questionnaires

| Medical History (f5)                          | X                |           |           |           |                        |            |
| Medication Form (f4)                         | X                | X         | X         | X         |                        |            |
| Runners’ Training History (f6)               | X                |           |           |           |                        |            |
| Runners’ Injury History (f8)                 | X                |           |           |           |                        |            |
| Interim Training History (f7)                |                  | X         | X         | X         |                        |            |
| Interim Injury History (f11)                 |                  | X         |           | X         |                        |            |
| Injury Report Form (f9)                      |                  |           |           | X         |                        |            |
| Demographics (f3)                            | X                |           |           |           |                        |            |
| PANAS (f19)                                  | X                | X         | X         | X         | X                      |            |
| SWL (f18)                                    | X                | X         | X         | X         | X                      |            |
| SF-12 (f17)                                  | X                | X         | X         | X         |                        |            |
| Run Adherence Efficacy (f21)                 | X                | X         | X         | X         |                        | X          |

#### Physical Exams & Physical Performance Tests

| Anthropometric Evaluation (f13)             | X                |           |           |           |                        |            |
| Flexibility Measurements (f13)              | X                |           |           |           |                        |            |
| Knee/Ankle Strength (f14)*                  | X                |           |           |           |                        |            |
| Gait Analysis (f15)*                         |                  |           |           |           |                        | X          |
| Hip Strength (f16)*                         |                  |           |           |           |                        | X          |
| Physical Exam/Injury Report (f10)            |                  |           |           |           |                        | X          |

#### Radiology/Imaging Tests

| Optional X-ray (Outpatient Imaging)         |                  |           |           |           |                        | X          |
| Optional MRI (Outpatient Imaging)           |                  |           |           |           |                        | X          |

#### Other

| Appointment with Study Physician             |                  |           |           |           |                        | X          |
| Optional PT appointment                      |                  |           |           |           |                        | X          |
APPENDIX C: TESTING

Participants in TRAILS completed several physical performance tests, including gait analysis, strength, flexibility, and anthropometrics. All of the physical performance tests were conducted at baseline. The baseline visit required 2 testing sessions. Reminder letters, instructions, including directions were sent to the participants 1-2 weeks prior to their appointment. Participants were contacted by phone 72 hours prior to the scheduled testing date.

**Anthropometrics**: Anthropometric testing included height and weight, Q-angle, and arch height. Q-angle and arch height were done on the first day of testing prior to the strength testing and height and weight were obtained on the second day of testing prior to gait testing.

**Knee and Ankle Strength Testing**: Participants completed isometric and isokinetic strength testing on their right and left knee and ankle using an isokinetic dynamometer during their first day of testing. Between ankle and knee strength testing participants completed study questionnaires.

**Gait Analysis**: 3D gait analysis was collected to analyze running mechanics at the runners preferred training pace. Gait data was collected during the second baseline visit. Gait data was analyzed using a biomechanical knee model further explained in the following pages.

**Hip Strength Testing**: Participants completed isometric and isokinetic strength testing on their right and left hip during their second visit following the gait analysis.

Performance tests were conducted in the J.B. Snow Biomechanics Laboratory (212 Reynolds Gymnasium) at Wake Forest University. All testing was performed by the same technician. In the event that the technician is unavailable, the testing was conducted by another technician who has been trained by and assisted the technician with previous testing.

The following pages include diagrams showing the order of the performance tests and the flow of the data from collection to processing and statistical analysis. The data was collected on data
collection forms and in various software packages. All processed data was uploaded onto an online database before statistical analyses were performed. All data, raw and processed, were backed up on CDs or external hard drives in a secure office. Data was also be backed up on a secure online folder. Detailed instructions for each of the performance tests are given in subsequent sections.

a. **Overview of Testing Flow**

```
Participant Arrival on 1st Day
  Obtain Informed Consent
  Participant changes into appropriate clothing
  Obtain Arch Index
  Flexibility Testing
  Obtain Q-angle
  Strength Testing of Knee
  Questionnaires
  Strength Testing of Ankle
  End Session

Participant Arrival on 2nd Day
  Questionnaires
  Participant changes into appropriate clothing
  Record Height and Weight
  Motion Capture of Gait
  Strength Testing of Hip
  End Session
```

Record on Gait Analysis Form

Record on Hip Strength Analysis Form

Record on Strength Analysis Form
b. **Overview of data flow for Gait Analysis**

![Data flow diagram for gait analysis](image)

Figure 2. Data flow for gait analysis.
ANTROPOMETRIC MEASUREMENTS

In addition to Quadriceps, hamstring, dorsiflexors, and plantar flexors being tested for flexibility, Q-angle and arch height were also measured. Retrospective studies implicate these variables in overuse running injuries. Height and weight were also measured during the second visit prior to the gait testing.

Procedure:

Height Measurement

1) Participant stands without shoes erect with back to vertically mounted metal ruler (stadiometer) located in the Clinical Research Center.

2) Heels should be together and against the vertical ruler.

3) Participant stands erect with weight distributed evenly across both feet; both feet are flat on the floor.

4) Participant faces forward with his/her head in the Frankfort horizontal plane (the horizontal plane which includes the lower margin of the body orbit (the socket containing the eye), and the most forward point in the supratragal notch (the notch just above the anterior cartilaginous projections of the external ear).

5) Bring the stadiometer square down snuggly but not tightly on the top of the head.

*Note: Examiner should use a stool to adjust the bar and read the measurement when a participant is taller than the examiner. Examiner’s eyes should be level with the point of measurement.

6) Record the measurement to the nearest 0.1cm.

Weight Measurement

1) Ask participant to step onto the scale. Participant should be wearing light clothing only (outer garments, i.e. jackets and coats, removed) with no shoes.

2) Instruct participant to stand in the middle of the platform on the scale with head erect and eyes looking straight ahead.

3) Weight should be equally distributed on both feet unless pain or other orthopedic abnormality inhibits equal weight distribution across both feet.
4) Instruct participant not to touch or support him/herself.

7) With participant standing quietly in the proper position wait until the scale reaches a steady value.

8) Record the weight to the nearest 0.1 kg.

9) Ask the participant to step off of the scale.

Arch Index

1) Have participant remove socks and shoes

2) Get participant weight with both feet on bathroom scale

3) Step off scale with one foot and onto paper that is on top of ink pad until ½ of total bodyweight is on scale

4) On paper with footprint, create an outline of the food (not toes) with pencil

5) Draw a line from the center of the heel through the center of the 2\textsuperscript{nd} toe

6) Divide the total length of the food (excluding toes) into 3rds. Make sure these lines are perpendicular to the vertical line (these 3 separate areas will be referred to as A, B, and C with A being the forefoot, B the midfoot, and C the heel region)

7) Scan image to computer

8) Open ImageJ

9) Using the polygon tool, trace the line you made earlier of the whole foot. You can do this by identifying numerous spots around the foot; Image J will connect all your dots using straight lines to outline the foot.

10) Once you complete your outline, you can move the points small amounts to outline the foot with more precision.

11) Calculate (Analyze \rightarrow measure) and record the area of that region (A+B+C)

12) Using the draw tool again, trace the middle third of the foot and calculate (Analyze \rightarrow measure) and record the area of that region

13) To obtain arch index, divide the area of the middle 3\textsuperscript{rd} by the area of the whole foot : \( AI = \frac{B}{(A+B+C)} \)
14) Repeat steps 9-13 until you have 3 measures on each foot. Take the average of the 3 measures to yield a representative value for each foot.

**Quadriceps Angle (Q-Angle)**

1) Have participant stand with shoes off and feet in a neutral position (foot placement standardized using template taped to floor).

2) Place a small dot in the center of a 3/4" inch circle markers and place one in the center of the patella, one on the tibial tuberosity, and one on the anterosuperior iliac spine (mark both legs).

3) A digital camera should be placed 5 feet from the participant at a height of 2 feet so it is centered at mid-thigh. A level should be used to ensure horizontal alignment of the lens both superiorly and inferiorly. One picture should then be taken ensuring all markers on both legs are visible.

4) Open picture using ImageJ (Image Processing and Analysis in Java 1.43). Using the angle tool draw a line from the dot at the anterosuperior iliac spine to the middle of the patella and then to the mark on the tibial tuberosity.

5) Go to Analyze --> Measure to obtain the angle

6) Subtract the angle given from 180 to obtain the Q angle

7) Repeat steps 4-6 and take an average of the 3 trials on each leg to yield a representative value for each limb.
References

STRENGTH MEASUREMENTS

Testing Instructions for the Knee

1) Turn KinCom on and move chair seat to side you want to test first

2) Go to main menu. Select KinCom then Evaluation

3) Either select existing or F2 for new patient

4) Screen should display joint being tested (knee), side (left or right), muscle group (ext/flex). If this needs to be changed, select Re-do and enter correct information.

5) Select Gravity Compensation. Lift lever with patient’s leg unattached, let go, hit Enter.

6) Select Isometric, or if past participant, select New Test then select Isometric.

7) Participants are positioned sitting (back supported) with hip flexed to approximately 100 degrees. Stabilizing straps are placed across the shoulders, pelvis, and distal thigh of the testing leg. During testing the participant’s hands will remain in his or her lap

8) After strapping patient in, align lever arm axis with joint center. This is accomplished by adjusting the seat height and table top. The resistance pad at the end of the lever arm is placed approximately 2 finger widths above the malleoli. Record seat height, table top length and lever arm length.

9) Enter lever arm length and press Enter

10) Select starting position. Place knee joint at 90 degrees and press enter. Type in 90 and press enter. To move joint positive, move leg backwards (so participant flexes slightly) and hit enter.

11) For gravity Comp, lift patients leg to about 30 degrees and hit enter. Next, release leg and hit enter at the same time. Instruct participant to relax completely. Either re-do or hit enter to accept.
Isometric Testing

Isometric testing was performed for the knee extensors and flexors in the approximate position where the force production was greatest based on the length-tension curve. This was approximately 75 degrees of knee flexion for the knee extensors (quadriceps) and 30 degrees of knee flexion for the knee flexors (hamstrings) (1,2).

12) To test extensors, set the stop angle at 70 degrees and hit Enter.

13) Set the start angle to 75 degrees and hit Enter. Hit S first to set angle then hit enter.

14) Once you press Enter to get to the testing screen, select Change, select Force Limits, select Isometric Settings. Select Contraction time to change it to 3 seconds.

15) Make sure direction is correct when force is applied. If not, gravity comp or the positive direction may have been done incorrectly.

16) Give participant instructions to push forward as hard and as fast as they can until you say stop. Hit enter and instruct participant to go. After trial is complete, record the maximum value. Save and repeat. Get 2-3 good trials.

17) Next, hit Esc to end test. Hit Esc again to end test. Select new test. Select Isometric and repeat steps 1-5 except testing flexors by making the stop angle 35 degrees and the start angle 30 degrees and instruct patient to pull backwards as hard and as fast as they can.

Isokinetic Testing (After Esc out of Isometric testing, select New Test, and select Isokinetic, Type of test Overlay)
18) Enter lever arm length and press Enter

19) Select starting position. Place knee joint at 90 degrees and press enter. Type in 90 and press enter. To move joint positive, move leg backwards (so participant flexes slightly) and hit enter.

20) Set Stop Angle at 30 degrees.

21) Set Start Angle at 90 degrees.

22) Once to testing screen, select Change, select Speed Limits. Select CON/CON.

23) Hit F to change the Speed Forward to 60. Hit B to change the Speed Backward to 60.

24) Select Change. Select Force Limits. Select Forward Force and enter in 50% of the max extensors force during the isometric test at 75 degrees. Select Backwards Force and enter in 50% of the max flexors force during the isometric test at 30 degrees.

25) Make sure direction is correct when force is applied. If not, gravity comp or the positive direction may have been done incorrectly.

26) Give participant instructions to push forward as hard and as fast as they can until you stay stop. Tell them the machine is going to begin to move up with their leg. Hit enter and instruct the participant to go. Next, give the participant instructions to pull back as hard and as fast as they can until you say stop. Hit enter and instruct participant to go.

27) Give participant 20 second- 1 minute rest between trials or longer if necessary. Repeat test. After the 2nd test you will be give the option to keep the current test. Select Yes. You will then be given the option to keep the previous test. Select No.

28) Hit Save after one trial has been performed for both the extensors and flexors.

29) Perform no more than 6 trials before quitting.

30) Change legs and repeat both isometric and isokinetic testing. Move the load cell to the other side before change any settings on the CPU, otherwise gravity compensation is reversed.

Testing Instructions for the Ankle

1) Go to main menu. Select KinCom then Evaluation

2) Either select existing or F2 for new patient
3) Screen should display joint being tested (ankle), side (left or right), muscle group (plantar flexion/dorsiflexion). If this needs to be changed, select Re-do and enter correct information. Make sure that the ankle attachment is attached to the load cell before going onto gravity compensation.

4) Select Gravity Compensation. Lift lever with patient’s leg unattached, let go, and hit Enter.

5) Select Isometric, or if past participant, select New Test then select Isometric.

6) Participants are positioned sitting (back supported) with hip flexed to approximately 100 degrees. Patient’s leg should be fully extended to 180 degrees. Stabilizing straps are placed across the shoulders, pelvis, and distal thigh of the testing leg. During testing the participant’s hands will remain in his or her lap

7) After strapping patient in, align lever arm axis with joint center. This is accomplished by adjusting the seat height and table top. Be sure that the ankle piece for the KinCom is securely fastened around the foot. Record seat height, table top length and lever arm length. Enter lever arm length and press Enter

8) Select starting position. Place ankle joint at 110 degrees (anatomical position) and press enter. Type in 110 and press enter. To move joint positive, plantar flex the foot slightly (so toe points) and hit enter.

9) For gravity Comp, lift patients foot to about 90 degrees and hit enter. Next, release foot and hit enter at the same time. Instruct participant to relax completely Either re-do or hit enter to accept.
**Isometric Testing**

Isometric testing was performed for the planarflexors and dorsiflexors from anatomical position where the force production was greatest based on the length-tension curve.

10) To test plantar flexors, set the stop angle at 115 degrees and hit Enter.

11) Set the start angle to 110 degrees and hit Enter. Hit S first to set angle then hit enter.

12) Once you press Enter to get to the testing screen, select Change, select Force Limits, select Isometric Settings. Select Contraction time to change it to 3 seconds.

13) Make sure direction is correct when force is applied. If not, gravity comp or the positive direction may have been done incorrectly.

14) Give participant instructions to push their toe forward as hard and as fast as they can until you say stop. Hit enter and instruct participant to go. After trial is complete, record the maximum value. Save and repeat. Get 2-3 good trials.

15) Next, hit Esc to end test. Hit Esc again to end test. Select new test. Select Isometric and repeat steps 1-5 except testing dorsiflexors by making the stop angle 105 degrees and the start angle 110 degrees and instruct patient to pull their toe back as hard and as fast as they can.

**Isokinetic Testing** (After Esc out of Isometric testing, select New Test, and select Isokinetic, Type of test Overlay)

16) Enter lever arm length and press Enter.

17) Select starting position. Place ankle joint at 110 degrees and press enter. Type in 110 and press enter. To move joint positive, plantar flex the foot slightly (so toe points) and hit enter.

18) Set Stop Angle at 145 degrees.

19) Set Start Angle at 100 degrees.

20) Once to testing screen, select Change, select Speed Limits. Select CON/CON.

21) Hit F to change the Speed Forward to 60. Hit B to change the Speed Backward to 60.

22) Select Change. Select Force Limits. Select Forward Force and enter in 50% of the max planarflexors force during the isometric test at 110 degrees. Select Backwards Force...
and enter in 50% of the max dorsiflexors force during the isometric test at 110 degrees.

23) Make sure direction is correct when force is applied. If not, gravity comp or the positive direction may have been done incorrectly.

24) Give participant instructions to push their toe forward as hard and as fast as they can until you say stop. Tell them the machine is going to begin to move forward with their foot. Hit enter and instruct the participant to go. Next, give the participant instructions to pull their toe back as hard and as fast as they can until you say stop. Hit enter and instruct participant to go.

25) Give participant 20 second- 1 minute rest between trials or longer if necessary. Repeat test. After the 2nd test you will be given the option to keep the current test. Select Yes. You will then be given the option to keep the previous test. Select No

26) Hit Save after one trial has been performed for both the extensors and flexors.

27) Perform no more than 6 trials before quitting.

28) Change legs and repeat both isometric and isokinetic testing. Move the load cell to the other side before change any settings on the CPU, otherwise gravity compensation is reversed.

Testing Instructions for the Hip: Abduction

1) Go to main menu. Select KinCom then Evaluation

2) Either select existing or F2 for new patient

3) Screen should display joint being tested (hip), side (left or right), muscle group (abduction). If this needs to be changed, select Re-do and enter correct information. You will need to attach the extension piece to the lever arm before going on to gravity compensation.

4) Select Gravity Compensation. Hit enter to turn on.

5) Select Isometric, or if past participant, select New Test then select Isometric. Participants are positioned supine with legs fully extended. Stabilizing straps are placed across the torso and contralateral limb strapped to the testing chair, hands across chest.

6) After strapping patient in, align lever arm axis with the greater trochanter. This is accomplished by adjusting the seat height and table top. The resistance pad at the end of the lever arm is placed approximately 2 finger widths below the knee (distal to the knee joint). Record seat height, table top length and lever arm length.
7) Enter lever arm length and press Enter. Be sure to add on the distance of the extension lever arm as well.

8) Select starting position. Place hip at anatomical 0 degrees and press enter. Type in 0 and press enter. To move joint positive, move leg outwards (so participant abducts slightly) and hit enter.

9) For gravity Comp, bring patients leg out to side so it is hanging off the seat and hit enter. Next, bring the leg back to neutral so the screen reads as close to zero as possible (no more than 3) and press enter. Either re-do or hit enter to accept.

Isometric Testing

10) To test abductors, set the stop angle at 5 degrees and hit Enter.

11) Set the start angle to 0 degrees and hit Enter. Hit S first to set angle then hit enter.

12) Once you press Enter to get to the testing screen, select Change, select Force Limits, select Isometric Settings. Select Contraction time to change it to 3 seconds.

13) Make sure direction is correct when force is applied. If not, gravity comp or the positive direction may have been done incorrectly.

14) Give participant instructions to push their leg out or away from their body as hard and as fast as they can until you say stop. Hit enter and instruct participant to go. After trial is complete, record the maximum value. Save and repeat. Get 2-3 good trials.

15) Next, hit Esc to end test. Hit Esc again to end test.
Isokinetic Testing (After Esc out of Isometric testing, select New Test, and select Isokinetic, Type of test Overlay)

16) Enter lever arm length and press Enter

17) Select starting position. Place knee joint at 0 degrees and press enter. Type in 0 and press enter. To move joint positive, move leg outwards (so participant abducts slightly) and hit enter.

18) Set Stop Angle at 30 degrees.

19) Set Start Angle at 0 degrees.

20) Once to testing screen, select Change, select Speed Limits. Select CON/CON.

21) Hit F to change the Speed Forward to 60. Hit B to change the Speed Backward to 60.

22) Select Change. Select Force Limits. Select Forward Force and enter in 50% of the max abductors force during the isometric test at 75 degrees. Select Backwards Force and enter in 0.

23) Make sure direction is correct when force is applied. If not, gravity comp or the positive direction may have been done incorrectly.

24) Give participant instructions to push outwards or away from their body as hard and as fast as they can until you stay stop. Tell them the machine is going to begin to move out with their leg. Hit enter and instruct the participant to go. Next, press enter and bring the participants leg back to starting manually.

25) Give participant 20 second- 1 minute rest between trials or longer if necessary. Repeat test. After the 2nd test you will be give the option to keep the current test. Select Yes. You will then be given the option to keep the previous test. Select No

26) Hit Save after one trial has been performed

27) Perform no more than 6 trials before quitting.

28) Change legs and repeat both isometric and isokinetic testing. More the load cell to the other side before change any settings on the CPU, otherwise gravity compensation is reversed.

Kin Com Saving Instructions (to be done for knee, ankle, and hip)

*There are 2 ways to save data. It is important to do both

Saving to diskette
1) From main menu. Select KinCom. Select Utilities. Select System Utilities

2) Select Copy Data

3) All files will be uploaded onto computer. Once finished select files you want to save by pressing enter. Hit Copy to put onto disk.

Saving as an ASCII or text file

1) From main menu. Select KinCom. Select Reports. Select Overlay or Isometric. Select Standard Report

2) Select Patient Name. Select Date Tested.

3) Scroll to the test you want to look at and Select Stats.

4) Select ASCII Data. Select File. Name file (you can only use up to 8 characters) type a:(name) Hit enter. For the isometric data the real time gravity will show up. Hit enter to begin the save. The output will be torque measured in Nm.

5) Once finished hit esc. Once on the Trial list screen repeat steps.

Kin Com Important Notes

1) The gravity compensation and setting the positive direction are important. If done incorrectly the Kin Com may not go in the correct direction.

2) Under system utilities you can set the date/time, erase data files, etc.

3) It is important to back up all data files once the Kin Com has too many files (this is when the KinCom is around 70-75% free.) You will be unable to back up files without (except in DOS Mode) erasing some patient files. If it has to be done in DOS mode you will only see the file #. You will have to erase some files in order to keep this from happening. If the Kin Com has too many files in addition to not being able to save the system may crash as well, causing you to lose some data.

4) Once files have been erased you will need to go to Database Utilities, to rebuild the database. This is a timely procedure.

5) To view data. From main menu. Select KinCom. Select Reports. Select Overlay or Isometric. Select From main menu. Select KinCom. Select Reports. Select Overlay or Isometric. Select Standard Report Standard Report to see one test or Compare Reports to see comparison. Select Patient Name. Select Date Tested. Scroll to the test you want to look at and press enter
6) When saving the data in ASCII mode you can only use up to 8 characters. After saving onto a disk you can transfer to a computer and rename the file using the format below.

The first four digits will represent the subject # (i.e. 1234)

The next (5th) digit will represent the leg being tested.

R will be for the right leg

L will be for the left leg

The next (6th) digit will represent the joint being tested

K will be the knee

A will be the ankle

H will be the hip

The next (7th) digit will represent the contraction type

0 will be for concentric contractions

1 will be for isometric contractions of the knee extensors at 75 degrees of flexion, ankle plantar flexors, or hip abductors

2 will be for isometric contractions of the knee flexors at 30 degrees of flexion, or the ankle dorsiflexors

The final (8th) digit will represent the trial number.

The file 1234RK01 would contain the concentric contraction data from the first trial for the right knee of subject 1234

The file 1234LA21 would contain the first trial of the isometric data for the left ankle dorsiflexors of subject 1234.

*In the ASCII files for concentric contractions, the top set of data is for the knee extensors and the bottom set of data is for the knee flexors.
7) The ascii files will need to be converted to .csv files for uploading onto the online database. The files will have the same name format as above with the extension _con.csv for concentric files, _flex.csv for isometric flexion files, and _ext.csv for isometric extension files.

8) If you wish to only do the isokinetic testing and not the isometric. To get the force limits after changing the speed limits and going to the main screen. Have the participant push/pull (depending on direction you are testing) as hard as the can. You will have to watch the forces displayed on the right side of the screen. Under force limits change the value to 50% of the value you observed. Then you can begin the test. You will have to do this again at the stop angle as well.

References:


GAIT MEASUREMENT

Gait analysis included examination of rearfoot biomechanics (including touchdown angle, maximum pronation angle, total rearfoot motion, velocity of pronation) and knee joint loads. Subjects ran in their normal training shoes at their average (± 3.5%) training speed on a 22.5 m runway while motion and force data was captured. A 33-reflective marker set, arranged in the Cleveland Clinic full-body configuration was attached to runners. An additional 15 markers were placed on the rearfoot and shank to calculate 3D rearfoot motion as well as additional markers on the pelvis to track pelvis motion. We obtained 3-D temporal/spatial and kinematic gait data using a 6-camera Motion Analysis System (see Figure 1) set to sample data at 200 Hz. Kinematic data which were collected, tracked, edited, and smoothed, using EVaRT 4.6 software (Motion Analysis Corp, Santa Rosa, CA), and a Butterworth lowpass filter with a cut-off frequency of 6 Hz on a PC (Gateway GT5220, Gateway, Inc., Irvine, CA).

The smoothed video-coordinate data, ground reaction, gravitational, and inertial forces provided input data to calculate temporal and lower extremity kinematic and kinetic variables using Orthotrak 6.0 β4 clinical gait analysis software (Motion Analysis Corp, Santa Rosa, CA) and Kintrak software (Version 6.2, Motion Analysis Corp, Santa Rosa, CA). Outcome variables included rearfoot motion parameter (subtalar inversion-eversion, time to maximum eversion and inversion, total eversion range of motion, and maximum eversion and inversion velocity), tibial medial/lateral rotation, knee flexion/extension, timing between lower extremity segments, and vertical and anteroposterior ground reaction forces.

A 6-channel force platform (OR6-5-1, Advanced Mechanical Technologies, Inc., Newton, MA) was integrated with the motion capture system and allowed simultaneous kinetic data collection at 480 Hz. Three acceptable trials for each side were averaged to yield representative values. In an acceptable trial, the runner ran within normal training pace and contacted the force platform
with the appropriate foot in normal stride. Running speed was recorded and monitored by a Lafayette Model 63501 photoelectric control system interfaced with a digital timer with photocells positioned 4.0 m apart. The smoothed coordinate data, ground reaction, and gravitational and inertial forces informed an inverse dynamics model to calculate 3-D hip flexion, extension, abduction, adduction, internal rotation, and external rotation; knee flexion, extension, abduction, internal rotation, and external rotation; and ankle plantar flexion moments. Knee-joint forces were calculated using a model developed by DeVita et al. (1; 3; 4). We have successfully applied this model to healthy and OA subjects (1); finding ranges (2.8 - 6.0 BW) similar to those of previous studies (2; 5). A description of the knee model is at the end of this section.


Figure 1. Diagram of the Data Collection System. There are 6 cameras (Eagle/Hawk, Motion Analysis Corporation, Santa Rosa, CA) surrounding a 22.5 meter walkway with a 6-channel force platform (OR6-5-1, Advanced Mechanical Technologies, Inc., Newton, MA) embedded in the center. The cameras are connected to a central hub (EagleHub2, Motion Analysis Corporation, Santa Rosa, CA) which is connected to the data collection computer (Gateway GT5220, Gateway, Inc., Irvine, CA). The force platform is connected to an amplifier (SGA6-4, Advanced Mechanical Technologies, Inc., Newton, MA) where the signal is amplified and sent to the data collection computer. The data collection computer simultaneously stores the kinetic data from the force platform with the kinematic data received from the 6 cameras using EVaRT 4.6 software (Motion Analysis Corporation, Santa Rosa, CA).
Gait Instructions

Calculating Gait Speed

Participants training speed was obtained via the questionnaires taken during SV1. Each method was followed by an accompanying oral dialogue which presents guidelines for testing procedures.

The speed during testing was monitored using an infrared photocell control system (Model 63501 IR, Lafayette Instrument Co., Lafayette, IN) set 3.4 m apart at waist level interfaced with digital timers (Model 54035, Lafayette Instrument Co., Lafayette, IN). A trial consisted of starting off the platform and running up the ramp onto the platform in order to get up to speed behind the initial timer and running past the first beam of light to activate the timer. As the participant ran past the second beam of the light the timer stopped and the time was recorded. The participant returned to the starting location and repeated the trial.

“We will use these digital timers to monitor your running speed. During testing you will need to start at this arrow, and then run up the ramp and onto the walkway and run down to the arrow on the opposite end. You should run at your normal training pace. I may tell you to slow down or speed up until you get into that pace. Make sure that you maintain this pace the entire way down the runway. Once at the other end please stop and return back to the start. Each time you reach the beginning of the runway please wait until I ask you to begin.”

1) From their reported training speed (min/mile), calculate a range of plus/minus 3.5%. The spreadsheet testingspeed_3.4m.xls located on the data collection computer will have the
computed average, range, and speed for you (see figure below). The file is a convenient way to compute the values quickly. The testing speeds and ranges should be recorded on the gait testing sheet.

<table>
<thead>
<tr>
<th>pace per mile</th>
<th>speed (s)</th>
<th>testing range</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-3.50%</td>
<td>+3.50%</td>
</tr>
<tr>
<td>4:30 13.33</td>
<td>0.5704</td>
<td>0.5505 0.5904</td>
</tr>
<tr>
<td>4:45 12.63</td>
<td>0.6021</td>
<td>0.5810 0.6232</td>
</tr>
<tr>
<td>5:00 12.00</td>
<td>0.6338</td>
<td>0.6116 0.6560</td>
</tr>
<tr>
<td>5:15 11.43</td>
<td>0.6655</td>
<td>0.6422 0.6888</td>
</tr>
<tr>
<td>5:30 10.91</td>
<td>0.6972</td>
<td>0.6728 0.7216</td>
</tr>
<tr>
<td>5:45 10.43</td>
<td>0.7289</td>
<td>0.7034 0.7544</td>
</tr>
<tr>
<td>6:00 10.00</td>
<td>0.7606</td>
<td>0.7339 0.7872</td>
</tr>
<tr>
<td>6:15 9.60</td>
<td>0.7922</td>
<td>0.7645 0.8200</td>
</tr>
<tr>
<td>6:30 9.23</td>
<td>0.8239</td>
<td>0.7951 0.8528</td>
</tr>
<tr>
<td>6:45 8.89</td>
<td>0.8556</td>
<td>0.8257 0.8856</td>
</tr>
<tr>
<td>7:00 8.57</td>
<td>0.8873</td>
<td>0.8563 0.9184</td>
</tr>
<tr>
<td>7:15 8.28</td>
<td>0.9190</td>
<td>0.8868 0.9512</td>
</tr>
<tr>
<td>7:30 8.00</td>
<td>0.9507</td>
<td>0.9174 0.9840</td>
</tr>
<tr>
<td>7:45 7.74</td>
<td>0.9824</td>
<td>0.9480 1.0168</td>
</tr>
<tr>
<td>8:00 7.50</td>
<td>1.0141</td>
<td>0.9786 1.0496</td>
</tr>
<tr>
<td>8:15 7.27</td>
<td>1.0458</td>
<td>1.0092 1.0824</td>
</tr>
<tr>
<td>8:30 7.06</td>
<td>1.0775</td>
<td>1.0397 1.1152</td>
</tr>
<tr>
<td>8:45 6.86</td>
<td>1.1091</td>
<td>1.0703 1.1480</td>
</tr>
<tr>
<td>9:00 6.67</td>
<td>1.1408</td>
<td>1.1009 1.1808</td>
</tr>
<tr>
<td>9:15 6.49</td>
<td>1.1725</td>
<td>1.1315 1.2136</td>
</tr>
<tr>
<td>9:30 6.32</td>
<td>1.2042</td>
<td>1.1621 1.2464</td>
</tr>
<tr>
<td>9:45 6.15</td>
<td>1.2359</td>
<td>1.1927 1.2792</td>
</tr>
<tr>
<td>10:00 6.00</td>
<td>1.2676</td>
<td>1.2232 1.3120</td>
</tr>
<tr>
<td>10:15 5.85</td>
<td>1.2993</td>
<td>1.2538 1.3448</td>
</tr>
<tr>
<td>10:30 5.71</td>
<td>1.3310</td>
<td>1.2844 1.3776</td>
</tr>
<tr>
<td>10:45 5.58</td>
<td>1.3627</td>
<td>1.3150 1.4104</td>
</tr>
<tr>
<td>11:00 5.45</td>
<td>1.3944</td>
<td>1.3456 1.4432</td>
</tr>
<tr>
<td>11:15 5.33</td>
<td>1.4260</td>
<td>1.3761 1.4760</td>
</tr>
<tr>
<td>11:30 5.22</td>
<td>1.4577</td>
<td>1.4067 1.5088</td>
</tr>
<tr>
<td>11:45 5.11</td>
<td>1.4894</td>
<td>1.4373 1.5416</td>
</tr>
<tr>
<td>12:00 5.00</td>
<td>1.5211</td>
<td>1.4679 1.5744</td>
</tr>
</tbody>
</table>

2) Once you begin the actual testing portion all good trials need to be within this average. If not, have the participant slow down or speed up in order to get the speed you want.
Motion Capture

1) Have participant change into appropriate clothing and shoes and explain procedures about to be performed (participants will remain in their own shoes they use most frequently when running). The participant will be informed ahead of time to bring close fitting shorts to wear during testing to minimize marker movement. If not, shorts and tight fitting shirts will be provided. They may change in Reynolds Gymnasium 212F if needed.

“We would like for you to change into the clothing that you will be wearing during testing. You may keep your own shoes on, however, we may need to cover some of the reflective parts of your shoe with tape. We will then place reflective markers on various anatomical landmarks so we can track your movements. The cameras that you see mounted on the wall surrounding the runway are infrared cameras which detect only the makers. There is no video of your face or body, only of these markers. It is important that you do not touch or move these markers during the testing period. If a marker falls off or moves please inform us and we will replace it. In order to place the markers in the correct positions, I will need to feel around a bit and at times press down hard to locate the right landmark. If I hit a sport that is tender or if you feel uncomfortable, please let me know.

2) Put the markers on using the Cleveland Clinic full-body marker set plus the additional markers to track rearfoot motion. See figure 2. Refer to OrthoTrak reference Manual Chapter 7 for details. The participants’ foot length and width will be measured at this time and recorded on the Gait Analysis Data Collection Form. The length will be measured as the distance from the back of the heel to the front of the toe. The width will be taken as the distance between the 1st and 5th metatarsal heads.
<table>
<thead>
<tr>
<th>Description</th>
<th>Eva/EVaRT Marker Name</th>
<th>Full Body – Run</th>
<th>Full Body Static</th>
<th>Placement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left Lateral Knee</td>
<td>L. Knee Lateral</td>
<td>X</td>
<td>X</td>
<td>Along the flexion/extension axis of rotation on lateral femoral condyle</td>
</tr>
<tr>
<td>Right Lateral Knee</td>
<td>R. Knee Lateral</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left Medial Knee</td>
<td>L. Knee Medial</td>
<td></td>
<td>X</td>
<td>Along the flexion/extension axis of rotation on medial femoral condyle</td>
</tr>
<tr>
<td>Right Medial Knee</td>
<td>R. Knee Medial</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left Lateral Ankle</td>
<td>L. Ankle Lateral</td>
<td>X</td>
<td>X</td>
<td>Along the flexion/extension axis of rotation on lateral malleolus</td>
</tr>
<tr>
<td>Right Lateral Ankle</td>
<td>R. Ankle Lateral</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left Medial Ankle</td>
<td>L. Ankle Medial</td>
<td>X</td>
<td>X</td>
<td>Along the flexion/extension axis of rotation on medial malleolus</td>
</tr>
<tr>
<td>Right Medial Ankle</td>
<td>R. Ankle Medial</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper L. Thigh Array Front L.</td>
<td>L. Thigh Upper</td>
<td>X</td>
<td>X</td>
<td>On the lower thigh below the mid-point, for best visibility by all cameras</td>
</tr>
<tr>
<td>L. Thigh Front</td>
<td>L. Thigh Front</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rear L. Thigh Array</td>
<td>R. Thigh Upper</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper R. Thigh Array Front R.</td>
<td>L. Thigh Rear</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L. Thigh Front</td>
<td>R. Thigh Front</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rear L. Thigh Array</td>
<td>R. Thigh Rear</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper L. Shank Array</td>
<td>L. Shank Upper</td>
<td>X</td>
<td>X</td>
<td>On the lower shank below the mid-point, for best visibility by all cameras</td>
</tr>
<tr>
<td>Front L. Shank Array</td>
<td>L. Shank Front</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rear L. Shank Array</td>
<td>R. Shank Upper</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper R. Shank</td>
<td>R. Shank Front</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Array</td>
<td>R. Shank Rear</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Array</td>
<td>Front R. Shank Array</td>
<td>Rear R. Shank Array</td>
<td></td>
<td></td>
</tr>
<tr>
<td>--------------</td>
<td>----------------------</td>
<td>---------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Left Toe</strong></td>
<td>L. Toe</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Right Toe</strong></td>
<td>R. Toe</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Left Heel</strong></td>
<td>L. Heel</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Right Heel</strong></td>
<td>R. Heel</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Left ASIS</strong></td>
<td>L. ASIS</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Right ASIS</strong></td>
<td>R. ASIS</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Sacro</strong></td>
<td>V. Sacral</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Left Scapula</strong></td>
<td>L. Scapula</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Left Shoulder</strong></td>
<td>L. Shoulder</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Right Shoulder</strong></td>
<td>R. Shoulder</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Left Elbow</strong></td>
<td>L. Elbow</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Right Elbow</strong></td>
<td>R. Elbow</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Left Wrist</strong></td>
<td>L. Wrist</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Right Wrist</strong></td>
<td>R. Wrist</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Additional Markers to be used for KinTrak and pelvis motion</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Right Femur</strong></td>
<td>R. Femur</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Left Tibia</strong></td>
<td>L. Tibia</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Right Tibia</strong></td>
<td>R. Tibia</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Lower Left Heel</strong></td>
<td>L. Heel.Lower</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Lower Right Heel</strong></td>
<td>R. Heel.Lower</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Left Pelvis</strong></td>
<td>Pelvis</td>
<td>X</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Center of the foot between the 2nd and 3rd metatarsals

Posterior Calcaneus at same height from floor as toe marker

Anterior Superior Iliac Spine

Superior Aspect of the L5-sacral interface

Inferior Aspect of the Scapula

Tip of the Acromion Process

Lateral Epicondyle of the Humerus

Centered between the styloid processes of the Radius and Ulna

On the midthigh along the femur

Left tibia on the upper third of the tibia; Right tibia on the lower third

Located directly under the heel mark, above the midsole of the shoe

Left Posterior Superior Iliac Spine
3) Have participant go to the force plate and turn to face camera 2. Place any static markers on that may have fallen off. Have participants stand with their arms extended out and legs apart.

4) Record for approximately 10 seconds when all markers are visible.

5) Once finished, remove the medial static makers. Load the “run” project file. Type in file name ‘run-pose’. Have participant stand again and record again. When finished, click ‘load last capture’ and use QuickID to make a model for that participant.

6) Once completed, click ‘Create Template’. Check the current box and ask to include the current frame. Click create template.

7) Click the motion capture tab and then check the identifying ticker. The subject should appear on the screen.

8) Have participant go to the starting point. Name file to subID_run. Check the auto-increment box to add trial numbers onto the end. The trial number will match the number on the data collection form. This form is used to keep track of the good and bad trials, as well as which foot strikes the forceplate. It is essential that these trial numbers match.

9) Instruct participant to run naturally to the opposite end without looking down and trying to aim for forceplate

10) After each trial, have participant return to starting point so they are always running towards camera 2.

11) After good trials, click ‘load last capture’ to ensure marker set is good and that participant fully struck forceplate.

12) Collect a total of 6 good trials (3 for left leg and 3 for right) where the participant struck the forceplate without altering their gait and maintained their reported training speed. On a recording sheet, you must record which trials are good and which foot hit the plate in order to make post processing easier.

Revert to EVaRT chapter 7 for further details.
Using Orthotrak

Orthotrak was used to calculate joint kinematics and kinetics. The forces and moments were first calculated from the global reference frame (lab coordinate system) and then rotated to the segment coordinate system so the final forces and moments output were relative to the segment coordinate system.

Using Excel and QuickBasic

Data Processing Instructions - 3D Model (Includes Frontal Plane Torques)

Data processing included two basic procedures:

1) Processing the static triads for left and right limbs (one trial for both limbs)
2) Processing running trials for left and right limbs (several trials for each limb)

Processing static trials

This describes how to use the Triad Eval spreadsheet

1) The purpose of this worksheet is to produce values used to predict knee and ankle sagittal plane positions from Orthotrak running trials.
2) This file assesses the planar relationships between the thigh triads and the knee joint and the leg triads and the ankle joint.
3) The analysis consists of producing predictors for the knee and ankle joint positions from the triads by:
   a. Assessing the angular relationship between a line from two of the three triads and a line from one of these triads to the knee or ankle joint.
   b. Assessing the distance between this particular triad and the knee or ankle joint.
   c. These two values represent polar coordinates of the knee or ankle in relation to the position of the particular triad.
   d. The process is repeated for all three possible combinations of two of the triads.
   e. The predictors are all then used with the actual trial data to predict joint position
   f. The position of each joint is predicted three times and averaged.
4) This file also graphs the sagittal plane view of the triads and knee and ankle joints and the positions of the triads during the calibration phase. These graphs may need some adjustment in their horizontal and vertical scales.

QuickBasic

1) The program will run and produce a .txt file containing the shear, compressive, and resultant forces for the knee, the patella-femoral compressive force, and the hamstring, quadriceps, and gastrocnemius muscle forces for each trial.

KinTrak

1) The program will give rearfoot motion data.

Reliability Testing

In order to ensure that the data collected was accurate each tester repeated the data collection visit to ensure that the results were reliable. This test/retest reliability was performed on up to 10% of the study population. In addition if a new staff member or graduate student assisted in the data processing intratester reliability was measured with the current data processor.
Biomechanical knee model

The biomechanical model of the knee calculated compressive, anterior-posterior shear, and resultant joint forces within the tibio-femoral compartment of the knee joint. The model included two basic components. The first component was a three dimensional inverse dynamics analysis of the lower extremity to obtain the joint torques and reaction forces at the hip, knee, and ankle. The second component used these results along with the kinematic description of the person’s lower extremity and related anatomical and physiological characteristics to calculate knee muscle, lateral ligament, and joint forces during the stance phase of running.

The lower extremity was modeled as a rigid, linked segment system. Magnitude and location of the segmental masses and mass centers in the lower extremity along with their moments of inertia were estimated from the position data using a mathematical model (10), relative segmental masses reported by Dempster (3), and the individual subject's anthropometric data. Inverse dynamics using linear and angular Newtonian equations of motion were used to calculate the joint reaction forces and torques at each joint. This process included applying the ground reaction forces to the foot at the center of pressure and calculating the three dimensional net joint reaction forces and torques at the ankle applied to the foot. The net forces and torques were then reversed and applied to the leg and the process was repeated for the knee net reaction forces and torques. The knee kinetics were then be used to calculate the hip forces and torques. This analysis is a standard biomechanical procedure.

The second component of the model calculated the forces in the three largest knee muscles and lateral soft tissue support structures (e.g. lateral collateral ligament) and combined these with the
knee joint reaction forces to determine the bone-on-bone forces. The model was a “torquedriven,” model in that it used the joint torques from the inverse dynamic analysis to determine the muscle forces. This general technique had been successful in predicting forces in various joints and soft tissues in the lower extremity (8; 18). The three basic steps in this component of the model are: 1) determine the forces in the gastrocnemius, hamstrings, and quadriceps muscles and in the lateral support tissues in the knee, 2) apply these forces along with the joint reaction forces onto the tibia and 3) determine the knee joint forces.

The gastrocnemius force was determined from the plantar flexor moment at the ankle joint during the stance phase of gait. It was assumed that the plantar flexor torque is produced by the triceps surae (gastrocnemius and soleus muscles) and that in our sample of knee OA participants, the tibialis anterior was co-active with the gastrocnemius during the initial 25% of the stance phase (2). Based on data in Childs’ et al (Table 4) and our own unpublished data (co-investigator P.D.) the increased co-activity across the ankle joint increased the gastrocnemius force 10% during the early stance phase thus increased the force applied to the knee joint. Triceps surae force was calculated as the quotient of the ankle joint torque and the moment arm for the triceps surae at the observed angular position of the ankle joint plus the additional 10% increase in force due to dorsiflexor coactivity. Muscle moment arm values for each ankle position were from moment arm-ankle joint position curves from the literature (13; 20). Gastrocnemius force was then calculated from triceps surae force based on its proportion of the total physiological cross sectional area (PCA) of the triceps surae which is 0.319. (24)
We justified these methods with a number of results in the literature and by present data. There was a strong association between gastrocnemius EMG and ankle plantar flexor torque in the literature (17; 18; 22; 23) and by our data. A few studies had also reported directly measured force in the Achilles tendon during walking (7; 8) and these values compared excellently with our predicted triceps surae values from healthy adults.

Figure 1. Gastrocnemius EMG (rectified) and measured Achilles tendon force in one individual walking at 2.1 m/s (8) and B) our measured EMG (raw signal) from one subject and predicted Triceps Surae force averaged over 9 healthy subjects. The measured and predicted force curves are nearly identical in shape and magnitude.

A) Figure from Finni at al. (1998) B) Our EMG (µV) and predicted Triceps Surae Force (N)
The direction of the gastrocnemius force was determined from the heel and knee marker positions and was expressed as $\alpha$, the angle between the gastrocnemius force and the tibia. The heel marker was used to represent the distal end of the gastrocnemius. The proximal end was positioned 0.020 m superior and 0.023 m posterior to the knee joint, along the line of the femur (15; 23). This position accounted for the gastrocnemius wrapping around the femoral condyles. The resultant direction of the gastrocnemius force was, on average, about $\alpha = 3^\circ$ from parallel with the leg and so this force applied a relatively large compressive load but small shear load on the knee.

Hamstrings force was calculated from the extensor torque at the hip joint observed typically during the first half of stance. This method was supported by our data (Figure 2) and the literature which showed a strong association between hip extensor torque and hamstrings EMG in early stance (16; 17; 23). The hip extensor torque was assumed to be produced by the hamstrings and gluteus maximus muscles and it was assumed that there was no co-contraction of the hip flexors during the first half of stance. This assumption was generally supported by EMG measures and muscle force predictions in the literature except that rectus femoris does contract and produce force during some of this period (1; 16).

Fig 2. Biceps femoris EMG ($\mu$V) hip torque (Nm) during the stance phase of walking. Positive torque values represent an internal extensor torque. Biceps femoris was active during the initial stance phase contributing to the extensor torque observed at this time.
The predicted hamstrings force accounted for both the hamstrings PCA relative to the total PCA of the hamstrings and gluteus maximus and the hamstrings moment arm at the hip relative to the gluteus maximus moment arm. The total hamstrings proportion to the hip torque was calculated as:

\[ Hp = \left( \frac{\text{Ham PCA}}{\text{Ham PCA} + \text{GM PCA}} \right) \left( \frac{H_d}{\text{GMd}} \right) \]  

where \( Hp \) was the proportion of the hip extensor torque generated by the hamstrings, Ham PCA and GM PCA were the hamstrings and gluteus maximus PCAs, and \( H_d \) and GMd were the hamstrings and gluteus maximus moment arms. Values for each of these constants were obtained from the literature (6; 24) and are: Ham PCA = 42.4 mm2, GM PCA = 17.36 mm2, Ham d = 0.042 m, and GM d = 0.047 m. The proportion of the hip extensor torque generated by the hamstrings (Hp) was equal to 0.63. The hamstrings force was then calculated as:

\[ H = Hp \left( \frac{\text{Het}}{H_d} \right) \]  

where \( H \) was the hamstrings force and Het was the hip extensor torque. Hamstrings force was assumed to be zero when the hip torque was in the flexor direction. Hamstring EMG data support this assumption (Fig 5, above). The direction of the hamstrings force was a line parallel to the femur and at angle \( \beta \) to the tibia.

The quadriceps force was calculated from the observed knee joint torque produced by the inverse dynamic analysis and the hamstrings and gastrocnemius forces. This calculation took into account co-contracting knee
The observed knee torque was the net torque at the knee and was a function of all muscles crossing the joint:

$$K_t = Q(Q_d) - H(H_d) - G(G_d) \quad (3)$$

where $K_t$ was the net knee torque from inverse dynamics, $Q$, $H$, and $G$ were the forces by the patellar tendon, hamstrings and gastrocnemius muscles, and $Q_d$, $H_d$, and $G_d$ were the respective moment arms for the muscles at the knee. The force in the quadriceps, $Q$, was then calculated as:

$$Q = (K_t + H(H_d) + G(G_d)) / Q_d \quad (4)$$

Moment arms at the knee were obtained from the literature by averaging the values from a number of studies and for each angular position of the knee joint (11; 12; 19; 21; 25). The mean values throughout the knee ROM for the three moment arms were, $Q_d = 0.035$ m, $H_d = 0.032$ m, and $G_d = 0.018$ m. The direction of $Q$, $\varphi$, was determined from the literature (12; 25) and was also a function of knee angle.

The muscle portion of the model was successfully applied to 10 healthy subjects and 9 subjects with ACL injury and reconstruction surgery while walking with and without a knee brace (4). Peak muscle forces for the healthy subjects were similar to predictions from other studies (Table 1, Fig 5). ACL subjects had lower quadriceps force and this force also changed with the brace, which has been shown to affect knee muscle function (5). Thus the model is sensitive to quadriceps dysfunction in a population known to have weaker quadriceps and poorly functioning quadriceps in walking. The shapes of the force curves were also similar to previous curves from healthy subjects. The hamstrings curve peaked early in stance and declined to zero near midstance, the quadriceps curve was bi-phasic with peaks at 20% and 80% of stance, and the gastrocnemius curve was zero at heel strike.
and reached a maximum value at 80% of stance. Based on a comparison with a number of other studies, the muscle force predictions appear reasonable and acceptable.

![Figure 3. Mean muscle force curves from healthy and ACL injured adults during walking](image)

<table>
<thead>
<tr>
<th>Reference</th>
<th>Hams</th>
<th>Quads</th>
<th>Gastroc</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>0.9</td>
<td>1.9</td>
<td>1.3</td>
</tr>
<tr>
<td>21</td>
<td>1.1</td>
<td>1.1</td>
<td>1.0</td>
</tr>
<tr>
<td>66</td>
<td>0.7</td>
<td>1.3</td>
<td>2.3</td>
</tr>
<tr>
<td>(75)</td>
<td>1.5</td>
<td>3.7</td>
<td>1.0</td>
</tr>
<tr>
<td>128</td>
<td>-</td>
<td>-</td>
<td>1.9</td>
</tr>
<tr>
<td>142</td>
<td>0.9</td>
<td>-</td>
<td>0.5</td>
</tr>
<tr>
<td>160</td>
<td>1.2</td>
<td>1.7</td>
<td>-</td>
</tr>
<tr>
<td>(178)</td>
<td>1.1</td>
<td>3.9</td>
<td>1.2</td>
</tr>
</tbody>
</table>

The methods of Schipplein et al. (14) were used to determine the distribution of frontal plane loads and in particular the force in the lateral support structures at the knee during the stance phase. The external loads place an adductor torque on the knee that is resisted by a combination of abductor torques from the quadriceps and the lateral structures. The quadriceps exerts a small to moderate abductor torque during walking because the center of pressure between tibia and femur is located on the medial tibial plateau which is medial to the center of the patellar tendon. The moment arms for the quadriceps and lateral support structures to the center of pressure on the medial tibial plateau were estimated from the X-ray films for each subject. These distances averaged \(\sim 2.5 \text{ cm} \) and...
~7.0 cm, respectively. The quadriceps abductor torque (product of the quadriceps force and its frontal plane lever arm) was subtracted from the observed net internal abductor torque calculated by the inverse dynamic analysis.

The remaining torque was distributed to the lateral knee tissues and the force in these tissues was calculated as the quotient of this torque and the lever arm. This force was considered to act parallel with the line of the tibia.

The final step was the calculation of knee joint forces. All muscle forces, the force in the lateral support structures and the joint reaction forces identified with inverse dynamics were partitioned into their compressive (parallel with the tibia) and anteroposterior shear (perpendicular to the tibia in the frontal plane) components and summed. The equations were:

\[
K_s = G \sin \alpha - H \sin \beta - Q \sin \varphi - Kz \sin \lambda + Ky \cos \lambda \quad (5)
\]

\[
K_c = G \cos \alpha - H \cos \beta + Q \cos \varphi - Kz \cos \lambda + Ky \sin \lambda + Lss \quad (6)
\]

Where \(K_s\) and \(K_c\) were the shear and compressive forces at the knee, \(Kz\) and \(Ky\) were the vertical and horizontal knee joint reaction forces, and \(Lss\) was the force in the lateral support structures. \(K_s\) was positive when the shear force applies an anterior load to the tibia and \(K_c\) was positive when the compressive force pushes into the tibia.

As described above the knee model was successfully applied to 153 participants of our previous NIH supported research (ADAPT trial). The results compared favorably to knee force predictions from those of Schipplein et al.(14) and Glitsch and Baumann (9).

**Limitations of biomechanical knee model**
The primary limitation was the absence of most knee ligaments. The absence of cruciate and medial collateral ligaments increased the knee muscle force predictions since these tissues must resist all external loads. However, we expected that total knee loads would not be severely affected because they would be produced by the sum of all tissues crossing the joint regardless of whether these tissues are muscle or ligament. The model did include the lateral collateral ligament, which was important and produces the principle, non-muscular restraint during the stance phase of walking. A secondary limitation was the assumption of no coactivation by the hip flexors during stance. The assumption of no co-activity at the hip introduced some error due to missing force production in the rectus femoris which also applied force at the knee. This issue was relevant during the initial part of the stance phase when the hamstrings were active and producing force. Thus the predictions of hamstrings force and subsequently, quadriceps and knee forces were probably underestimated. However, force in the rectus femoris during the first half of stance and relative EMG activation of this muscle among others) were relatively low. We therefore suggested that our error in hamstrings force would be relatively low, possibly around the 25% level. We performed a sensitivity analysis of the effect of hamstring error on knee force predictions. An underestimate of hamstrings force by 25% produced only a 5% error on knee force predictions. We emphasized that the model does include co-activation of knee flexors and extensors, and ankle dorsiflexors and plantar flexors during the stance phase.

While the model only estimated actual knee joint biomechanics, based on the similarity between its predictions and those of other knee models, we proposed that it is reasonable, valid, and appropriate for our purposes.

Reference List


APPENDIX D: TESTING QUESTIONNAIRES

Demographics Form

**Questionnaire:** Demographics Form

**Construct:** Demographics Information

**Rationale:** Form will provide information regarding the participant’s demographics. Information will be used to describe, in general terms, the persons who are participating in the study.
The following section asks about your general background. This information will be used to describe persons that participate in our study.

INSTRUCTIONS: Please check the appropriate box or fill in the correct response that best answers each question.

1. What is your birth date?  __ __ / __ __ / __ __ __  
   M M D D Y Y Y Y

2. What is your gender?  
   0 □ Male  
   1 □ Female

3. What is your marital status?  
   1 □ Never Married  
   2 □ Presently Married  
   3 □ Living in a marriage-like relationship  
   4 □ Divorced/Separated  
   5 □ Widowed

4. Including yourself, what is the total number of persons who are currently living in your household?  ___ ___ persons

5. Are you of Hispanic or Latino origin?  
   1 □ Yes  
   0 □ No
6. What category below best describes your racial background? *Select all that apply.*

1 □ **White/Caucasian**

(People having origins (ancestry) in any of the original people of Europe, North Africa, or the Middle East)

2 □ **Black or African American**

(People having origins (ancestry) in any of the Black racial groups of Africa)

3 □ **Asian**

(People from or having ancestors from the Far East, Southeast Asia, or the Indian subcontinent. This area includes, for example, China, India, Japan, the Philippine Islands, Korea, etc)

4 □ **Native Hawaiian or other Pacific Islander**

(People from or having ancestors from Hawaii or the Pacific Islands. This area includes Samoa, etc)

5 □ **American Indian or Alaskan Native**

(People from or having ancestors from any of the original peoples of North America and who maintain cultural identification through tribal affiliation or community recognition)
7. Which category below best describes the highest level of formal education you completed? Please check one.

1 □ No formal education
2 □ Grade School (1st-8th)
3 □ Some High School (9th through 11th grade)
4 □ High School diploma or G.E.D
5 □ Business/Vocational training school after high school graduation
6 □ Some College (no degree obtained)
7 □ Associate Degree (A.D or A.A)
8 □ College Graduate
9 □ Some College or professional school after college graduation
10 □ Master’s Degree
11 □ Doctoral Degree

8. What was your total family income (before taxes) from all sources last year?

(This information is important for describing the participants in the study as a group and is kept strictly confidential). Please check one.

1 □ Less than $10,000
2 □ $10,000 to $19,999
3 □ $20,000 to $34,999
4 □ $35,000 to $49,999
5 □ $50,000 to $74,999
6 □ $75,000 to $100,000
9. What is your current employment status?

1 □ Unemployed/Looking for work
2 □ Retired
3 □ Disabled, unable to work
4 □ Employed – full-time
5 □ Employed – part-time
6 □ Full-time Homemaker
7 □ Other (Please list): _______________

7 □ More than $100,000
10. Which category best describes the occupation you occupied for most of your life?

Please check one.

1 □ Homemaker or housewife

2 □ Managerial, professional specialty

[Executive, managerial, administrative, professional occupations. Job titles include teacher, guidance counselor, registered nurse, doctor, lawyer, accountant, architect, computer/systems analyst, personnel manager, sales manager, etc.]

3 □ Technical, sales, and administrative support

[Technical and related support occupations, sales, administrative support, clerical work. Job titles include computer programmer/operator, vocational/practical nurse, dental assistant, laboratory technician, sales clerk, cashier, receptionist, secretary, word processor, etc.]

4 □ Service

[Protective service (police, fire), health or food services,
etc., craft and repair occupations, farming, forestry, or fishing occupations. Job titles include police, nursing assistant, teaching assistant, child care attendant, maid, cook, waitress, food service clerk, seamstress, etc.]

5□ Operators, fabricators, and laborers
[Factory, transport, and constructions work. Job titles include factory, assembly, truck driver, construction worker, etc.]

6□ Other (Please describe): ________________

☐ This form has been reviewed with the participant---Staff Initials______Date______
Injury History

**Questionnaire:** Runner’s Injury History Form

**Construct:** Injury history

**Rationale:** Form will provide information regarding the participant’s injury history. Information will be used to further determine the participant’s eligibility.
The following section asks questions about your injury history.

INSTRUCTIONS: Please check the appropriate box or fill in the correct response that best answers each question.

1. Have you ever been injured due to running?  
   1 □ Yes  
   0 □ No

   If you answered yes to question 1, please answer questions 2-5. If you answered no, go to question 6.

Please answer the following questions (2-4) regarding the LAST 3 injuries you have had. Describe injuries in order (most recent injury first)

2. Injury 1 (most recent)

   2a. Location
       1 □ Pelvis
       2 □ Hip
       3 □ Thigh
       4 □ Knee
       5 □ Leg
       6 □ Ankle
       7 □ Foot
       8 □ Other ____________________

   2b. First noticed symptoms
       ___ ___/___ ___ ___ ___ ___  
       m m y y y y y

   2c. Date symptoms resolved
       ___ ___/___ ___ ___ ___ ___  
       m m y y y y y
2d. Was this injury diagnosed by a physician?  
1 □ Yes
0 □ No

2e. If yes, what was the diagnosis? 
1 □ Sacroiliac injury
2 □ Hamstring strain
3 □ Adductor strain
4 □ Anterior knee pain
5 □ Femoral stress fracture
6 □ Tibial stress fracture
7 □ Metatarsal stress fracture
8 □ Iliotibial band friction syndrome
9 □ Medial tibial stress syndrome (shin splints)
10 □ Anterior compartment syndrome
11 □ Achilles tendinitis
12 □ Plantar fasciitis
13 □ Metatarsalgia
14 □ Osteoarthritis of the knee
15 □ Patellar tendinitis
16 □ Spinal injury
17 □ Meniscal tear
18 □ Popliteal tendinitis
19 □ Morton’s neuroma
20 □ Peroneal tendinitis
21 □ Calf strain
22 □ Calcaneal apophysitis
23 □ Quadriceps tendinitis
24 □ Chondromalacia
25 □ Medial plica syndrome
26 □ Pes anserinus bursitis
27 □ Prepatellar bursitis
28 □ Ligament injury
29 □ Other: ____________________________

3. Injury 2

3a. Location

1 □ Pelvis
2 □ Hip
3b. First noticed symptoms

___ ___/___ ___ ___ ___
m m y y y y y

3c. Date symptoms resolved

___ ___/___ ___ ___ ___
m m y y y y y

3d. Was this injury diagnosed by a physician?
1 □ Yes
0 □ No

3e. If yes, what was the diagnosis?
1 □ Sacroiliac injury
2 □ Hamstring strain
3 □ Adductor strain
4 □ Anterior knee pain
5 □ Femoral stress fracture
6 □ Tibial stress fracture
7 □ Metatarsal stress fracture
8 □ Iliotibial band friction syndrome
9 □ Medial tibial stress syndrome
   (shin splints)
10 □ Anterior compartment syndrome
11 □ Achilles tendinitis
12 □ Plantar fasciitis
13 □ Metatarsalgia
14 □ Osteoarthritis of the knee
15 □ Patellar tendinitis
16 □ Spinal injury
17 □ Meniscal tear
18 □ Popliteal tendinitis
19 □ Morton’s neuroma
20 □ Peroneal tendinitis
21 □ Calf strain
22 □ Calcaneal apophysitis
23 □ Quadriceps tendinitis
24 □ Chondromalacia
25 □ Medial plica syndrome
26 □ Pes anserinus bursitis
27 □ Prepatellar bursitis
28 □ Ligament injury
29 □ Other: ________________________

4. Injury 3 (oldest)

4a. Location

□ Pelvis
□ Hip
□ Thigh
□ Knee
□ Leg
□ Ankle
□ Foot
□ Other ________________________

4b. First noticed symptoms

___ ___/___ ___ ___ ___
 m  m  y  y  y  y  y

4c. Date symptoms resolved

___ ___/___ ___ ___ ___
 m  m  y  y  y  y  y

4d. Was this injury diagnosed by a physician?

□ Yes
□ No
4e. If yes, what was the diagnosis?

1. Sacroiliac injury
2. Hamstring strain
3. Adductor strain
4. Anterior knee pain
5. Femoral stress fracture
6. Tibial stress fracture
7. Metatarsal stress fracture
8. Iliotibial band friction syndrome
9. Medial tibial stress syndrome (shin splints)
10. Anterior compartment syndrome
11. Achilles tendinitis
12. Plantar fasciitis
13. Metatarsalgia
14. Osteoarthritis of the knee
15. Patellar tendinitis
16. Spinal injury
17. Meniscal tear
18. Popliteal tendinitis
19. Morton’s neuroma
20. Peroneal tendinitis
21. Calf strain
22. Calcaneal apophysitis
23. Quadriceps tendinitis
24. Chondromalacia
25. Medial plica syndrome
26. Pes anserinus bursitis
27. Prepatellar bursitis
28. Ligament injury
29. Other: ________________________

5. How long have you been free from pain due to your
most recent running injury?  ____ ____ years ____ ____ months

6. Do you currently have any other running-related problems?  (aches, pains, etc) 1□Yes 0 □ No

_If you answered yes to question 6, please answer questions 7-15._

7. If yes, where is the problem? 1□Pelvis 2□ Hip 3□ Thigh 4□ Knee 5□ Leg 6□ Ankle 7 □ Foot 8 □ Other ______________________

8. Is the problem on the: 1□ Inside 2□ Outside 3 □ Front 4 □ Back

9. Side of problem: 1□ Right 2 □ Left 3 □ Both sides

10. Have you had this problem before? 1□Yes 0 □ No, it is a new injury
11. How long have you had it? _____ _____ years _____ _____ months

12. What was the onset of your symptoms related to? (check all that apply)
   1 □ Change in surface
   2 □ Increase in mileage
   3 □ Running hills
   4 □ Change in speed
   5 □ Change in shoes
   6 □ Don’t know
   7 □ Other____________________________

13. When do your symptoms occur?
   1 □ As soon as I start to run
   2 □ During my run, but not during normal activity
   3 □ After I have finished running and for a short time after
   4 □ During normal activity, but not during the run
   5 □ It hurts all the time
   6 □ Other____________________________

14. What helps relieve your symptoms? (check all that apply)
   1 □ Ice
   2 □ Stretch
   3 □ NSAIDS
   4 □ Physical Therapy
   5 □ Reduce running
15. What effect do your symptoms have on your workouts?

1. Pain during workout, but I am able to finish my normal workout

2. I workout, but the intensity (frequency, distance, or training pace) is less

3. Unable to workout, the pain is too great

4. I don’t workout because I don’t want to make it any worse

5. My problem has no affect on my workout

6. Other

☐ This form has been reviewed with the participant——Staff Initials——Date——
Training History

**Questionnaire:** Runner’s Training History Form

**Construct:** Training history

**Rationale:** Form will provide information regarding the participant’s training history.
The following section asks questions about your training history.

**INSTRUCTIONS:** Please check the appropriate box or fill in the correct response that best answers each question.

1. What type of runner are you? *(check one)*
   
   1 □ Recreational (for fitness only)
   
   2 □ Competitive (for fitness and compete in local races regularly)
   
   3 □ Highly competitive (professional or intercollegiate runner)

2. How many years have you been running regularly?   ____ ____ years ____ ____ months

3. Current average weekly running distance   ____ ____ miles per week

4. Current average training speed per mile   ____: ____ minutes per mile

5. How long have you been running at this distance and speed?   ____ ____ years ____ ____ months

6. Average competition/race speed per mile *(if applicable)*   ____: ____ minutes per mile
7. How long have you been competing at this speed? _____ _____ years _____ _____ months (if applicable)

8. How much time do you spend doing the following activities?

8A. Running _____ _____ hrs/wk
8B. Cycling _____ _____ hrs/wk
8C. Aerobics (Group Exercise Classes) _____ _____ hrs/wk
8D. Rowing _____ _____ hrs/wk
8E. Swimming _____ _____ hrs/wk
8F. Strength Training _____ _____ hrs/wk
8G. Other ________________ _____ _____ hrs/wk

TOTAL _____ _____ hrs/wk

9. Of the hrs/wk you spend running (from question 8A), how many are done during the following parts of the day? Total should add up to answer to 8A.

9A. Morning _____ _____ hrs/wk
9B. Afternoon _____ _____ hrs/wk
9C. Evening _____ _____ hrs/wk

10. Of the hrs/wk you spend running (question 8A), how many are done on the following surfaces? Total should add up to answer to 8A.

10A. Road (Asphalt) _____ _____ hrs/wk
10B. Sidewalk (Concrete) _____ _____ hrs/wk
10C. Track _____ _____ hrs/wk
10D. Treadmill _____ _____ hrs/wk
10E. Trails  _____ _____ hrs/wk

10F. Other  _____ _____ hrs/wk

11. Of the hrs/wk you spend running (question 8A), how many are spent on flat versus hills?
   Total should add up to answer to 8A.

   11A. Hills  _____ _____ hrs/wk
   11B. Flat  _____ _____ hrs/wk

12. Of the hours/wk you spend running (question 8A), how many are spent on crowned roads?
   Crowned roads are higher in the center and lower at the sides, usually for drainage.

   12A. Crowned roads  _____ _____ hrs/wk

13. Brand and model of shoes you wear presently?
   (example: Nike Shox, Asics Cumulus, New Balance 991, etc)

   13A. __________________
       Brand (Nike, Asics, New Balance, etc)

   13B. __________________
       Model (Shox, Cumulus, 991, etc)

For staff only:

14. Shoe classification:

1 □ Motion-control
2 □ Stability
3 □ Lightweight trainer
4 □ Racing flat

15. How long have you been wearing this brand and model?

   _____ _____ years _____ _____ months

16. Approximately how many miles do you usually wear your running shoes before buying a new pair for training?

   _____ _____ _____ miles

17. Do you wear orthotics or other corrective devices now?

   1 □ Yes
   0 □ No
If you answered yes to question 17, please answer questions 18a-b. If you answered no, go to question 19.

18a. If yes, for what mechanical function are they primarily designed?

1 □ Motion-control
2 □ Shock absorption
3 □ Heel lift
4 □ Other __________________

18b. Are the orthotics: (check one)

1 □ Custom made
2 □ Store bought
3 □ Home made

19. Do you stretch?

1 □ Yes
0 □ No

If you answered yes to question 19, please answer questions 20a-c. If you answered no, you are finished with this form.

20a. When do you normally stretch? (check the appropriate box)

1 □ Before run
2 □ After run
3 □ Both before and after run

20b. How much time do you spend stretching on the days that you run?

_____ _____ minutes

20c. I stretch: (check the appropriate box)

1 □ Regularly
2 □ Irregularly (i.e., only when time allows)
Only when I have an injury

☐ This form has been reviewed with the participant---Staff Initials_______Date__
CURRICULUM VITAE

John S. King

Education

M.S.  Health and Exercise Science, 2013
Wake Forest university, Winston Salem, NC
GPA: 3.85
Thesis:

University of North Carolina at Chapel Hill,
Chapel Hill, NC

Research Experience

2011 – present  Research Assistant
J. B Snow Biomechanics Laboratory
Department of Health and Exercise Science,
Wake Forest University

The Runners and Injury Longitudinal Study (TRAILS)
PI: Dr. Stephen Messier, Ph. D.

• Trained to obtain informed consent, administer
questionnaires, collect anthropometric data including
flexibility, arch height, and Q-angle, collect strength data
using isokinetic dynamometer, and apply marker set and
conduct gait analysis.
• Assisted in gait analysis, marker application, and isokinetic
dynamometer strength testing
• Processed gait data using EVaRT, Orthotrac, and Kintrak
software
• Met with and escorted participants during injury recovery
visits

Strength Training for Arthritis Trial (START)
PI: Dr. Stephen Messier, Ph. D

• Assisted in gait analysis, marker application, and isokinetic
dynamometer strength testing
• Assisted with exercise intervention
• Met with and escorted participants during hospital visits
**Professional Experience**

2011 – 2012  Exercise Leader/Lab technician, Health Exercise and Lifestyle Programs (HELPs)
Wake Forest University
- Lead group exercise for cardiac patients
- Monitored heart rhythm, blood pressure, and blood glucose
- Conducted GXTs for chronic disease populations

**Teaching Experience**

2011 – 2013 Graduate Teaching Assistant, Wake Forest University
HES 101: Exercise for Health

2012 Laboratory Assistant, Wake Forest University
HES 370: Biomechanics of Human Movement

**Professional Societies**

2011 – present Southeast Chapter of American College of Sports Medicine (SEACSM)

**Certifications**

2011 – present CPR and AED for the Professional Rescuer and Health Provider – American Red Cross

2011 – present Basic Life Support (BLS), CPR, and AED – American Heart Association