DOES INTRA-INDIVIDUAL VARIABILITY AND COORDINATION OF CHRONIC
ANKLE INSTABILITY INDIVIDUALS DURING SQUAT DIFFER BY ELEVATING THE REARFOOT?

by

CHRISTINE OLIVIA SAMSON

(Under the Direction of Cathleen Brown Crowell)

ABSTRACT

The combination of joint kinematic variability and time spent in coordination patterns throughout a closed chain task may provide insight to why CAI individuals have a greater risk of posttraumatic osteoarthritis development. The purpose of this dissertation was to identify intra-individual lower extremity kinematic variability and coordination differences between CAI and healthy individuals during normal and elevated rearfoot double-leg squat tasks to identify changes in lower kinematic chain coordination with alleviation of anatomical constraints. Motion capture data were collected as participants performed four trials of 10 squat repetitions for each squat task. Joint and segment angles were processed and analyzed for eight repetitions to determine kinematic variability and segment coordination, respectively. The summated integrated joint angle standard deviation time series across 32 squat repetitions captured total joint kinematic variability throughout a task. Time spent in coordination patterns (e.g., in-phase, anti-phase) throughout the squat for the shank-rearfoot and shank-femur was also identified. Groups were not significantly different with respect to height, mass, age, or physical activity levels ($p > .05$). Test limb closed chain dorsiflexion identified with the weight bearing lunge test
(WBLT) distance was not different between groups, $t(26)=1.62, p=.09, d=0.67, (1-\beta)=0.50$. No significant interaction effects between group, task, and anatomical plane were identified for summated joint kinematic variability. However, variability in the sagittal plane was identified as greatest in the knee and hip for both tasks in both groups. No differences in time spent in major coordination patterns of the shank-rearfoot were identified between groups or task in any anatomical plane ($p>.05$). CAI individuals spent significantly less time in shank-femur in-phase motion than anti-phase motion compared to controls, $F(1,26)=6.02, p=0.02, \eta^2=0.19, (1-\beta)=0.66$, suggesting altered knee neuromuscular control. Both groups had significantly different coordination patterns throughout the squat with the rearfoot elevated compared to flat on the floor (normal). The lack of significant differences in WBLT between groups may explain the similar amounts of variability and changes in coordination between tasks. This study revealed similar squat depths between groups for both tasks but significant differences in shank-femur segment coordination suggests altered neuromuscular control throughout the squat is different for those with CAI.

INDEX WORDS: double-leg squat, joint kinematics, lower extremity, vector coding variability, distribution, rearfoot manipulation, closed-chain dorsiflexion, motion analysis
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by

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B.S., University of Nevada Las Vegas, 2012
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The University of Georgia
May 2018
DEDICATION

To those who have taught me a little something about
the things I did not know, myself, and life over the past four years--

I would not be who I am today without you.

and

In memory of Dr. Brian Ragan

You are the reason I started this adventure in the first place. Thank you for convincing me to submit my UGA application, and then for making fun of me daily because writing about myself has never been a strength.
ACKNOWLEDGEMENTS

I am thankful to all of the individuals I have met over the past four years whose regular interactions have made this process enjoyable. However, there are a handful of individuals I would like to extend my sincerest gratitude to for their unwavering support.

First, I would like to thank my committee members for providing continual help, guidance, and expertise throughout the completion of my PhD. To Dr. Cathleen Brown Crowell, my major professor, advisor, and mentor – thank you for agreeing to stay in a long distance relationship the last two years of my doctoral studies. Even with miles between us, your continued leadership and mentorship has been critical to my success at UGA. To Dr. Kathy J. Simpson, my “content” advisor and mentor – thank you for postponing your “enjoy-life” retirement the past two years to provide continued advisement in all things biomechanics while touring various Athens coffee shops with me. To Dr. Karl M. Newell – thank you for exposing me to a new perspective and challenging me to think differently. I am grateful for having the opportunity to be mentored by and learn from these three individuals.

The success of my dissertation would not be possible without the support and hard work of the amazing humans I have had the opportunity of working with in the Biomechanics Lab throughout my time at UGA. Of the many I could thank, I am grateful to Daniel Couper, Chelsea Keown, and Haley Pierce who willing worked hard to ensure the successful completion of my dissertation and shared some laughs with me along the way. And, to my brother, David Samson, for coming to my rescue by discovering the ultimate data processing cheat.
Lastly, to the people whose support kept me sane and pushing through the difficult times – my family, friends, and mentors – thank you for allowing me to take you on this rollercoaster ride with me.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>v</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>ix</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>xi</td>
</tr>
<tr>
<td>CHAPTER</td>
<td></td>
</tr>
<tr>
<td>1 INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>Specific Aims</td>
<td>9</td>
</tr>
<tr>
<td>Research Questions</td>
<td>9</td>
</tr>
<tr>
<td>Hypotheses and Rationales</td>
<td>14</td>
</tr>
<tr>
<td>Definitions</td>
<td>16</td>
</tr>
<tr>
<td>Assumptions</td>
<td>17</td>
</tr>
<tr>
<td>Limitations</td>
<td>17</td>
</tr>
<tr>
<td>2 LITERATURE REVIEW</td>
<td>18</td>
</tr>
<tr>
<td>Chronic Ankle Instability</td>
<td>19</td>
</tr>
<tr>
<td>Squats</td>
<td>27</td>
</tr>
<tr>
<td>Coordination</td>
<td>31</td>
</tr>
<tr>
<td>Variability</td>
<td>36</td>
</tr>
<tr>
<td>3 METHODS</td>
<td>46</td>
</tr>
<tr>
<td>Participants</td>
<td>46</td>
</tr>
<tr>
<td>Research Protocol</td>
<td>50</td>
</tr>
</tbody>
</table>
LIST OF TABLES

Table 1.1: Dependent Variables Defined for Sub-study 1: Task Outcomes and Joint Angular Displacement Variability ...................................................................................................11

Table 1.2: Dependent Variables Defined for Sub-Study 2: Lower Extremity Coordination and Variability Throughout the Squat ......................................................................................13

Table 3.1a: Anatomical landmark placement of reflective markers for the pelvis and lower extremity ............................................................................................................................52

Table 3.1b: Anatomical landmark placement of reflective markers for the thorax and upper extremity ............................................................................................................................52

Table 3.2: Dempster Defined Calculations for Body Segments ............................................................................................................................55

Table 4.1: Summary of Participant Characteristics (Mean and SD) ............................................................................................................................76

Table 4.2: Group Means(SD) of Involved Limb Joint Angular Displacement (degrees) for the Ankle, Knee, and Hip in All Three Anatomical Planes for Compiled Squat Trials ........76

Table 4.3: Group Means(SD) of Summated Kinematic Variability of the Involved Limb Across Compiled Squat Trials for the Ankle, Knee, and Hip in All Three Anatomical Planes ....77

Table 4.4: Summary of Main Effects on Summated Joint Kinematic Variability ..................... ..77

Table 5.1: Group Means and Standard Deviations for Participant Characteristics ......................103

Table 5.2: Summary of Shank-Femur Significant Group X Coordination and Task X Coordination Simple Main Effects by Anatomical Plane .........................................................104
Table 5.3: Group Means(SD) of Percent Time Spent in Each Coordination Pattern for Shank-Rearfoot for the Normal and Elevated Rearfoot Squats ..................................................105

Table 5.4: Group Means(SD) of Percent Time Spent in Each Coordination Pattern for Shank-Femur for the Normal and Elevated Rearfoot Squats .................................................. 106
### LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Normal squat task</td>
<td>16</td>
</tr>
<tr>
<td>1.2</td>
<td>Elevated rearfoot squat task</td>
<td>16</td>
</tr>
<tr>
<td>3.1</td>
<td>Anatomical locations of reflective markers</td>
<td>51</td>
</tr>
<tr>
<td>3.2</td>
<td>Participant set up for normal squat task and elevated rearfoot squat</td>
<td>54</td>
</tr>
<tr>
<td>3.3a</td>
<td>Anterior and lateral views of lower extremity segment axes orientation</td>
<td>57</td>
</tr>
<tr>
<td>3.3b</td>
<td>Anterior and posterior views of upper extremity segment axes orientation</td>
<td>57</td>
</tr>
<tr>
<td>4.1</td>
<td>Example of integrated sagittal ankle kinematics standard deviation time series to determine summated ankle kinematic variability</td>
<td>65</td>
</tr>
<tr>
<td>4.2</td>
<td>Retro-reflective marker placement and orientation of joint and global coordinate systems</td>
<td>69</td>
</tr>
<tr>
<td>4.3</td>
<td>CONSORT flow diagram of group allocation</td>
<td>74</td>
</tr>
<tr>
<td>4.4</td>
<td>Summated lower extremity joint kinematic variability by group and task</td>
<td>78</td>
</tr>
<tr>
<td>5.1</td>
<td>Retro-reflective marker placement and orientation of segment and global coordinate systems</td>
<td>95</td>
</tr>
<tr>
<td>5.2</td>
<td>CONSORT flow diagram of group allocation</td>
<td>100</td>
</tr>
<tr>
<td>5.3</td>
<td>Coordination patterns visual representation based on mean coupling angles</td>
<td>101</td>
</tr>
<tr>
<td>5.4</td>
<td>Time Spent in Sub-coordination Patterns for the Shank-Rearfoot by group and task for all three anatomical planes</td>
<td>107</td>
</tr>
</tbody>
</table>
Figure 5.5: Time Spent in Sub-coordination Patterns for the Shank-Femur by group and task for all three anatomical planes..........................................................................................................................108

Figure 6.1: Representative internal/external rotation of the foot relative to the rearfoot motion and vertical COM position........................................................................................................................................119
CHAPTER 1
INTRODUCTION

Approximately 1 in 5 individuals aged 18 to 65 years is affected by a chronic musculoskeletal ankle disorder due to a previous ankle injury.\(^1\) Chronic ankle instability (CAI) is an example of a common musculoskeletal disorder that may develop following a lateral ankle sprain.\(^2\) Individuals with CAI have a history of (1) ‘giving way’, (2) suffering recurrent sprains, and/or (3) experiencing ‘feelings of instability’ to the previously sprained ankle during physical activities.\(^3\) Anatomical changes, such as increased lateral ligament complex laxity and arthokinematic changes, resulting from the initial ankle sprain, may lead to mechanical insufficiencies and/or functional insufficiencies such as impaired proprioception, neuromuscular control, and postural control.\(^2\) The risk of ankle osteoarthritis increases following ankle instability compared to those with healthy ankles.\(^4,5\) Individuals with CAI display potentially detrimental movement patterns, decreased knee flexion on landing\(^6,7\), and increased ankle plantarflexion and ankle and rearfoot inversion during walking and running\(^8\), which may be driven by mechanical and/or functional insufficiencies. There is a need to define abnormal movement patterns throughout various functional tasks that could increase the risk of ankle osteoarthritis. Developing prevention and intervention strategies for CAI rely on appropriately classifying and organizing movement characteristics that consider the presence of mechanical and functional insufficiencies and frequency of sprain.\(^9\)

Ankle braces worn during activity and balance training are the only interventions shown to reduce incidence of recurrent sprains\(^10,11\) and consistently improve self-reported function\(^12\),
respectively, despite the broad range of therapeutic interventions implemented and studied for CAI individuals. Many other treatment strategies are currently employed by clinicians including stretching, strengthening, and improving neuromuscular control.\textsuperscript{12,13} However, the re-injury rate and prevalence of CAI in a physically active population is still quite high at over 20-60% depending on the sport.\textsuperscript{14} This results in a higher rate of post-traumatic ankle osteoarthritis in those with CAI\textsuperscript{4,5} and lower levels of physical activity\textsuperscript{15} compared to uninjured controls. With better acute treatment following the index sprain, these negative outcomes are potentially preventable. Additionally, the lack of success of current treatments may be due to those with CAI having different clusters of symptoms, either mechanical laxity, perceptual deficits in stability, and recurrent sprains.\textsuperscript{9,16,17} Understanding how overlapping and unique deficiencies affect functional task movement abilities in CAI individuals is necessary to develop a more systematic, targeted, and personalized approach for prevention and intervention efforts.

Task performance \textit{outcomes} are often compared between CAI and healthy individuals, but do not consider how the movement occurs throughout the task to obtain the outcome. There is a need to consider alternative assessment techniques quantifying segment organization throughout task performance to identify how pathological insufficiencies determine movement abilities in those with CAI. Abnormal movements between two adjacent segments or joint kinematic variability quantification across multiple repetitions of a task will provide the reason why task outcomes may vary between groups. More effective intervention strategies can be developed for the CAI individual to address abnormal movements or kinematic chain variability discrepancies. Focusing on discrete task performance measures (outcomes) ignores the organization of body segments throughout the movement to achieve the outcome that can be influenced by intrinsic or task constraints.\textsuperscript{18} Most CAI literature to date has compared movement
characteristics in various functional tasks with a broad range of those on the CAI continuum, or multiple sub-groups, to healthy controls\textsuperscript{19}, often with conflicting or insignificant results\textsuperscript{20,21,22}. The presence and severity of mechanical and functional insufficiencies and sprain recurrence variability among CAI individuals along the continuum may explain these results.\textsuperscript{9} There is a need to quantify the quality of movement abilities throughout tasks to determine the influence of intrinsic constraints in those with CAI that may contribute to treatment response variability among CAI individuals.

Consideration of organism (or intrinsic), environmental, and task constraints has been proposed as necessary to implement individualized assessments that highlight differences between movement patterns.\textsuperscript{23} Movement patterns macroscopically represent the individual’s ability to self-organize redundant degrees of freedom (DOF) in human movement\textsuperscript{24} based on constraints placed on the system.\textsuperscript{25} Three main categories of constraints have been proposed and somewhat vary depending on which theoretical model of interacting constraints is referenced. Constraints may be classified either as pertaining to the organism, task, and environment according to Newell’s model\textsuperscript{26} or as biomechanical, morphological, and environmental according to Higgin’s model\textsuperscript{27}. Organism, or intrinsic, constraints include limitations due to anatomical structure and function (or combination of biomechanical and morphological constraints\textsuperscript{27}). Task constraints are specific to the overall performance objective of the task, instructions given to the individual, and equipment used to complete the task.\textsuperscript{26,28} Lastly, environment constraints pertain to all aspects outside of the individual in the surrounding environment.\textsuperscript{26} The interaction of the organism, task, and environment constraints define the ability of the system to self-organize to complete the task and is reflected in the coordination and control.\textsuperscript{26} Application and manipulation of various constraints will provide a better understanding and means of how CAI
individuals control their lower extremity throughout a task compared to healthy individuals. The following will outline task and intrinsic constraints to be considered for manipulation highlighting lower kinematic chain coordination abilities of those with CAI.

A double-leg squat, a clinically relevant task, has not been effectively utilized in ankle instability research despite the ease of test standardization, applicability across activities of daily living, sports and strength training, and low physical demands of the task. Walking\textsuperscript{29,30}, jogging\textsuperscript{29,30}, and jump landing\textsuperscript{31,32} are examples of functional tasks commonly used to discern if movement abilities differ in those with and without CAI. However, a squat task is commonly utilized clinically to assess bilateral active range of motion (ROM) and strength of the lower extremity, and to increase strength for functional improvement.\textsuperscript{33} Moreover, the squat movement is an important task to assess, as it is a closed kinematic-chain task similar to multiple athletic movements and everyday tasks,\textsuperscript{34} and allows for bilateral comparisons of the lower extremity. The task performance outcome of interest for a squat is the lowest vertical minima of the center of mass (COM), or squat depth magnitude, based on the overall performance objective of a squat which is to lower the COM within the base of support and return to standing. Utilization of the squat as the task of interest will allow for comparison of task performance outcome with the quality of lower kinematic chain movement abilities throughout task completion.

The task demands of the squat require adequate closed chain dorsiflexion range of motion (ROM) and an individual without the necessary ROM would be considered to present with an intrinsic constraint. A lack of active closed-chain dorsiflexion range of motion (ROM) is prevalent and well documented in those with CAI and may restrict or alter movement abilities.\textsuperscript{35} This intrinsic constraint during a squat may cause the CAI individual to limit squat depth, alter lower extremity coordination patterns suggesting altered neuromuscular control, or decrease
inter-trial kinematic variability when completing multiple repetitions suggesting restricted articular surface area in which load is distributed.\textsuperscript{36} The depth of a squat may be easily manipulated, such as with the addition of a block under the rearfoot to alleviate the inadequate closed-chain dorsiflexion.\textsuperscript{33} However, segment coordination differences with and without the intrinsic constraint at the ankle is unknown. Implementation of a block in this position has been found to alter trunk flexion kinematics in healthy resistance-trained males.\textsuperscript{37} There is no current evidence of lower extremity kinematic chain assessment with and without the presence of an intrinsic constraint during a closed-chain task such as double-leg squats of CAI individuals. Removing this intrinsic constraint may alter joint kinematics and coordination patterns to reflect similar increases in proximal joint ROM displacement throughout the task associated with greater closed-chain dorsiflexion as found in healthy physically active adults.\textsuperscript{38} There is a need to understand lower kinematic chain alterations \textit{throughout} closed-chain tasks with and without restricted ankle ROM (intrinsic constraint presence) to demonstrate the ability to and justify the need to restore normal arthro-and osteokinematics in those with CAI.

Coordination assessment provides awareness as to how segments within a kinematic chain move relative to one another \textit{throughout} a task and provides a method to quantify the quality of movement abilities of those with CAI. Coordination assessment methods (e.g., vector coding) quantify the spatio-temporal movement (e.g., in-phase or anti-phase) of one segment or joint relative to another throughout multiple repetitions of a task.\textsuperscript{39} Assessing coordination variability throughout a task in comparison to an outcome measure identifies how an individual masters multiple DOFs to complete a task and has often been compared across skill levels in motor control studies.\textsuperscript{40,41} Variability assessments of specific segment coordination \textit{throughout} task completion and relative to task performance outcome measures is needed to better
understand if CAI individuals self-organize lower extremity DOF differently than healthy controls that may predispose them to develop post-traumatic ankle osteoarthritis.

Segment coordination throughout various functional tasks in those with CAI is not well understood due to the few studies quantifying shank-rearfoot\textsuperscript{29,30,42} and hip-ankle\textsuperscript{43} relative coordination during walking and jogging in those with CAI. Identifying the shank movement relative to rearfoot is the most intuitive because the ankle is defined by the interaction of these two segments, which are involved in the mechanism of injury and complaints of giving way. Studies have identified altered knee neuromuscular control\textsuperscript{7}, kinematics\textsuperscript{6,44}, and kinematic variability\textsuperscript{32}. Therefore, consideration of the shank movement relative to the femur is necessary to further understand changes proximal in the kinematic chain resulting from CAI. While other studies have looked at the effects of CAI\textsuperscript{45} and ankle restriction\textsuperscript{46} on lower extremity “coordination” during a vertical jump task, quantification of spatio-temporal segment pair movement relative to one another was not determined. Identification of adjacent segments (e.g., shank-rearfoot or shank-femur) moving in-phase or out-of-phase (anti-phase) cannot be determined without relative spatio-temporal coordination assessments. Anti-phase movement of adjacent segments may suggest a rotational or grinding of the articular surface throughout motion as one segment moves the opposite direction of the other.\textsuperscript{47} Abnormal segment coordination is not visible during qualitative assessments and may be highlighted with certain coordination assessment techniques to provide new considerations for neuromuscular control improvement. Further research employing these types of coordination assessments are necessary to determine if abnormal segment movements exist and are similar in other functional tasks other than walking and jogging for those with CAI.
The last proposed intrinsic constraint to consider is the presence and magnitude of variability throughout multiple repetitions of task performance to represent the overall neuromuscular control of the system. Variability has different meanings with respect to biological systems (e.g., identifying regularity, self-similarity, and dimensionality) and statistical perspectives (e.g., inter- and intra-differences between trials or subjects).\textsuperscript{48} Different unhealthy pathological states of biological systems, such as post-concussion\textsuperscript{49} and Parkinson’s disease\textsuperscript{50}, have been associated with organization of system variability that is too rigid or unstable hindering the ability to adapt to perturbations.\textsuperscript{51} An “optimal” amount of system variability of an individual performing a task has been supported for healthy and functional movement.\textsuperscript{51} This theory could be applied to inter- or intra-individual differences. If there is too little variability of joint kinematics across multiple trials, the movement abilities could be considered too rigid that may predispose the individual to chronic injuries.\textsuperscript{52} Conversely, too much variability of joint kinematics across multiple trials could identify movement abilities that may predispose the individual to acute injuries due to less control and inability to adapt to perturbations.\textsuperscript{52} Therefore, intra-individual variability throughout multiple task performance repetitions should be assessed between CAI and healthy individuals to determine if joint kinematics variability differences exist that may predispose CAI individuals to develop certain sequelae. However, inter-individual variability during functional tasks are commonly identified between healthy and CAI individuals\textsuperscript{29,30,53} and less commonly reported within CAI individuals whether between mechanical and functional ankle instability groups, or sub-groups of different insufficiencies under the CAI umbrella\textsuperscript{31,54}. Investigation of intra-individual joint kinematic and coordination variability between CAI and healthy individuals will provide information on the presence or absence of lower kinematic chain rigidity to guide intervention efforts.
Further investigation of lower extremity coordination and coordination variability are necessary to identify how CAI individuals self-organize the kinematic chain compared to healthy controls throughout functional tasks. First, differences in joint displacement with respect to task performance outcomes can be used to determine the influence of intrinsic constraints on lower kinematic chain function.\textsuperscript{36,38} Comparison of task performance outcomes between groups provides a reference for comparing performance abilities. Similar task outcomes with differing joint kinematics would suggest different coordination strategies between CAI and healthy individuals whereas different task outcomes with similar joint kinematics would suggest the presence of a constraint in the kinematic chain. If task performance outcome and kinematic chain coordination differences between CAI and healthy individuals are reduced with the artificial removal of an intrinsic constraint common to those with CAI, then the need to develop effective therapeutic interventions to remove the intrinsic constraint is established. Second, intra-individual variability within CAI individuals during various functional tasks has been reported to be both greater and less than healthy controls for the same task.\textsuperscript{30,32,55,56} While these conflicting results may be dependent upon the overlap and unique deficiencies of the CAI individuals included in the analysis, further investigation of intra-individual joint kinematic variability across multiple repetitions may highlight restricted movement variability in CAI individuals not seen in their healthy counterparts. If CAI groups have diminished variability, it could restrict articular surface area contact area to a limited percentage of the talus or increase loads on certain anatomical structures that may lead to the development of additional chronic pathologies or posttraumatic osteoarthritis. However, due to varying methodologies in the current literature, it is unknown if the amount of intra-individual variability for more than 15 repetitions is similar across CAI individuals and/or differs from healthy controls.\textsuperscript{57} The percentage of significant
kinematic, kinetic, and temporal variables in healthy single subject comparisons (necessary to assess intra-individual variability) are dependent upon trial number with the percentages for 25 and 50 trials more than twice that of 5 trials.\textsuperscript{58} Therefore, an increase in trial size will provide a more accurate representation of movement abilities. Intervention strategies should not be generalized to all CAI patients until it is understood if those with CAI collectively perform and behave in the same manner.

Therefore, the \textbf{overall purpose of the proposed study} is to assess differences in lower extremity kinematic chain movement and coordination between CAI individuals and healthy controls during normal and elevated rearfoot double-leg squat tasks to identify squat depth (task performance outcome) relative to joint angular displacement variability (sub-study 1) and lower extremity segment coordination variability (sub-study 2) with and without the presence of an intrinsic constraint.

\textbf{Specific Aims}

Sub-study 1: Squat Task Performance Outcomes and Joint Angular Displacement Variability

1. To determine the differences in squat task performance outcome (lowest vertical minima) and joint angular displacement variability of the ankle, knee, and hip in all 3 anatomical planes during a normal and elevated rearfoot squat task in CAI and healthy individuals.

Sub-study 2: Lower Extremity Coordination and Variability Throughout the Squat

1. To determine shank-rearfoot and shank-femur relative coordination throughout a squat with and without the presence of an intrinsic constraint in CAI and healthy individuals.

\textbf{Research Questions}

There will be two groups consisting of CAI individuals and healthy controls. Each group performed 40 total repetitions (4 trials of 10 consecutive squats) of the two squat conditions:
normal (flat surface) and elevated rearfoot (4cm wooden block under each rearfoot). The squat task for the first trial was randomized and then counterbalanced for subsequent trials with matched CAI and healthy participants performing the squat tasks in the same order. The aforementioned specific aims are explained more thoroughly with the following research questions and variable definitions.

Sub-study 1: Squat Task Performance Outcomes and Joint Angular Displacement Variability

1. Do anatomical constraints (i.e., inadequate closed-chain dorsiflexion) common in those with CAI alter task performance outcomes and lower extremity kinematic chain movement during a normal versus elevated rearfoot squat task compared to healthy individuals?

   a. Dependent variables are defined in Table 1.1
Table 1.1. Dependent Variables Defined for Sub-study 1: Task Performance Outcomes and Joint Angular Displacement Variability

<table>
<thead>
<tr>
<th>Dependent Variable</th>
<th>Variable Name</th>
<th>Definition</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Task Performance Outcome</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normalized squat depth magnitude to leg length</td>
<td>Squat depth</td>
<td>Lowest COM vertical minima expressed as a percentage of average leg length* between the two limbs</td>
<td>m</td>
</tr>
<tr>
<td>Normalized squat depth magnitude to leg length SD</td>
<td>SD&lt;sub&gt;squat depth&lt;/sub&gt;</td>
<td>SD of the normalized squat depth magnitude to leg length for the 40 trials of the individual</td>
<td>m</td>
</tr>
<tr>
<td><strong>Kinematic Chain Movement</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ankle displacement SD</td>
<td>SD&lt;sub&gt;ankle-disp&lt;/sub&gt;</td>
<td>Summated integrated SD time series of ankle displacement throughout a squat trial across the 32 trials of the individual in each of the 3 anatomical planes</td>
<td>degrees·%squat</td>
</tr>
<tr>
<td>Knee displacement SD</td>
<td>SD&lt;sub&gt;knee-disp&lt;/sub&gt;</td>
<td>Summated integrated SD time series of knee displacement throughout a squat trial for the 32 trials of the individual in each of the 3 anatomical planes</td>
<td>degrees·%squat</td>
</tr>
<tr>
<td>Hip displacement SD</td>
<td>SD&lt;sub&gt;hip-disp&lt;/sub&gt;</td>
<td>Summated integrated SD time series of hip displacement throughout a squat trial for the 32 trials of the individual in each of the 3 anatomical planes</td>
<td>degrees·%squat</td>
</tr>
</tbody>
</table>

*Note. SD = standard deviation; disp = displacement.  
*Leg length identified as the distance from the anterior superior iliac spine (ASIS) to the medial malleolus.*
b. Hypothesis 1: CAI individuals will have less joint displacement variability (i.e., $SD_{sagittal\text{-}ankle\text{-}disp}$, $SD_{sagittal\text{-}knee\text{-}disp}$, $SD_{sagittal\text{-}hip\text{-}disp}$, $SD_{frontal\text{-}ankle\text{-}disp}$, $SD_{frontal\text{-}knee\text{-}disp}$, $SD_{frontal\text{-}hip\text{-}disp}$) during the normal squat compared to healthy controls.
   i. $H_0$: CAI individuals will have the same joint displacement variability (i.e., $SD_{sagittal\text{-}ankle\text{-}disp}$, $SD_{sagittal\text{-}knee\text{-}disp}$, $SD_{sagittal\text{-}hip}$, $SD_{frontal\text{-}ankle\text{-}disp}$, $SD_{frontal\text{-}knee\text{-}disp}$, $SD_{frontal\text{-}hip\text{-}disp}$) during the normal squat task compared to healthy controls.

c. Hypothesis 2: CAI individuals will have similar joint displacement variability (i.e., $SD_{sagittal\text{-}ankle\text{-}disp}$, $SD_{sagittal\text{-}knee\text{-}disp}$, $SD_{sagittal\text{-}hip}$, $SD_{frontal\text{-}ankle\text{-}disp}$, $SD_{frontal\text{-}knee\text{-}disp}$, $SD_{frontal\text{-}hip\text{-}disp}$) during the elevated rearfoot squat as healthy controls.
   i. $H_0$: CAI individuals will have the different joint displacement variability (i.e., $SD_{sagittal\text{-}ankle\text{-}disp}$, $SD_{sagittal\text{-}knee\text{-}disp}$, $SD_{sagittal\text{-}hip}$, $SD_{frontal\text{-}ankle\text{-}disp}$, $SD_{frontal\text{-}knee\text{-}disp}$, $SD_{frontal\text{-}hip\text{-}disp}$) during the elevated rearfoot task compared to healthy controls.

d. Hypothesis 3: CAI individuals will have a greater squat depth increase during the elevated rearfoot squat than the normal squat task compared to healthy controls.
   i. $H_0$: CAI individuals will have the same change in Squat depth from the normal squat to the elevated rearfoot squat task as healthy controls.

Sub-study 2: Lower Extremity Coordination and Variability Throughout the Squat

2. Is there a difference in intra-limb LE segment coordination with the presence of an anatomical constraint (i.e. inadequate closed-chain dorsiflexion) common in CAI individuals compared to healthy controls?
   a. Dependent Variables are defined in Table 1.2
<table>
<thead>
<tr>
<th>Dependent Variable</th>
<th>Variable Name</th>
<th>Definition*</th>
<th>Measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shank-rearfoot coupling angle (θ) mean</td>
<td>$\theta_{\text{shank-rearfoot}}$</td>
<td>Excursion of rearfoot relative to the shank; used to define coordination pattern between segments (i.e., in-phase, anti-phase, rearfoot dominant, shank dominant)</td>
<td>degrees</td>
</tr>
<tr>
<td>Shank-femur coupling angle (θ) mean</td>
<td>$\theta_{\text{shank-femur}}$</td>
<td>Excursion of shank relative to the femur used to define coordination pattern between segments (i.e., in-phase, anti-phase, shank dominant, femur dominant)</td>
<td>degrees</td>
</tr>
<tr>
<td>Shank-rearfoot magnitude ($m$) mean</td>
<td>$\text{mag}_{\text{shank-rearfoot}}$</td>
<td>Magnitude of the coupled motion between shank/rearfoot</td>
<td>degrees</td>
</tr>
<tr>
<td>Shank-femur magnitude ($m$) mean</td>
<td>$\text{mag}_{\text{shank-femur}}$</td>
<td>Magnitude of the coupled motion between shank/femur</td>
<td>degrees</td>
</tr>
<tr>
<td>Inter-trial variability of shank-rearfoot coordination (VCV)</td>
<td>$\text{VCV}_{\text{shank-rearfoot}}$</td>
<td>Intra-individual trial variability of shank-rearfoot relative motion</td>
<td>--</td>
</tr>
<tr>
<td>Inter-trial variability of shank-femur coordination (VCV)</td>
<td>$\text{VCV}_{\text{shank-femur}}$</td>
<td>Intra-individual trial variability of shank-femur relative motion</td>
<td>--</td>
</tr>
</tbody>
</table>

*Note. VCV = vector coding variability.*

*All variables were obtained for every time point within the normalized squat cycle.*
3. Hypothesis 1: CAI individuals will have 1) less in-phase shank-rearfoot direction ($\theta_{\text{transverse-shank-rearfoot}}$) throughout the normal squat compared to healthy controls.
   a. $H_0$: There will be no difference in shank-rearfoot direction ($\theta_{\text{transverse-shank-rearfoot}}$) between groups.

4. Hypothesis 2: CAI individuals will have 1) less in-phase shank-femur direction ($\theta_{\text{transverse-shank-femur}}$) throughout the normal squat compared to healthy controls.
   a. $H_0$: There will be no difference in shank-femur direction ($\theta_{\text{transverse-shank-femur}}$) between groups.

**Hypotheses and Rationales**

**Sub-study 1: Squat Task Outcomes and Joint Angular Displacement Variability**

Individuals with CAI are predicted to have less lower kinematic chain joint sagittal displacement during the normal squat compared to the elevated rearfoot squat task due to the presence of inadequate closed-chain dorsiflexion (i.e., an intrinsic constraint associated with CAI$^{53}$). Closed-chain dorsiflexion ROM identified in CAI individuals was significantly positively correlated with maximum knee flexion when landing from an elevated platform, wherein a lack of dorsiflexion resulted in decreased maximum knee flexion.$^{59}$ Landing from the platform is somewhat similar to the descent portion of the squat because an individual must control the lowering of their center of mass within their base of support to avoid falling over and bring the body’s downward momentum to zero. Therefore, similar decreased knee joint angular displacement of the lower kinematic chain is expected to be present in those with CAI during the normal squat task.

Limited closed-chain dorsiflexion due to anatomical limitations$^{38}$ and created by laboratory wedge implementation under the forefoot$^{36}$ during double-leg squat tasks resulted in
less knee and ankle joint displacement and peak angles in the sagittal and frontal planes during a squat. The removal of the anatomical constraint in the elevated rearfoot task would allow more movement in the proximal joints (i.e., knee and hip). Removal of the anatomical restriction via rearfoot elevation is hypothesized to increase ankle, knee, and hip joint displacement in the sagittal plane which will allow a lower squat depth to be achieved in the elevated rearfoot squat task.

Sub-study 2: Lower Extremity Coordination and Variability Throughout the Squat

Individuals with CAI are predicted to have less in-phase shank-rearfoot direction ($\theta_{\text{transverse-shank-rearfoot}}$) compared to healthy controls. CAI individuals have less in-phase shank-rearfoot motion in the transverse plane throughout stance than their healthy counterparts in walking and jogging.\textsuperscript{29,30,42} The stance phase of walking and jogging is similar to a squat in that all three are closed chain activities. Therefore, similar shank-rearfoot relative motion (i.e., less in-phase) is expected throughout the normal squat task with the presence of the anatomical constraint. Removal of the anatomical constraint in the elevated rearfoot squat should allow the CAI individual to move similar to their healthy counterparts.\textsuperscript{36,37,38} Additionally, the mechanism of injury for index sprain results from movement of just the rearfoot. Those with CAI suffer from recurrent sprains which suggest more rearfoot movement during activity and therefore less in-phase movement of the shank-rearfoot.

Individuals with CAI are predicted to have less in-phase shank-femur direction ($\theta_{\text{transverse-shank-femur}}$). Based on rationale provided for Sub-study 1, less in-phase shank-femur coordination is expected in the transverse plane during the normal squat task due to the decreased amount of joint angular displacement within the kinematic chain due to the presence of the anatomical constraint.
Definitions

1. Normal squat task- A double-leg squat holding straight arms in front of the body in 90° of shoulder flexion with feet hip distance apart and flat on the ground.

![Normal squat task](image1)

b. Figure 1.1 Normal squat task.

2. Elevated rearfoot squat task- Similar to the normal squat task except with each rearfoot elevated 4.5cm with a wooden block.

![Elevated rearfoot squat task](image2)

b. Figure 1.2 Elevated rearfoot squat task.

3. Center of Mass- The point representing the concentrated mass of the individual and estimated with a 14-segment model.\textsuperscript{162}

4. Squat descent phase- When the COM begins to descend to the instant when it reaches the lowest height.\textsuperscript{60}

5. Squat ascent phase- When the COM from the lowest height begins to ascend until the instant of COM returns to standing height.\textsuperscript{60}
6. Intra-limb segment coordination pairs- Relative motion of two segments of the same limb.

7. Intra-individual variability- the difference between subsequent squats of one individual.

**Assumptions**

The following assumptions were made during the study:

1. Participants self-reported ankle sprain history and associated functional instabilities as identified by the questionnaires as accurately as possible.

2. Participants performed the squat tasks to the best of their ability, communicate any pain or discomfort throughout the testing session, and complete entire duration of the rest periods to minimize fatigue.

**Limitations**

Limitations for the proposed study include the identification of CAI via self-report questionnaire performance, possibility of fatigue influencing the results of the trials near the end of the testing session, and convenience sampling. The questionnaires were selected based on good psychometric properties to determine the presence of CAI and endorsement by the International Ankle Consortium. Rest periods between trials are included and of sufficient length to mitigate the effects of fatigue on latter trials. Convenience sampling within a college age population may not provide an accurate representation of the variability within the CAI population.
CHAPTER 2
LITERATURE REVIEW

This review of literature serves to discuss aspects of chronic ankle instability (CAI), squat tasks, coordination, and human movement variability pertaining to the proposed study. First, CAI is defined by proposed models used to highlight the differences within CAI individuals based on the presence of mechanical and/or functional insufficiencies to support the rationale that not all CAI individuals will perform the squat similarly. Epidemiology, pathomechanics, and assessment techniques associated with CAI are also presented. Second, squat mechanics and movement phase definitions are highlighted in addition to the clinical application and modification of squats in healthy and CAI individuals. Third, coordination is defined to provide an understanding of intralimb coordination prior to presenting dynamical systems theory and its current application in CAI research. An overview of two most common coordination analysis techniques is presented prior to discussing previous coordination studies conducted (1) in the CAI population and (2) with a squat task as the experimental task. Fourth, human movement variability as it pertains to the proposed study is defined along with presentation of previous results highlighting (1) association with injury, (2) comparison between CAI and healthy individuals, and (3) presence during squat tasks. Finally, variability analysis techniques and current motion capture methodology will be reviewed to explain rationale for selection of certain methodological and assessment techniques.
2.1 Chronic ankle instability (CAI)

Lateral ankle sprains are one of the most commonly reported sports-related injury.62,63,64,65,66 Of those with a history of ankle sprain, 32-74% individuals will incur residual and/or chronic symptoms, such as recurrent sprains and/or perceived instability.67,68 Chronic ankle instability (CAI) is the term used to identify individuals who have a history of at least one significant ankle sprain and at least one of the following: history of the previously injured ankle ‘giving way’, recurrent sprains (2 or more), or ‘feelings of instability’ during physical activities.61

The direct cause(s) of chronic ankle instability (CAI) development following a lateral ankle sprain is/are still undetermined and present unique challenges for clinical assessment and intervention. Mechanical and functional discrepancies between those with and without CAI have been assessed in the literature and have contributed to the development of current clinical assessment techniques to identify those with CAI and consequently their movement pattern characteristics when performing daily tasks.

2.1.1 Classification of CAI

The original CAI model explained individuals with CAI suffer from both mechanical and functional insufficiencies on an overlapping continuum and the degree to which patients experience either may result in recurrent ankle sprains.2 Mechanical insufficiencies result from anatomical changes following the initial lateral ankle sprain and may include alterations in laxity, arthokinematics, and synovial characteristics.2 Whereas functional insufficiencies include impaired proprioception, neuromuscular control, and postural control in addition to strength deficits.2
The original CAI model evolved to include the number of recurrent sprains with either or both mechanical and functional insufficiencies contributing to the development of CAI. Inclusion of recurrent sprains improved the original model from identifying approximately 57% to 100% of individuals suffering from CAI. The three factor model takes into consideration those with residual symptoms and recurrent sprains with either mechanical or functional instabilities in addition to those who suffer from both mechanical and functional instabilities, creating seven possible subgroups. This suggests multiple subgroup classifications within CAI exist and may translate to multiple subgroups of movement abilities during functional tasks, based on specific limitations in that patient.

2.1.2 Epidemiology of CAI

Various age, gender, and sporting populations have differing levels of CAI prevalence. Epidemiological studies have determined the onset of CAI as early as adolescence. In a general adult population 18-65 years of age, approximately 20% of individuals are affected by chronic musculoskeletal ankle disorders. Approximately 23% of high school and collegiate athletes are affected by CAI with CAI more prevalent among high school and females athletes compared to their collegiate and male counterparts, respectively. However, CAI has been identified as more prevalent in young adult males (1.1%) compared to females (0.7%) in the general public. Recurrent ankle sprains are the most commonly reported aspect of CAI in court and field sports whereas track and field athletes reported perceived instability and gymnastics reported residual symptoms.

2.1.3 Pathomechanics of CAI

Characteristics of CAI can be described by the pathomechanics resulting in mechanical insufficiencies and perceived instability that may contribute to the recurrence of ankle sprains.
Mechanical insufficiencies present in CAI individuals are dependent upon the initial sprain with injury to the anterior talofibular ligament (ATFL) and/or calcaneofibular ligament (CFL) leading to talocrural and subtalar joint instability, respectively.\textsuperscript{2} Restricted arthrokinematics of the talocrural, subtalar, and/or distal tibiofibular joints may be present with or without decreased dorsiflexion range of motion.\textsuperscript{2} Arthrokinematics may also be restricted by the impingement of hypertrophied synovial tissue or the development of degenerative joint lesions.\textsuperscript{2} Lateral and anterior joint mechanical laxity of the ankle as measured by an arthrometer have been determined to have large effect sizes of 0.84 to 2.61 with inversion talar tilt and 0.32 to 1.82 with anterior drawer within a CAI population, respectively.\textsuperscript{72} This mechanical laxity is consistent with the primary mechanism of the initial lateral ankle sprain. Lastly, a more anterior fibular position has been identified in the CAI limb compared to the uninvolved limb and health controls.\textsuperscript{73}

\textbf{2.1.4 Assessment Methods to Determine CAI Presence}

Due to the multiple factors contributing to the development of CAI, a multi-step approach is necessary to determine the presence of CAI by identifying mechanical and functional insufficiencies with clinical objective measures and subjective questionnaires, respectively.

\textit{2.1.4.1 Clinical Measures}

Various clinical measures are used to determine deficits in CAI individuals with respect to ligamentous laxity, restricted range of motion (ROM), self-report function, and functional performance.

\textit{2.1.4.1.1 Ligamentous laxity}

The presence of mechanical insufficiencies can be determined by identifying ligamentous laxity in CAI individuals with manual or instrumented arthrometer testing. Manual stress tests,
such as the inversion talar tilt and anterior drawer, are commonly performed following an ankle injury to assess lateral ankle ligament complex integrity. Within a CAI population the accuracy of a manual talar tilt test has been determined to be poor as a single diagnostic measure (sensitivity=0.49 and specificity= 0.78-0.88). The diagnostic accuracy of the manual anterior drawer test in those with a history of one or more lateral ankle sprains, not confirmed to have CAI, has been determined to be good at ruling out anterior mechanical laxity as a single diagnostic measure (sensitivity=1.00 and specificity=0.62). Instrumented arthrometer testing is more commonly used in research labs than in clinical settings. However, instrumented ligamentous testing allows for quantification of laxity and stiffness. In CAI individuals, the effects of lateral ligament complex laxity have been identified with instrumented inversion (0.84 to 2.61) and anterior drawer (0.32 to 1.82) measures which are consistent with the primary mechanism of injury for the initial ankle sprain.

2.1.4.1.2 Restricted range of motion

Active ankle range of motion (ROM) can be evaluated in either an open or closed chain position with goniometry or a weight-bearing assessment, respectively. Weight-bearing assessment of ankle dorsiflexion ROM is more representative of the ROM available during closed-chain functional tasks than a goniometric assessment. Closed chain dorsiflexion ROM is significantly less in those with CAI compared to healthy controls. There are multiple versions of the weight-bearing lunge test (WBLT) to assess closed chain dorsiflexion ROM. The original WBLT described by Bennell et al. measures (1) the angle between the tibial shaft and the vertical with an inclinometer and (2) the greatest distance of the great toe from the wall when the knee is in contact with the wall. The inter- and intra-rater reliability for the original WBLT is excellent (ICC=0.97 (angle) and 0.99 (distance); and ICC=0.97-0.98, respectively).
simplified version of the WBLT elevates the testing leg on a box and has the patient displace the hips and trunk forward with the knees flexed, measuring the same angle as the original WBLT.  
Regardless of WBLT method, strong evidence of good to excellent inter- and intra-rater reliability and a minimum detectable change of 4.6° between clinicians has been found in the literature.

2.1.4.2 Patient Reported Outcomes (PROs)

Functional instability can be identified by a clinician through the implementation of patient reported outcomes (PROs). Region-specific PROs have been used to identify functional and health-related quality of life deficits in CAI individuals. There are currently eight questionnaires available for clinicians to use to identify functional instability in patients with a history of ankle sprains: Ankle Instability Instrument (AII), Ankle Joint Functional Assessment Tool (AJFAT), Chronic Ankle Instability Scale (CAIS), Cumberland Ankle Instability Tool (CAIT), Foot and Ankle Ability Measure (FAAM), Foot and Ankle Instability Questionnaire (FAIQ), Foot and Ankle Outcome Score (FAOS), and Identification of Functional Ankle Instability (IdFAI). A gold standard in which to compare these questionnaires for the identification of self-reported functional ankle instability has not been identified. These eight questionnaires have been utilized in an attempt to identify two minimum criteria for functional ankle instability: history of at least one ankle sprain and experiencing an episode of ‘giving way’. The IdFAI questionnaire and the combined use of the CAIT and AII were able to provide an accurate prediction of meeting the two minimum criteria for functional ankle instability and are recommended by the International Ankle Consortium to identify those with CAI in research. The psychometric properties of the AII, CAIT, Quick-FAAM, and IdFAI are presented to justify the implementation of these specific PROs for the proposed study.
2.1.4.2.1 Ankle Instability Instrument (AII)

The Ankle Instability Instrument was developed to objectively measure functional insufficiencies associated with CAI. The instrument consists of 9 yes or no questions with 3 questions asking the individual to select specific criteria pertaining to why “yes” was chosen. The AII collects information pertaining to the occurrence, severity, and assistance needed following an initial ankle sprain and perceived feelings of instability during various activities (e.g., walking, sport activity, stair climbing). The overall test-retest reliability and internal consistency of the AII was determined to be excellent (ICC=0.95) and good (Cronbach’s α=0.89), respectively.

2.1.4.2.2 Cumberland Ankle Instability Tool (CAIT)

The Cumberland Ankle Instability Tool (CAIT) was developed to determine chronic ankle instability and grade the severity of the instability present. The instrument consists of 9 multiple choice questions with each answer scored differently as it pertains to ankle instability and a maximum possible score of 30. The CAIT collects information pertaining to pain and when sensations of instability occur during certain activities of daily living and sport-related tasks. The overall test-retest reliability and internal consistency of the CAIT was determined to be excellent (ICC=0.96) and good (Cronbach’s α=0.83), respectively. Initially a score of ≥28 identified those who were unlikely to have functional ankle instability and those with ≤27 identified those who were likely to have functional ankle instability (sensitivity =82.9% and specificity=74.7%). A repeated study found a cutoff score of ≤25 to identify those likely to have functional ankle instability produced better diagnostic properties (sensitivity = 96.6% and specificity 86.8%).
2.1.4.2.3 Foot and Ankle Ability Measure (FAAM)

The Foot and Ankle Ability Measure (FAAM) was developed to assess self-reported changes in activities of daily living (ADLs) and sport-related tasks for individuals with musculoskeletal disorders of the leg, ankle, and foot. The instrument consists of 2 subscales (i.e., ADLs and sports) with 29 likert-scale questions for individuals to rate ability to complete the task relative to foot and ankle function and 3 questions to rate percentage of current level of function. The test-retest reliability of the FAAM-ADL and FAAM-Sport subscales were determined to be good (ICC=0.89 and ICC=0.87, respectively). The internal consistency of the FAAM-ADL and FAAM-Sport subscales were excellent (α=0.98 and α=0.96, respectively).

The Quick-FAAM is a 12-item shortened version of the FAAM to assess function in individuals with CAI pertaining to ADLs and sport-related tasks. The Quick-FAAM was strongly correlated with the original FAAM ($r=0.95$) to determine convergent validity. Test-retest reliability was not determined. The internal consistency of the Quick-FAAM was determined to be excellent (Cronbach’s α=0.94).

2.1.4.2.4 Identification of Functional Ankle Instability (IdFAI)

The Identification of Functional Ankle Instability (IdFAI) was developed to identify functional ankle instability deficits with a single questionnaire. The instrument consists of 10 likert-scale questions for individuals to report characteristics of ankle sprain history and instability sensations. The overall test-retest reliability and internal consistency was determined to be excellent (ICC=0.92 and Cronbach’s α=0.96, respectively). A score of ≤10 and ≥11 best determined individuals unlikely and likely to have functional ankle instability, respectively (Youden index=0.77; sensitivity=83%; specificity=94%).
2.1.4.3 Functional tests

The functional or perceived instability aspect of CAI has been associated with poor static and dynamic balance and poor performance on various functional tests in individuals with CAI compared to their healthy counterparts.\textsuperscript{90,91,92} Commonly utilized functional tests include the Star Excursion Balance Test (SEBT) to identify dynamic postural control deficits\textsuperscript{93} and various hop tests to stress the lateral ligament complex\textsuperscript{91,92}. All of these functional performance tests measure task outcomes and do not consider how the individual moves to complete the task. A performance test or functional task needs to be identified to allow assessment of lower extremity movement function rather than task outcomes to understand how CAI affects lower chain function and improvement following an intervention.

2.1.5 Current Treatment Strategies for CAI

Of the various treatment strategies used by clinicians to address the mechanical and functional insufficiencies associated with CAI, balance training and multimodal rehabilitation (e.g. addressing strength, range of motion, and balance deficits)\textsuperscript{94} have consistently shown moderate-to-strong effects of improvements in self-reported function for ADLs and physical activity.\textsuperscript{12} Dynamic, closed-chain activities used as functional rehabilitation tasks have also been associated with improved self-reported ankle function and postural control.\textsuperscript{13} However, a consensus on the best prevention and intervention approaches to improve self-reported function is still not apparent due to the lack of literature focusing on how CAI individuals perform tasks. Selecting the best intervention strategy has previously used a “one-size-fits-all” approach, which may not be warranted given the continuum of dysfunction and variety of insufficiencies across those with CAI. Additionally, a biomechanical or neuromechanical rationale based on task performance may be necessary for selecting the best prevention and intervention strategies.
Currently, that approach is not used, but could be of greater benefit and efficiency to clinicians and patients.

2.2 Squats

A squatting movement can be used as a functional strengthening or rehabilitation exercise as well as a clinical assessment tool. The squat is used as a functional strengthening and rehabilitation exercise because of the similarities in demand to a variety of athletic movements and activities of daily living (ADLs).\textsuperscript{34} Clinical use of the squat allows bilateral assessment of multiple lower extremity joints with respect to joint range of motion and musculature strength. It is easy to perform, well known and practiced among participants, and easy to standardize for research. Focusing on the interaction of the adjacent segments rather than the depth of the squat during a clinical assessment accounts for how an individual moves, or the identification of movement pattern characteristics that are associated with overactive and underactive musculature.\textsuperscript{95} Aspects of the squat task or initial starting position may be manipulated by a clinician to increase or alleviate the contribution of certain musculature.\textsuperscript{96} The double-leg squat has been used as an assessment technique in the anterior cruciate ligament (ACL) literature and provided useful information on strength and range ROM of the lower extremity\textsuperscript{97}, and muscle activity disparity.\textsuperscript{98} It is well studied at the knee, however, only a few studies were found to assess squatting abilities in CAI individuals.\textsuperscript{99,100,101,102} Application of a squat assessment in CAI individuals will allow bilateral assessment of how the lower extremity moves in a closed-chain functional task representative of common sport movements and activities of daily living.

2.2.1 Squat Mechanics

The overall performance objective of a squat is to lower the center of mass (COM) with control to a desired depth and then raising the COM to the starting position while maintaining the
COM within the base of support. Squatting kinematics and kinetics can be influenced by gender and age making it necessary to understand characteristics of typical performance in a select group. The two primary phases of a squat task can be defined as the descent (0-53%) and ascent phases (53-100%). The descent phase can be defined as the individual starting in an upright standing posture and ending with the ankles, knees, and hips fully flexed to the maximum flexion angle achieved. The ascent phase can be defined as starting from the fully flexed position in all three joints extending to return to the initial upright posture. The ankle, knee, and hip joints will simultaneously flex and transition into extension during the descent and ascent phases, respectively. Hip and ankle extensor moments occur during both phases, whereas, knee flexor moments occur at the beginning and end of a squat with a knee extensor moment occurring during the middle 70% of the squat. During the descent, the extensor moments of the hip and ankle dissipate energy to due to the eccentric movement to control the rate and amount of descent. During the first 15% of descent the knee flexor moment initiates the downward motion followed by an eccentric contraction for the remaining portion of descent to control the amount of knee flexion. The knee extensor moment during the first portion of the ascent phase (53-85%) works simultaneously with the extensor moments of the hip and ankle to drive the concentric movements needed to return to standing. The knee flexor moment during the remaining portion of the ascent phase (85-100%) slows the rate of knee extension as the individual returns to the starting position.

2.2.2 Clinical Use of Squats

The overhead deep squat is a variation often used by clinicians to assess muscle flexibility and strength. The general alignments expected in a double-leg squat include: neutral head position, slightly extended thoracic spine, neutral lumbar spine, flexed and aligned
hips, knees aligned with feet in frontal plane, and feet flat with the ground. Various movement deviations screened for by the clinician as the patient performs multiple repetitions of the overhead deep squat include: flattening of the medial longitudinal arch, foot external rotation, knee valgus, excessive forward trunk flexion, and arm extension (lowering). Common deviations with inadequate closed-chain dorsiflexion include: femur not parallel or past parallel with the floor, forward trunk flexion, or rearfoot elevation. Inclusion of the upper extremity in the overhead deep squat allows the clinician to assess potentially overactive or underactive muscles in the upper extremity to be identified, but the overhead aspect of the squat is not necessary to assess movement abilities of the lower extremity and trunk.

2.2.3 Rearfoot Manipulation in Squat

Rearfoot elevation during squat descent suggests increased flexibility is needed in the talocrural joint. During an overhead squat, individuals with limited closed-chain dorsiflexion range of motion had less knee flexion and ankle dorsiflexion displacement. It has been suggested implementation of a wedge under the rearfoot, or a method to elevate the rearfoot during the squatting task, may increase range of motion proximally up the lower extremity kinematic chain. Increases in proximal joint range of motion may allow the individual to achieve the proper depth and alignment of femur past parallel, upper body parallel with tibia, and knees aligned over feet. In healthy resistance trained individuals, less forward trunk flexion angles at peak knee flexion and external hip joint moments occurred during squats with a heel wedge versus barefoot squats. These are both positive changes in squat mechanics. As mentioned, those with CAI commonly demonstrate loss of closed chain dorsiflexion. The implementation of a wedge under the rearfoot to alleviate inadequate closed-chain dorsiflexion in
those with CAI may allow similar changes in proximal lower extremity joints, resulting in more positive squat mechanics.

2.2.4 Squats in CAI population

There are a limited number of studies assessing various squat abilities in the CAI population, none of which assess or compare lower extremity kinematics.\textsuperscript{100,101,102} No differences were observed between Functional Movement Screen (FMS) deep overhead squat scores between CAI and healthy individuals, but CAI individuals significantly differed from controls in asymmetrical loads generated by the limbs with and without CAI.\textsuperscript{100} The FMS characterizes the movement characteristics based on a 0-3 scale focused on movement of individual segments in the frontal and sagittal planes.\textsuperscript{33} FMS scoring does not quantifying the degree of interaction between segments, which may better identify altered mechanics in this population. During a single-limb rotational squat, less gluteus maximus activation in CAI individuals than the healthy controls occurred at the position of maximum knee and hip flexion and rotation.\textsuperscript{102} This may identify altered neuromuscular control patterns resulting in compensatory movements or inability to fully complete the task.

Therefore, the current squat assessment comparisons between CAI and healthy individuals suggest there are differences between the two in asymmetrical distribution of the load between the limbs\textsuperscript{100} and altered muscular activation to complete the task\textsuperscript{102}. However, there is a need to quantify how segment pairs interact with one another throughout a squat to understand the associated altered mechanics likely resulting from inadequate closed-chain dorsiflexion ROM that could predispose the individual to other orthopedic injuries.
2.3 Coordination

Coordination is the organization and integration of multiple joint movements to complete a task. Movement changes of one joint during locomotion or other movement tasks (e.g. a squat) corresponds with changes in adjacent segments and corresponding joints resulting in whole-body movement pattern changes. Each of the joints contributing to movement of the lower extremity has a certain number of degrees of freedom (DOF) based on constraints (e.g. anatomical restrictions) in which the joint is free to move. The act of mastering redundant DOFs to perform a task is referred to as Bernstein’s DOF problem. When the lower extremity joints are considered linked to one another, the summation of the degrees of freedom for each joint provides the total number of DOFs for the lower extremity and how it is constrained to act as a functional unit, defining movement capabilities in open kinematic chains. Additional constraints are placed on the system when the distal limb is in contact with the ground in closed chain activities. Establishing and defining constraints via linkage of joints within the lower extremity allows for the study of joint coordination during movement.

Aspects of human movement that have contributed to the understanding and further investigation of coordination include: automatization, generality, synergies, and the structure of movement. Automatization of intra- and inter-limb coordination in movements such as walking is considered to be the succession of phases and similar movement characteristics within each phase across multiple cycles. This in conjunction with generality, or the aspect in which locomotor tasks (e.g. walking or squatting) are mastered by a large majority of the general population, allows for common characteristics to be discovered and compared to pathological populations. The structure and associated synergies of human movement are the two aspects more frequently studied in coordinative literature. The underlying rhythms and amplitudes of
structural elements ratios determine inter-individual differences not the task parameters. Examples of this have been found in bimanual coordination research in which a fixed amplitude and frequency between the two hands was maintained after applied perturbations to either hand and manipulation of mechanical restraints and visual frequency stimuli. Synergy of the musculoskeletal and nervous systems are said to provide a “reflection of the integration of central and peripheral processes”. Synergies, or coordinative structures, are a functional group of anatomical structures across several joints constrained to act as a single unit to perform a task (e.g. the right lower extremity during walking gait).

Multiple theories and analysis techniques exist to define and identify movement coordination, respectively. Emphasis on the dynamical systems theory to explain the coordination progression and analysis techniques identified in the CAI literature are summarized.

2.3.1 Dynamical Systems Theory

The application of dynamical systems theory in the study of coordination seeks to identify the evolution of a spatio-temporal patterns over time with respect to movement pattern and perception-action pattern stability. Coordination is a consequence of self-organization of multiple systems which can be described by collective variables, or commonly referred to as order parameters. Variability, stability, complexity, and adaptability are the common aspects studied to understand the dynamics of movement over time. Coordination pattern variability compared to task end-point variability is associated with mastering redundant degrees of freedom to perform a task versus poor performance, respectively. Stability is the ability of a system to return to its original state following a perturbation. The number of interacting parts determines the complexity of a system in which greater complexity allows a greater range of adaptable responses to change in movement patterns based on intrinsic or extrinsic changes. A decrease
in complexity is not necessarily associated with disease or age, but rather a change in complexity of measured system outcomes is dependent upon the demands of the task and intrinsic dynamics of the system.\textsuperscript{115} Lastly, adaptability refers to the flexibility of a system to change following a perturbation.\textsuperscript{113}

Dynamical systems theory has been proposed to understand and treat lateral ankle sprains and CAI with a constraints-based approach.\textsuperscript{16,116} Consideration of organismic, task, and environmental constraints to understand and address alterations in the sensorimotor system following a lateral ankle sprain are said to improve intervention strategies to prevent the development of CAI.\textsuperscript{16} Inadequate closed-chain dorsiflexion present in a majority of CAI individuals\textsuperscript{53} may be one organismic constraint confining movement abilities. Similarly, the consideration of manipulating task constraints has been proposed to effectively develop balance training programs for those with CAI.\textsuperscript{116}

\textbf{2.3.2 Coordination Analysis Techniques}

Analysis techniques have been developed to quantify relative motion between two intra-limb joints during cyclic tasks to understand movement coordination. Conventional techniques (e.g. plotting angular position versus time) lead to the development of quantification methods such as relative phase and vector coding.\textsuperscript{117,118,119}

\textit{2.3.2.1 Continuous Relative Phase}

Continuous relative phase (CRP) is one of the most common used measures to assess spatio-temporal coordination variability of human movement kinematics.\textsuperscript{120} Relative phase as a function of time is considered CRP whereas relative phase measured at one time point is discrete relative phase.\textsuperscript{121} CRP identifies in-phase and anti-phase coordination by determining the phase angles of the two joints of interest.\textsuperscript{39} The phase angle for each joint is defined as the arctangent
of angular velocity/angular position at a given instant in time. CRP is then the difference of the two phase angles determined at that time point and repeated within the cycle. Overall, CRP quantifies the kinematic relation of two body segments. Various normalization techniques and phase angle definitions exist in the CRP literature but due to the velocity-displacement ratio within the computation, normalization techniques and use of a singular phase angle definition may be inconsequential. However, the need of normalization techniques is still undetermined and should be determined by the type of movement and the research question. Other parameters that have been shown to influence continuous phase outcomes include nonstationarity and frequency of human movement.

2.3.2.2 Vector Coding

Vector coding is the other most commonly used measure to assess spatio-temporal coordination of human movement kinematics. Vector coding as proposed by Tepavac and Field-Forte addresses the modification of two separate repetitions or cycles of different lengths (different number of data points) when quantifying angle-angle data relative to the length of the interval between frames over multiple cycles or repetitions as proposed by Sparrow et al. The coupling angle is the quantification of two segments moving relative to one another over multiple repetitions of a task (e.g. walking) normalized to the mean cycle period. Overall, the angular displacement between the two joints of interest is represented by the magnitude of the vector determined by the frame-to-frame angular differences of each joint. The relation of intra-limb joint angular motion can be analyzed relative to angles (shape), length of between frame intervals (magnitude), a combination of shape and magnitude, dispersion of relative joint motion about the mean, and overall variability for all cycles collectively.
2.3.3 Coordination in CAI

Coordination in CAI individuals has been studied during walking and jogging gait treadmill tasks.\(^{29,30,42,43}\) During walking, the shank-rearfoot coupling relationship in CAI individuals was more out of phase than healthy controls with the rearfoot leading the shank in terminal swing of walking gait and before terminal stance and swing of jogging gait.\(^{29}\) Herb et al.\(^{30}\) found similar rearfoot motion compared to the shank during the late swing phase of walking gait but found greater rearfoot motion relative to the shank during early stance, midswing, and terminal swing. The application of ankle tape decreased the magnitude of shank-rearfoot motion for initial contact of walking and the swing phase of jogging in those with CAI and healthy controls.\(^{42}\) Significantly altered hip-ankle coordination has also been identified in those with CAI during walking gait.\(^{43}\) Sagittal hip-ankle coordination was less during the first half of midstance but more during terminal stance and pre-swing; frontal hip-ankle coordination was less during loading response.\(^{43}\) Current coordination research in CAI has focused on various types of gait but has not considered coordination during other functional tasks such as a squat. The squat represents common sport-related movement and activities of daily living, and could be applied to determine if similar coordination changes in CAI individuals are present across multiple tasks.

The inclusion of a task outcome, such as lowest vertical minima of a squat, that best measures the overall performance objective of the task will allow more direct comparisons of coordination abilities across pathological and healthy groups to confirm the assumption that the two achieve similar outcomes with varied self-organization. If the outcome (lowest vertical minima in a squat) is the similar between the two, then we know CAI is in fact varying their DOF differently to achieve the same goal. If similar changes are identified in gait-related and
other functional tasks (e.g., the squat) with similar outcome variables between groups, it could result in changes in rehabilitation, assessment, and return to play approaches.

2.3.4 Coordination in Squats

Double-leg bodyweight squat coordination has not been reported in the literature; studies either identify joint kinematics\textsuperscript{105,125} or use a variation of the squat such as the squat-lift\textsuperscript{117,126,127}. Squat-lifting is similar to the ascent phase of squat due to the individual starting at the lowest point and lifting an object to waist height. For a stand-squat-stand lift, positive relative phase angles were identified during the descent to pick up the box and negative relative phase angles were identified during the ascent to bring the box to waist height.\textsuperscript{117} Relative phase angles that were positive identified the proximal joints lead the distal, while negative identified the proximal joints were behind the distal.\textsuperscript{117} For a squat-lift task with an unloaded crate, similar results were found for knee-shoulder and ankle-hip relative phase.\textsuperscript{126} Lastly, two categories of knee-lumbar coordination strategies were prominent within a group of males during the ascent phase and may be applicable when performing bilateral bodyweight squats.\textsuperscript{127} These previous studies provide an idea of what would be expected in a normal individual during the ascent phase of a bodyweight squat to discern if proximal and distal joint coordination differs in CAI individuals. If identified in the squat task as proposed there may be similar coordination changes affecting CAI individuals in everyday tasks such as lifting a box with compounding effects.

2.4 Variability

Variability for the purpose of this study is the degree to which a measured value differs from a mean value or expected norm. In human research, there are two types of variability that can influence statistical results: inter-individual and intra-individual variability. An “optimal” range has been theorized to be the desirable range of coordination variability during human
movements to mitigate injury risk. Variability differences for inter-joint coordination, joint kinematics and kinetics, and temporal variables during functional tasks have been identified in pathological populations including CAI. More than 70 variability analysis techniques have been identified in the literature with respect to statistical, geometric, energetic, informational, and invariant domains. For the purpose of this study, inter- and intra-variability will be emphasized to determine if multiple movement strategies exist within a CAI population, aligning with the seven subgroups proposed to exist in the CAI continuum. Inter- and intra-variability will also be used to determine the amount of variability present over multiple repetitions which may explain the long-term consequences of CAI. Identifying if too little or too much variability exists between multiple repetitions of functional tasks in those with CAI compared to healthy individuals will provide insight to how mechanical loading of anatomical structures over time may result in certain sequelae, such as posttraumatic osteoarthritis.

2.4.1 Inter-individual versus Intra-individual Variability

Human movement behaviors evolve as a function of time and place for an individual. The inherent nature of human movement does not allow an individual to perform a task in the same manner twice even if the outcome of the task is the same. For example, less movement variability of a pistol barrel and greater variability within the upper extremity joints was observed in experienced pistol shooters, whereas, the opposite variability of the pistol barrel and upper extremity joints was observed in less experienced shooters. Inter-individual and intra-individual variability are two measures influenced by the dynamics of human movement throughout a lifespan. Inter-individual variability within behavior space is determined as the difference of values on a selected subset of variables at one time point, e.g. the differences observed between the experienced and novice pistol shooters. Intra-individual variability
within behavior space is determined as the difference of values for one subject on a selected subset of variables pooling across time points, e.g. comparing multiple trials of one pistol shooter.\textsuperscript{131}

Inter- and intra-variability are related measures based on ergodic theorems in which every individual is representative of the whole group.\textsuperscript{131} Generalization of inter-individual analyses to an individual within a group can only be done if two aspects of the ergodic theorem are true: stationarity of measures and the same dynamics among individuals within the group.\textsuperscript{131} If there is non-homogeneity across the sample (nonergodic), then intra-individual analyses are necessary to understand individual results.\textsuperscript{131} Increased sample size has been associated with increased differences or non-homogeneity of treadmill walking kinematic variables within groups.\textsuperscript{58} Additional studies support the notion of nonergodicity in human movement research in which multiple strategies within a group of individuals during walking and landing were identified questioning the validity of group analyses.\textsuperscript{132,133,134} Because of this and the idea of seven subgroups within the CAI continuum, it is expected that non-homogeneity also exists within CAI individuals and questions the validity of group analyses.

2.4.2 Association with Injury

Kinematic and coordination variability throughout functional tasks has become of interest in the injury prevention and care literature. An inverted “U” relationship has been proposed to describe “optimal” variability occurring in human movement as the desirable amount of variability associated with good health and no injury.\textsuperscript{128} Too little variability would make the individual more rigid and unable to adapt to perturbations.\textsuperscript{128} Too much variability would make the individual’s movements more unstable, unable to adapt to perturbations, and experience a greater frequency of end- or out-of-range movement that may predispose them to an acute
Correspondingly, others have proposed the application of the loss of complexity hypothesis to injury meaning injury or pathology may emerge when coordinative variability and degrees of freedom are reduced to or below a critical threshold. The over-arching premise is degree of movement variability and injury are somehow related, but that relationship is still unclear in specific injury situations.

The type of pathology may determine the subsequent increase or decrease of movement variability following injury. Decreased stride-to-stride and intralimb joint coordination variability has been identified in CAI and unilateral patellofemoral pain (PFP) individuals compared to healthy controls, respectively. The chronic nature and/or associated pain of these two pathological groups with decreased variability supports the idea of the system being more rigid and unable to adapt to perturbations of the environment or task in which repetitive loads over a constrained area may occur. Conversely, greater lower extremity variability for multiple hip-knee and knee-knee joint coordination pairs were present in female soccer players following ACL reconstruction during a side-step cutting task and greater peak ankle moments in an injury-prone cohort during a drop-landing task. The acute nature of the two groups with increased variability supports the idea of instability and inability to adapt to perturbations of the environment or system that result in injury.

### 2.4.3 Variability in CAI

Movement variability in CAI individuals has been investigated during walking, running gait, single-leg landings, and stop jump maneuvers. Overall, CAI individuals have demonstrated less variability than healthy controls during the stance phase of gait with respect to temporal frontal plane ankle kinematics and frontal and sagittal ankle kinematics from loading response to midstance. Frontal plane ankle kinematics, however, are greater in
CAI individuals throughout the entire running gait cycle compared to healthy controls.\textsuperscript{55} During single-leg landing tasks, CAI individuals displayed greater ankle frontal and sagittal plane variability throughout the entire movement and just before touchdown, respectively, compared to healthy controls using Principal Components Analysis (PCA).\textsuperscript{56} Conversely, CAI individuals have also been found to have no difference in ankle kinematic variability during multidirectional single-leg landing tasks than healthy controls.\textsuperscript{32} However, the healthy controls had greater variability in knee rotation before initial contact and during stance, greater hip sagittal plane variability during lateral jumps, and greater hip frontal plane variability during forward jumps compared to those with functional insufficiencies.\textsuperscript{32} During a stop jump maneuver, CAI individuals differed in variability based on mechanical and functional insufficiencies with greater anterior-posterior ground reaction force variability and ankle frontal plane kinematic variability, respectively.\textsuperscript{31}

Overall the literature shows CAI individuals have less variability in most functional tasks when the limb is in contact with the ground and other variability differences among CAI individuals based on the type of insufficiencies present. Too little variability may restrict the articular surface that is loaded throughout the task which increases the stress of the area that could cause a more rapid onset of cartilage degeneration. Variability differences based on type of insufficiency present suggests not all those suffering from CAI perform functional tasks in the same manner and would benefit from more individualized interventions. Identifying the presence of too much or too little variability in CAI individuals during specific tasks at specific joints may provide rationale for additional rehabilitation interventions.
2.4.4 Variability in Squat

Only a couple of studies have reported joint kinematic variability during a squat task. The mild (less than 90° knee flexion) and deep (as low as possible) squat had greater knee joint kinematic inter- and intra-individual variability in the sagittal and frontal planes compared to walking in healthy males.\textsuperscript{138} This may suggest a squat task is either a more suitable task to identify joint coordination variability restrictions in CAI individuals compared to walking or the participants were more skilled in walking than squats. Two different knee-lumbar spine coordination strategies in healthy individuals did not vary as the load for a squat-lift task increased between 15% to 75% maximum lift capacity.\textsuperscript{139} More than one coordination strategy has been identified among healthy males, supporting the need to identify if all individuals within a group perform the same based on individual analyses prior to group comparisons for a squat task in healthy as well as CAI individuals. If multiple coordination strategies are present, multiple therapeutic rehabilitation interventions may be needed across a population.

2.4.5 Analysis Techniques to Identify Variability

Different analysis techniques exist to identify the many aspects of variability. In biomedical research, variability has become more than just inter-and intra-individual differences but as the degree and characterization of patterns within time series to which the presence of pathology can be predicted and assessed.\textsuperscript{48} Emphasis on understanding dataset properties include statistical and geometric techniques, whereas, understanding time series properties include analysis of the energetic, informational, and invariant domains.\textsuperscript{48}

\textbf{2.4.5.1 Statistical Variability Techniques}

Statistical techniques that have been used in functional movement studies to identify variability in CAI individuals include: standard deviation\textsuperscript{31,55}, coefficient of variation\textsuperscript{31,32}, and
variability of vector coding (VCV)\textsuperscript{30,42}. The use of standard deviation assumes a Gaussian distribution of the data\textsuperscript{48} across trials or participants within a group depending on intra-individual or inter-individual variability, respectively. The coefficient of variation is the standard deviation expressed relative to the mean of the distribution. VCV is the average standard deviation over a time interval of the joint coordination determined with vector coding\textsuperscript{135}. All three techniques quantify the presence of inter- or intra-individual variability but cannot explain the sources of variability.

The assumptions associated with the previously mentioned statistical variability measures were considered to determine the selection of statistical variability measures for the proposed study. Without knowing the distribution characteristics of multiple movement trials, standard deviation will not be used assuming a normal distribution is not present. Therefore, to determine the amount of variation about a mean not in the center of 68\% of the middle values the coefficient of variation is used to determine distribution variation. Reliable measures of VCV were attained from multiple segment pair couples when 10 trials were used to calculate VCV for walking and running gait\textsuperscript{140}. The squat procedure for the proposed study is cyclic similar to walking and VCV will be used to determine coordination variability.

\textbf{2.4.5.2 Time Series Variability Techniques}

Other analysis techniques used to assess variability focus on identifying nonlinear dynamic properties of a time series\textsuperscript{48}. Energetics of a time series may include frequency analysis to determine frequencies driving the waveform of the time series\textsuperscript{48}. Informational aspects of a time series identify regularity via entropy measures to determine how predictable the next state is from the previous\textsuperscript{48,141}. Lastly, features that are not supposed to change over time or space are analyzed in the invariant domain and may include scaling exponents, detrended fluctuation
analysis, or computing the correlation dimension.\textsuperscript{48} The use of these measures requires considerations for stationarity, length, and noise of the signal.\textsuperscript{142} These variability measures will not be used to address the aims of the proposed study because the measures assess the underlying biological systems controlling movement and do not quantify the amount of inter-or intra-individual variation between trials.

\textit{2.4.5.3 Coordination Variability Techniques}

Various analysis techniques exist to quantify spatio-temporal coordination variability and should be used appropriately to address the research question.\textsuperscript{143} For the purpose of coordination variability, principal components analysis (PCA) determines the primary kinematic variables needed to explain the majority of movement variation of how an individual performs the task from numerous kinematic variables.\textsuperscript{144} Angular deviations of the coupling angle between two segments in a plane of interest quantifies coordination variability in continuous relative phase (CRP) and vector coding.\textsuperscript{120} Therefore, the determination of a smaller group of kinematic variables to describe movement variation calls for the use of PCA and quantifying the degree of coordination variability relative to two segments determined \textit{a priori} calls for the use of CRP or vector coding.

Current coordination segment pairs selected are based on clinical experience or judgment and may limit the information obtained studying coordination patterns in functional tasks. Subjective visual assessment to determine segment pairs may mislead the researcher away from other segment pair relations that are more meaningful. Therefore, an exploratory approach such as with PCA will allow the identification of multiple segments that collectively explain a certain amount of variation of the movement without clinical bias and provide a new perspective.
Follow up analyses with CRP or vector coding to quantify the degree of coordination will then have justification for certain segment pairings.

2.4.5.3.1 Continuous Relative Phase (CRP) versus Vector Coding

Continuous relative phase (CRP) and vector coding both quantify coordination by considering phase plane trajectories of two segments relative to one another, but vary in how the phase planes are constructed.\textsuperscript{120} With respect to variability, angular deviations are considered similar to standard deviations of normal data.\textsuperscript{120} Theoretical and experimental comparisons of the two measures determined state space transitions determined with CRP variability agreed more with dynamical systems theory and appeared to be more conservative, whereas, aspects of variability (e.g., magnitude and peak timing) varied with technique.\textsuperscript{120} Although variability changed similarly in both measures as treadmill speed increased, results from the two measures should not be directly compared across studies.\textsuperscript{120} Movement variability during gait has been assessed in CAI individuals primarily using vector coding.\textsuperscript{30,42,43}

2.5 Review of Methodological Techniques

Self-reported questionnaires will be used to determine physical activity level and presence of CAI. Recreationally active individuals will be determined with a score of ≥24 on Godin-Shephard Leisure-Time Physical Activity Questionnaire (GSLTPAQ).\textsuperscript{145} The GSLTPAQ is endorsed by the International Ankle Consortium to report physical activity levels in CAI\textsuperscript{61} and has been validated with comparisons to VO\textsubscript{2}max and physical activity participation frequency\textsuperscript{145}. The Identification of Functional Ankle Instability (IdFAI), Cumberland Ankle Instability Tool (CAIT), and the Ankle Instability Instrument (AII) will be used to identify the presence of CAI. Feelings of instability will be identified with either a score of score ≥11 on the IdFAI\textsuperscript{83} or the
combined results of a CAIT score ≤24 and “yes” to at least 5 yes/no questions (including question 1) on the AII.

The use of 3D motion capture and force plates are necessary to quantify coordination variability within the squat tasks between CAI and healthy individuals. Motion capture will be completed with a 7-camera motion capture system VICON system (v2.2, Vicon Motion Systems Ltd., UK) in which reliability of lower extremity kinematic variables were determined to be good to excellent (ICC=0.82-0.99) and moderate to good (ICC=0.54-0.96) for within-day and between-day comparisons, respectively. Kinematic reliability and error can be influenced by marker placement and skin motion. Therefore, one testing session will be used to avoid between-day error. A modified combination of the Plug-in-Gait and Oxford foot models based on a modified Helen Hayes model will be used to capture kinematic variables.

Ground reaction forces (GRFs) throughout the squat tasks will be collected with two Bertec force plates (Bertec 4060-NC, Bertec Corp. USA) aligned side-by-side to calculate joint torques via inverse dynamics. Each force plate is made of non-conductive material with a housed 16-bit digital gain amplifier and signal conditioning unit. With respect to the full-scale output signal, the maximum error due to linearity is 0.2%. Force plates will be separated by the recommended 1-2mm between the plates or other surrounding structures to decrease the occurrence of measurement errors. Separate GRFs for each foot are desired to calculate center of pressure. To obtain valid GRFs, each foot must be completely inside the surface and no extraneous objects on or touching the force plates during data collection. A recursive scheme within Visual 3D will use inverse dynamics to calculate internal joint torques.
CHAPTER 3

METHODS

Experimental Design

This was a cross-sectional study. In one session, participants were asked to complete multiple perceived ankle function questionnaires, anthropometrics, relative clinical weight bearing measures, a warm-up task, and 40 repetitions of the normal and elevated rearfoot squats for a total of approximately 1.5 hours in the biomechanics laboratory.

Participants

Following IRB approval, a convenience sample of 64 individuals (18-35 years old) with and without CAI (see CONSORT in Chapter 4) was recruited from a university population via club sports and university classes. Individuals interested in the study contacted the principal investigator or was contacted by the principal investigator based on expressed interest to participate in the study from recruitment flyers or sign-up sheets during announcements, respectively. Initial participant eligibility was determined with a prescreening survey via Qualtrics to determine age, number of hours per week of physical activity, history of ankle sprain, and exclusion criteria, but no identifiable information was recorded. If the results of the survey indicated the individual met the criteria, then participants were scheduled for a data collection session in the University of Georgia, Department of Kinesiology Biomechanics Laboratory to complete the consent, screening, and testing aspects of the study.

Participants were grouped into CAI and healthy groups based on the following criteria:
Inclusion Criteria

For all groups:

1. College age: 18-35 years

2. Recreationally active, determined by a score ≥ 24 on Godin-Shephard Leisure-Time Physical Activity Questionnaire (GSLTPAQ)\textsuperscript{61,145}

For CAI Group\textsuperscript{61}:

1. History of at least 1 significant ankle sprain
   a. Ankle sprain defined as: “acute traumatic injury to the lateral ligament complex of the ankle joint as a result of excessive inversion of the rearfoot or a combined plantarflexion and adduction of the foot. This usually results in some initial deficits of function and disability.”\textsuperscript{61}

2. Initial ankle sprain occurred at least 12 months prior to study enrollment and:
   a. Was associated with inflammatory symptoms (pain, swelling, etc)
   b. Created at least 1 interrupted day of desired physical activity

3. Most recent injury occurred more than 3 months prior to study enrollment

4. History of previously sprained ankle “giving way” and/or recurrent sprain and/or “feelings of instability”
   a. Identified with either:
      i. Identification of Functional Ankle Instability (IdFAI; score ≥11)
      ii. Or the combined results of:
         1. Cumberland Ankle Instability Tool (CAIT; score ≤24)
         2. Ankle Instability Instrument (AII; answer “yes” to at least 5 yes/no questions (including question 1)
For Control Group:

1. Pair matched control to CAI

2. Based on: gender, age, height, mass, limb dominance
   a. Gender: self-described as male or female
   b. Age within ±2 years
   c. Height and mass within ±10%
   d. Limb dominance, defined as preferred limb to kick a ball
      i. Limb dominance will be matched between groups.

Exclusion Criteria

For all groups

1. History of surgery in either lower extremity

2. Previous fracture in either lower extremity

3. Acute musculoskeletal injury (e.g., sprains, fractures) to the lower extremity in the
   previous 3 months resulting in at least 1 interrupted day of desired physical activity,
   other than the ankle sprain of interest.

4. Current pain, swelling or discoloration in either limb.

Sample Size Justification

An a-priori power analysis using G*Power™ (Version 3.0.10, Kiel University, Germany)
was completed to determine the appropriate sample size necessary to detect significant
differences between groups for kinematic and coordination variables as reported in the literature.
Reported means and standard deviations for CAI and healthy groups using vector coding
analyses were utilized to estimate an appropriate sample size for between independent groups
comparisons. For vector coding variability differences in intralimb coordination pair variability
during walking, an estimated 17 participants per group was determined necessary to obtain a similar effect size of 0.89 with power \((1-\beta) =0.80\) and \(\alpha \leq 0.05^\text{30}\).

Reported means and standard deviations for CAI and healthy groups assessing kinematic variability and squat kinematics were used to estimate an appropriate sample size for between group comparisons. Although kinematic variability throughout a squat has not been compared between healthy and injured populations, an estimated sample of 25-61 per group was determined necessary to obtain similar effect sizes of 0.23-0.91 with power \((1-\beta) =0.80\) and \(\alpha \leq 0.05\) for ankle frontal joint kinematic variability in CAI individuals, depending on the specific variable.\textsuperscript{31} An estimated sample of 7-41 participants per group was determined necessary from a previous study conducted on healthy individuals to obtain a similar effect sizes of 0.31-0.85 with power \((1-\beta) =0.80\) and \(\alpha \leq 0.05\) for sagittal ankle and knee joint displacement throughout a squat with and without a wedge implement.\textsuperscript{36}

Differences in kinematic variables within individuals and are dependent upon the number of trials collected and independent of the sample size.\textsuperscript{58} The percentage of significant intra-individual joint kinematic variable comparisons identified with 50 trials during a walking treadmill task was approximately 1.6 times that identified with 5 and 1.2 times that identified with 10 trials.\textsuperscript{58} There is a minimal increase in the percentage of significant intra-individual joint kinematic variable comparisons between 25 and 50 trials.\textsuperscript{58} A total of 40 trials were determined necessary for each task to capture a significant amount of intra-individual joint kinematic variability with consideration for the physical demands to complete numerous repetitions in one testing session.
**Research Protocol**

Research participation for subjects lasted approximately 1.5 hours for the duration of the single testing session. Participants completed an IRB approved consent form upon arrival prior to completing the physical activity (Appendix A) and ankle instability questionnaires (Appendix B). Review and scoring of the questionnaires was completed prior to the obtaining anthropometric, clinical, and experimental data to ensure all inclusion and exclusion criteria were met. The lowest scoring limb in participants with bilateral CAI was identified. Height, mass, and anthropometric measures of limb length and girth was measured with a wall mounted stadiometer, digital scale, tape measure, and sliding calipers, respectively. A tape measure was used to measure closed-chain dorsiflexion as described by Bennell et al.\(^\text{76}\) Excellent intra-rater reliability for all measures was established prior to all participant testing (ICC\(_{2,1}\) = 0.90-0.99).

Participants were instructed at the beginning of the testing session to report pain at any time during the squatting tasks, and if reported the task was stopped immediately. The participant continued if pain was no longer present after a two-minute rest period; if pain was still present, their study participation ended.

**Instrumentation**

**Motion Analysis**

Kinematic data were captured using 61 retro-reflective markers (14mm) and a 7-camera VICON-MX40 motion capture system (Vicon Motion Systems Ltd., UK) to record marker trajectories with a sampling rate of 240Hz.\(^\text{156}\) Right-handed global and local reference systems were adopted and used based on ISB recommendations.\(^\text{157,158}\) The global reference system was defined as +X projecting to the right, +Y in the anterior direction, and +Z in the upward
direction. A customized lower body and foot marker set was used based, on the Plug-in-Gait\textsuperscript{148} and Oxford foot\textsuperscript{149} models (Figure 3.1). Anatomical landmarks for the lower extremity and pelvis markers are listed in Table 3.1a and anatomical landmarks for the upper extremity and thorax markers are listed in Table 3.1b.

![Figure 3.1 Anatomical locations of reflective markers](image-url)
### Table 3.1a. Anatomical landmark placement of reflective markers for the pelvis and lower extremity.

<table>
<thead>
<tr>
<th>Pelvis</th>
<th>Leg</th>
<th>Foot</th>
</tr>
</thead>
<tbody>
<tr>
<td>anterior superior iliac spine</td>
<td>lateral aspect of thigh</td>
<td>achilles tendon insertion</td>
</tr>
<tr>
<td>posterior superior iliac spine</td>
<td>lateral femoral epicondyle</td>
<td>10mm distal to achilles tendon insertion</td>
</tr>
<tr>
<td>highest point of iliac crest</td>
<td>medial femoral epicondyle</td>
<td>10mm distal to lateral malleolus</td>
</tr>
<tr>
<td>tibial tuberosity</td>
<td>10mm distal to medial malleolus</td>
<td></td>
</tr>
<tr>
<td>lateral aspect of shank</td>
<td>navicular tuberosity</td>
<td></td>
</tr>
<tr>
<td>lateral malleolus</td>
<td>5th styloid process</td>
<td></td>
</tr>
<tr>
<td>medial malleolus</td>
<td>metatarsal heads (1,3,5)</td>
<td></td>
</tr>
</tbody>
</table>

**Note.** Markers were placed on the right and left sides of the body. The right lateral aspect of all segment markers was placed higher than the marker placed on the left limb.

### Table 3.1b. Anatomical landmark placement of reflective markers for the thorax and upper extremity.

<table>
<thead>
<tr>
<th>Thorax</th>
<th>Upper Extremity</th>
<th>Head</th>
</tr>
</thead>
<tbody>
<tr>
<td>manubrium</td>
<td>acromioclavicular joint</td>
<td>front head</td>
</tr>
<tr>
<td>xiphoid process</td>
<td>lateral aspect of upper arm</td>
<td>back head</td>
</tr>
<tr>
<td>C7</td>
<td>lateral humeral epicondyle</td>
<td></td>
</tr>
<tr>
<td>T10</td>
<td>dorsum of forearm</td>
<td></td>
</tr>
<tr>
<td>Right scapula</td>
<td>radial styloid process</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ulnar styloid process</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2nd Metacarpophalangeal joint</td>
<td></td>
</tr>
</tbody>
</table>

**Note.** Markers were placed on the right and left sides of the body. The right lateral aspect of all segment markers was placed higher than the marker placed on the left limb.
Force Platforms

Ground reaction forces (GRFs) were collected with two Bertec 4060-NC force platforms (Bertec Corp., USA) using a sampling rate of 960Hz to obtain GRFs in the anteroposterior, mediolateral, and vertical directions. Sampling frequency for kinetic analysis of squat tasks is typically reported around 1000Hz.156

Testing Procedures

Participants were asked to change into non-reflective compression shorts, and a sports bra if female and compression shirt or shirtless if male, to allow marker placement following the warm-up task. Prior to the squatting tasks, participants completed a five-minute warm-up on a stationary bike at a comfortable speed with no resistance and were given the opportunity to complete any self-selected dynamic warm-up exercises or stretches as desired. Participants were then asked to remove shoes and socks to allow foot marker placement and perform the squat tasks unshod. Retro-reflective markers were adhered to the anatomical locations previously described. Participants completed 4 trials of 10 repetitions for each of the squatting tasks (i.e., normal squat and elevated rearfoot squat) with at least two-minutes rest between each task for a total of four completed trials (or 40 repetitions) per task. The first squat task was randomized among participants and counterbalanced through the remaining of the testing session. Matched CAI and healthy participants performed the squat tasks in the same order.

Participants received standardized instructions prior to each of the squatting tasks. For the normal squatting task, participants were instructed to stand with toes facing forward, feet parallel, shoulder width a part, and with each foot on a force platform (Figure 3.2). For the elevated rearfoot squat task, participants were instructed to maintain the same starting position with the addition of a 4cm wooden block under the rearfoot (Figure 3.2). This set up mimics the
block modification used during the deep squat test of the Functional Movement Screen (FMS), a commonly used clinical assessment tool.\textsuperscript{33} Both squat tasks were completed with shoulders flexed, elbows extended, and arms parallel to the ground.\textsuperscript{159} Participants were instructed to squat as low as possible for each of the 10 repetitions, follow the previous alignment instructions, and maintain their balance throughout the entire trial. Failure to maintain alignment resulted in a bad trial. Because the participants were instructed to squat to the lowest depth comfortable while maintaining balance throughout the trial, if a noticeable difference of the squat depth was observed for any repetition within a trial or between trials then the trial was stopped, not used for analyses, and started over after the duration of a 2 minute rest period. Additionally, if the participant lost their balance at any point in the trial, the trial was stopped immediately, not used for analyses, and started over.

![Figure 3.2 Participant set up for normal squat task (left) and elevated rearfoot squat (right).](image)

**Data Reduction**

Marker trajectory gaps in the dynamic trials were filled with rigid body or pattern fill as determined appropriate in VICON Nexus (v2.4, Vicon Motion Systems Ltd., UK). The longest gap that was manually filled was 100 frames, similar to the default gap length setting in VICON Nexus.\textsuperscript{148} Raw marker coordinate data were filtered with a fourth-order Butterworth filter with zero-phase lag.\textsuperscript{160} A 4Hz cutoff frequency was determined based on visual inspection of a
spectrum analysis for marker trajectories in all three anatomical planes for the first 5 CAI and
healthy participants (Visual 3D; version 5.02.22, C-Motion, Inc., Germantown, MD).161

Anthropometric data of Dempster as summarized in Winter162 was used to determine
center of mass (COM) trajectories in Visual 3D. The mass of each segment is based on
Dempster’s calculation for the corresponding’s segment proportion to the body. The COM was
estimated as a point along the line from the distal joint center towards the proximal joint center
that is a proportion of the distance determined by Dempster (1955) (see Table 3.2).163

<table>
<thead>
<tr>
<th>Segment</th>
<th>COM(%)</th>
<th>Mass(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foot</td>
<td>0.5000</td>
<td>0.0145</td>
</tr>
<tr>
<td>Shank</td>
<td>0.5670</td>
<td>0.0465</td>
</tr>
<tr>
<td>Femur</td>
<td>0.5670</td>
<td>0.1000</td>
</tr>
<tr>
<td>Pelvis</td>
<td>0.8950</td>
<td>0.1420</td>
</tr>
<tr>
<td>Thorax</td>
<td>0.3700</td>
<td>0.3550</td>
</tr>
<tr>
<td>Upper arm</td>
<td>0.5640</td>
<td>0.0280</td>
</tr>
<tr>
<td>Forearm</td>
<td>0.5700</td>
<td>0.0160</td>
</tr>
<tr>
<td>Hand</td>
<td>0.4940</td>
<td>0.0060</td>
</tr>
<tr>
<td>Head</td>
<td>--</td>
<td>0.0810</td>
</tr>
</tbody>
</table>

Note. Adopted from Winter.162 COM is the percentage of segment length from the distal segment. Mass is expressed as the percentage of total mass.

Model segments were defined in Visual 3D using a modified Helen Hayes model150 and
segment axes and orientations were defined using the VICON Plug-in-Gait Model148 (see Figure
3.3a, Figure 3.3b) ISB recommendations157,158, respectively. The Plug-in-Gait Model is based on
the collective work of Kadaba et al.150 and Davis et al.164. Thigh segmental axes were defined
proximally with the hip joint center and distally by the lateral and medial femoral epicondyle
markers. The hip joint was defined based on the CODA pelvis using regression equations.164
Shank segments were defined proximally as the midpoint between the lateral and medial femoral
epicondyle marker and distally with the lateral and medial malleoli markers. The knee joint
center was offset from the thigh segment origin with a -1% vertical offset. Foot segmental axes
were defined proximally with the created ankle joint center and distally with the second
metatarsophalangeal marker. The ankle joint center was defined as the midpoint between the
lateral and medial malleoli markers.\textsuperscript{165} Initially, the thorax was defined proximally as the
midpoint between the manubrium and C7 marker and distally as the midpoint between the
xiphoid process and T10 marker. A virtual marker was defined to replace the manubrium and
was defined as half the distance between the two AC joint markers due to long gaps of the
manubrium marker missing within the trials. Therefore, upper arm segments were defined
proximally by the shoulder joint center and distally by the elbow joint center. The shoulder joint
center was defined as the axial offset of the shoulder offset distance and marker radius sum from
the acromioclavicular marker. The elbow joint center was defined along the line between the
shoulder joint center and the wrist joint center with a medial/lateral offset of the elbow radius
and marker radius sum from the lateral humeral epicondyle marker. The wrist joint center was
defined as the midpoint between the radial and ulnar styloid processes. Forearm segments were
defined proximally and distally by the elbow and wrist joint centers, respectively. Hand
segments were defined proximally by the wrist joint center and distally as by the hand joint
center. The hand joint center is the medial offset from the second metacarpophalangeal marker.
Figure 3.3a Anterior (a) and lateral (b) views of lower extremity segment axes orientation. 
*Note.* Red axis = x; green axis = y; and blue axis = z.

Figure 3.3b Anterior (a) and posterior (b) views of upper extremity segment axes orientation 
*Note.* Red axis = x; green axis = y; and blue axis = z.
The orientation of all joint axes were defined using the proximal segment coordinate system. The default calculation of joint angles in Visual 3D uses a Cardan sequence of rotations (x-y-z). The proximal segment was identified as the reference segment to calculate joint angles. Joint angles were calculated for the ankle with the rearfoot relative to the shank with dorsiflexion (+X), plantarflexion (-X), inversion (+Y), eversion (-Y), rearfoot internal rotation (+Z), and rearfoot external rotation (-Z). Knee joint angles were calculated and aligned with extension (+X), flexion (-X), knee valgus (+Y), knee varus (-Y), internal rotation (+Z), and external rotation (-Z). Hip joint angles were calculated and aligned with flexion (+X), extension (-X), adduction (+Y), abduction (-Y), internal rotation (+Z), and external rotation (-Z). The whole body COM trajectory in the vertical direction was determined in Visual 3D as the weighted sum of the segmental COM based on a 14-segment model.

Temporal normalization of each squat to percentage of squat time (101 points per squat; 10 squats per trial) for all corresponding variables was completed in MATLAB (v.R2017b, Mathwork Inc., Natick, MA). The start of the squat was identified as the first instant where COM lowers from standing height and the end of the squat was identified as the first instant to reach standing height after the lowest vertical minima. The normalized squat depth magnitude was determined as the lowest vertical minima of the COM expressed as a percentage of the leg length average between the two limbs.

Data Analysis

Mean and standard deviation of normalized squat depth magnitude across the 32 repetitions within each condition were calculated for the individual participant (8 consecutive repetitions within a trial of 10 repetitions). All variables were calculated for the involved limb. The involved limb was identified as the lower performing ankle via ankle questionnaires used to
determine inclusion criteria for those with CAI. If both ankles reported the same level of poor function on all questionnaires, the dominant limb was identified as the involved limb. The involved limb identified for controls corresponded to the matched CAI individual’s involved limb, with respect to dominance.

Joint Kinematic Variability. Joint angular displacement throughout a squat was determined for the ankle, knee, and hip joints in all three anatomical planes. The summated joint angular displacement variability for each participant was determined as the integrated standard deviation time series of the 32 repetitions within each task. This considers the standard deviation of the dependent variable (joint angle) at each normalized time point (to the cycle) across multiple trials and provides one value to reflect the total joint kinematic standard deviation (variability) throughout the task.

Vector Coding. The coupling angle was calculated between the horizontal axis and a displacement vector created between two consecutive time points on angle-angle diagram of two segments. Mean coupling angle for the shank-rearfoot and shank-femur were calculated across the 32 squat repetitions for each task and participant, then within groups using circular statistics as previously described. Coordination patterns for each condition at each percentage in time of the squat were determined based on ranges of mean coupling angle to identify the coordination of the two segments as in-phase (both segments moving in the same direction at the same time), anti-phase (both segments moving in opposite directions at the same time), superior-segment dominant (superior segment displacing while inferior minimally displaces) and inferior segment dominant (inferior segment displacing while superior minimally displaces). Total time spent in each coordination pattern was determined relative to the total squat time (percentage of squat time).
Prior to data analysis participant and squat outliers were identified, defined as individual participant or squat averages that fall >3SD from the respective group mean. Outliers were not removed unless abnormal kinematic values were due to kinematic or kinetic data capture or processing errors. Because of convenience sampling of participants, it was unknown if more than one participant exhibited a movement profile corresponding with different aspects of the CAI continuum. Therefore, removal of an outlier was not warranted unless kinematic or kinetic data processing results in significant marker trajectory distortion.

All 40 squat repetitions of the two squat tasks (4 complete trials each of 10 repetitions) were desired to be analyzed. However, the middle eight squats of each trial were compiled and included in the analyses (32/40 total squats per condition). The first and last squats were not included in the analyses to remove effects associated with beginning or ending the bout of 10 squat repetitions in a trial.

**Preliminary Analysis**

Independent samples t-tests were used to identify group differences in closed-chain dorsiflexion (WBLT distance) and physical activity and CAI questionnaire scores ($p \leq .05$). Independent samples t-tests were used to confirm an absence of statistically significant differences in demographics with respect to height, mass, and age between groups.

**Statistical Analysis**

*Sub-Study 1: Squat Task Outcomes and Joint Angular Displacement Variability*

A two-way Repeated Measures ANOVA was used to determine normalized squat depth magnitude standard deviation differences by group (CAI, healthy) and squat task (normal, elevated rearfoot). To determine joint angular displacement variability differences by group (CAI, healthy) and squat task (normal, elevated rearfoot) for all three anatomical planes at the
ankle, knee, and hip separately, a series of factorial (2 group x 2 task x 3 anatomical plane) ANOVAs were used. Separate factorial ANOVAs for each joint were determined necessary to identify if the task altered variability in specific planes. Differences in the sagittal plane were expected due to the change in sagittal ankle range of motion with the elevated rearfoot. The mechanism of injury for the index sprain includes ankle frontal and sagittal plane movement and changes in more than one plane may be possible. If a statistically significant interaction effect was present, then simple main effects were determined. If the interaction was not statistically significant, then main effects for group were assessed.

Sub-Study 2: Lower Extremity Coordination and Variability Throughout Squat

A series factorial (2 x 2 x 4) analysis of variance (ANOVA) was planned to determine mean differences in time spent in the four coordination patterns between tasks (normal, elevated rearfoot) and between groups (CAI, CON). This was necessary to determine if groups spent a different amount of time in the major coordination patterns (i.e., in-phase, anti-phase, superior only, or inferior only) throughout the squat for shank-rearfoot and shank-femur separately. If a statistically significant interaction effect was present, then simple main effects were determined. If the interaction was not statistically significant, then main effects for group were assessed.
CHAPTER 4
SUMMATED JOINT KINEMATIC VARIABILITY DIFFERENCES IN THOSE WITH AND WITHOUT CHRONIC ANKLE INSTABILITY DURING NORMAL AND ELEVATED REARFOOT SQUAT TASKS

\footnote{Samson CO, Simpson KJ, Newell KM, Brown CN. To be submitted to \textit{Clinical Biomechanics}}
Introduction

Of those with a history of ankle sprain, 32-74% individuals will incur residual and/or chronic symptoms, such as recurrent sprains and/or perceived instability.\textsuperscript{1,2} Chronic ankle instability (CAI) is used to identify individuals with history of at least one significant ankle sprain and at least one of the following: history of the previously injured ankle ‘giving way’, recurrent sprains (2 or more), and/or ‘feelings of instability’ during physical activities.\textsuperscript{3} Approximately 20% of high school and collegiate athletes\textsuperscript{4} and 20% of the general adult population (18-65 years)\textsuperscript{5} are affected by CAI. Furthermore, epidemiological studies have determined the onset of CAI as early as adolescence.\textsuperscript{4,6,7} Anatomical changes associated with CAI, such as increased lateral ligament complex laxity and arthrokinematic changes resulting from the initial ankle sprain, may lead to mechanical and/or functional insufficiencies such as impaired proprioception, neuromuscular control, and postural control.\textsuperscript{8} Untreated or poorly managed CAI can lead to the development of post-traumatic osteoarthritis\textsuperscript{9}, osteochondral lesion of the talus\textsuperscript{10,11}, anterolateral impingement\textsuperscript{10,12}, and peroneal tendon pathologies\textsuperscript{12}.

A higher rate of post-traumatic ankle osteoarthritis has been observed in those with CAI compared to those with a single lateral or medial ankle sprain and may be influenced by current functional abilities in everyday tasks.\textsuperscript{9,11} Residual articular surface incongruity (e.g., varus rearfoot malalignment common in those with persistent lateral ankle instability\textsuperscript{9}) and joint instability associated with CAI may increase the number and intensity of rapid loadings to the talar articular surface which may lead to cartilage degeneration after years of accumulation.\textsuperscript{13,14,15} In-vivo contact of talocrural articular cartilage in healthy ankles was less than 50% of the cartilage coverage area in specific simulated (static) phases of gait.\textsuperscript{16} These results suggest the talocrural articular cartilage contact area differs with ankle joint angular displacement throughout
a task. Thus, movement and variability of that movement throughout a task could identify potential causes of post-traumatic osteoarthritis development in those with CAI.

The majority of the current CAI literature has focused on joint kinematic group averages at discrete movement time points, such as initial contact or maximal knee flexion, but does not provide a complete representation of how a task is performed. Additionally, the conflicting results of studies with these discrete movement time points may be attributed to the lack of consideration of the entire movement profile. There is a need to consider alternative assessment techniques highlighting these pathologic insufficiencies throughout task performance to highlight intrinsic factors that will help develop more effective intervention strategies for the CAI individual. Comparison of kinematic variability throughout a task relative to the task outcome will provide a reference point (task outcome) to compare between CAI and healthy individuals and help determine if the variability difference throughout a task is clinically meaningful. This approach has been used in motor control to differentiate coordination patterns of novice and expert skill levels to understand how individuals organize various degrees of freedom in a kinematic chain.\textsuperscript{17,18} If CAI individuals have similar task outcomes but differing amounts of variability, this would be clinically meaningful and would drive the need to include intervention exercises inducing or reducing movement variability to traditional rehabilitation programs.

In this manuscript we are introducing to CAI research the concept of summated variability quantification throughout task performance instead of traditional variability measures (e.g., standard deviation or coefficient of variation) at a discrete time point or average. Area under the curve has been used in electromyography (EMG) to determine the estimated cumulative muscular activity throughout an entire movement or movement phase.\textsuperscript{19} In this study, the integrated standard deviation time series considers the standard deviation of the dependent
variable (joint kinematics) at each normalized time point (of the squat) across multiple trials and provides one value to reflect the summated joint kinematic standard deviation (variability) throughout the task, see Figure 4.1. The larger the value is, the greater amount of joint kinematic variability throughout the task.

**Figure 4.1.** Example of integrated sagittal ankle kinematics standard deviation time series to determine summated ankle kinematic variability. The red box identifies one interval between two consecutive points in the squat cycle (2% to 3%) in which the area is determined. The gray identifies the area under the curve, or the summation of all intervals throughout the time series, representing the summated kinematic variability of the trial.

Summated joint kinematic variability throughout multiple repetitions of a functional task may determine if dynamic assessment of articular cartilage contact area is necessary to understand the development of posttraumatic ankle osteoarthritis. An individual with less variable joint kinematics across multiple repetitions of a closed chain task, may potentially apply constant stress or chronic overload to a confined area of the joint’s articular surface. If so, then this measure may provide quantification of a potential problem. More specifically this measure would allow quantification of kinematic variability throughout the entire movement and/or allow comparisons of kinematic variability between phases. Cumulative quantification of kinematic
variability throughout functional tasks is needed to identify if movement abilities, or inabilities, are predisposing certain CAI individuals to develop the aforementioned sequelae.

Walking\textsuperscript{20,21}, jogging\textsuperscript{20,21}, jump landing\textsuperscript{22,23}, and various performance tests (e.g., Star Excursion Balance Test (SEBT)\textsuperscript{24} and hop tests \textsuperscript{25,26}) are examples of functional tasks commonly used to discern if movement abilities differ in those with and without CAI. Different aspects of CAI movement abilities may be highlighted by selecting functional tasks in which task outcomes can be compared between CAI and healthy individuals completed with the presence and removal of intrinsic constraints\textsuperscript{27,28}. The double-leg squat has not been effectively utilized in ankle instability research despite the ease of test standardization and applicability across activities of daily living, sports, and strength training. A squat task is commonly utilized clinically to assess bilateral active range of motion (ROM) and strength of the lower extremity, and to increase strength for functional improvement\textsuperscript{29}. The task demands of the squat require adequate closed kinematic chain dorsiflexion range of motion (ROM). Considering a lack of active closed-chain dorsiflexion ROM is prevalent and well documented in those with CAI\textsuperscript{30}, identification of squat performance with and without this intrinsic constraint may provide insight to how CAI insufficiencies alter movement abilities that contribute to the development of sequelae. There is no current evidence of lower extremity kinematic chain assessment with and without the presence of an intrinsic constraint during a closed-chain task such as double-leg squats of CAI individuals.

Thus, the purpose of this study was to determine if differences in squat task outcome (lowest vertical minimum) and summated joint angular displacement variability of the ankle, knee, and hip in all 3 anatomical planes throughout a double-leg squat exist between CAI and healthy individuals with and without the presence of an intrinsic constraint (inadequate closed-chain
dorsiflexion). We hypothesized CAI individuals will have less joint kinematic variability in the sagittal plane throughout the normal squat (intrinsic constraint present) and a different task outcome than healthy controls based on previous studies identifying less knee and ankle joint displacement with limited closed-chain dorsiflexion during similar squat tasks\textsuperscript{30,31,32}. Due to the decreased sagittal plane variability, we hypothesized greater joint kinematic variability in the frontal and transverse planes will be present as compensation. Additionally, we hypothesized CAI and healthy individuals will have similar joint kinematic variability in the sagittal, frontal, and transverse planes throughout the elevated rearfoot and a similar task outcome once the CAI group’s intrinsic constraint is removed.

**Methods**

**Participants**

An a-priori power analysis using G*Power\textsuperscript{TM} (Version 3.0.10, Kiel University, Germany) was completed to determine the appropriate sample size necessary to detect significant differences between groups for joint kinematic variables reported in the literature. An estimated sample of 7-41 participants per group was determined necessary from a previous study conducted on healthy individuals to obtain a similar effect sizes of 0.31-0.85 with power (1-\(\beta\)) =0.80 and \(\alpha\leq0.05\) for sagittal ankle and knee joint displacement throughout a squat with and without a wedge implement.\textsuperscript{32} Although kinematic variability of an entire squat has not been compared between healthy and injured populations, an estimated sample of 25-61 per group was determined necessary to obtain similar effect sizes of 0.23-0.91 with power (1-\(\beta\)) =0.80 and \(\alpha\leq0.05\) for ankle frontal joint kinematic variability in CAI individuals, depending on the specific variable.\textsuperscript{22}
A total of 64 recreationally active participants were recruited, with “active” identified as \( \geq 24 \) on the Godin-Shephard Leisure-Time Physical Activity Questionnaire (GSLTPAQ).\(^3\) CAI individuals were identified according to recommended International Ankle Consortium guidelines using the Identification of Functional Ankle Instability(IdFAI) or the combined results of the Cumberland Ankle Instability Tool (CAIT) and Ankle Instability Instrument (AII).\(^3\) Controls were pair matched to a CAI participant based on gender and limb dominance\(^34\) and within \( \pm 10\% \) of age, height and mass. Exclusion criteria for both groups included: history of surgery or fracture in either lower extremity, acute musculoskeletal injury in the previous 3 months resulting in at least one day of interrupted physical activity, and current pain, swelling or discoloration of either limb.\(^3\)

**Instrumentation**

Marker trajectories were captured using 61 retro-reflective markers (14 mm) and a 7-camera motion capture system (VICON-MX40, 240Hz; Vicon Motion Systems Ltd., UK) to determine kinematic variables.\(^35\) A customized body and foot marker set was used based on the Plug-in-Gait\(^36\) and Oxford foot\(^37\) models (Figure 4.2).
Figure 4.2. Retro-reflective marker placement and orientation of joint and global coordinate systems.

Data collection

Informed consent was obtained prior to data collection, as approved by the university institutional review board. Participants completed the ankle and physical activity questionnaires to determine eligibility. Anthropometric data and WBLT to measure closed chain dorsiflexion as described by Bennell et al.\textsuperscript{38} were measured. Excellent intra-rater reliability for all measures was established prior to all participant testing (ICCs (2,1) = 0.90-0.99).

Participants completed a five-minute warm-up on a stationary bike at a comfortable speed with no resistance and were given the opportunity to complete any self-selected dynamic warm-up exercises or stretches as desired. Participants wore non-reflective compression shorts and shirt
with no shoes to allow accurate marker placement on anatomical locations, particularly the rearfoot, following the warm-up task.

Standardized instructions were given prior to each of the squatting tasks. For the normal squatting task, participants were instructed to stand with toes facing forward, feet parallel, shoulder width a part, and with each foot on a force platform. For the elevated rearfoot squat task, participants were instructed to perform the same task but with the addition of a 4cm wooden block under each rearfoot. This set up mimics the block modification used during the deep squat test of the Functional Movement Screen (FMS)\textsuperscript{29}, a commonly used clinical assessment tool. Both squat tasks were completed with elbows extended and arms parallel to the ground.\textsuperscript{39} Participants were instructed to squat as low as possible for each repetition while maintaining the initial foot and arm alignment and their balance throughout the entire trial. Failure to maintain alignment, balance, or similar squat depth across repetitions within a trial resulted in a bad trial and was stopped, not used for analyses, and started over after the duration of a two- minute rest period.

Participants completed four trials of 10 repetitions at a comfortable pace for each of the squatting tasks (i.e., normal and elevated rearfoot squat) with at least two-minutes rest between each task for a total of 8 completed trials (or 40 repetitions) per task. Differences within individuals in kinematic variables are due in part to the number of trials collected. The percentage of significant intra-individual joint kinematic variable comparisons increased approximately 44-47\% with 25 or 50 trials compared to 5 trials, during a walking treadmill task, regardless of sample size.\textsuperscript{40} Because the standard deviation measure is affected by the differences in kinematic variables across trials, 40 trials were determined necessary for each task. The squat task order (normal or elevated rearfoot) was randomized among participants, and
counterbalanced through the rest of the testing session. Matched CAI and healthy participants performed the squat tasks in the same order.

Data processing

All joint kinematic variables were calculated for the test limb. The test limb was identified as the lower scoring ankle on ankle questionnaires used to determine inclusion criteria for those with CAI. If both ankles reported the same level of poor function on all questionnaires, the dominant limb was identified as the test limb. The test limb identified for controls corresponded to the matched CAI individual’s test limb, with respect to dominance.

Marker trajectory gaps were filled with rigid body or pattern fill as determined appropriate in VICON Nexus (v2.4, Vicon Motion Systems Ltd., UK) prior to exporting the raw, three-dimensional reconstructed marker positions. Minor gaps (≤10 frames) were manually filled with a cubic spline interpolation. Raw marker coordinate data were filtered with a 4 Hz low-pass fourth-order Butterworth filter; cutoff frequency was determined based on visual inspection of spectral plots of all markers and anatomical planes for the first 5 CAI and healthy participants.

Model construction was completed with filtered marker trajectories and anthropometric data in Visual 3D (Version 5.02.22, C-Motion, Inc., Germantown, MD). Right-handed orthogonal global and joint coordinate systems were defined as +X projecting to the right, +Y in the anterior direction, and +Z in the upward direction. Joint angles were calculated using an x-y-z Cardan sequence of rotations and the proximal segment as the reference segment. Ankle joint angles were calculated for rearfoot relative to the shank with dorsiflexion (+X), plantarflexion (-X), inversion (+Y), eversion (-Y), rearfoot internal rotation (+Z), and rearfoot external rotation (-Z). Knee joint angles were calculated and aligned with extension (+X), flexion (-X), knee valgus (+Y), knee varus (-Y), internal rotation (+Z), and external
rotation (-Z). Hip joint angles were calculated and aligned with flexion (+X), extension (-X), adduction (+Y), abduction (-Y), internal rotation (+Z), and external rotation (-Z). Joint angular displacement throughout an entire squat was determined for the ankle, knee, and hip in all three anatomical planes.

The whole body COM position in the vertical axis was estimated using Dempster’s 14-segment model. Further data analysis of each squat was completed using MATLAB (R2017b, Mathwork Inc., Natick, MA). Time was expressed as a percentage of squat time, with the start and end of each squat determined by COM vertical position. The middle eight squats of each trial were included in the analyses (32/40 total squats per condition). The first and last squats were not included in the analyses to remove effects associated with beginning or preparing to end the bout of 10 squat repetitions within a trial. Squat depth magnitude was calculated as the lowest COM vertical minimum expressed as a percentage of the leg length average between the two limbs.

Data analysis

Mean and standard deviation of squat depth magnitude across the 32 repetitions within each task were calculated for the individual participant. Summated joint angular displacement variability for each participant was calculated as the integrated standard deviations from the ensemble curve of the 32 repetitions within each task.

Of the 64 participants, 40 were included in the analysis. Participants were removed for several reasons (see CONSORT diagram, Figure 4.3). Of the initial 40 participants, 12 participants were removed because of technical difficulties related to identifying markers needed for accurately determining the COM location for the eight middle squats of each trial. If one participant was removed, the matched pair also was removed from the sample. Prior to statistical
analyses data were checked for squat joint kinematics and participant outliers >3SD from the group mean. No joint kinematics or participants were identified as outliers and a total of 28 (14 CAI, 14 CON) participants were included in the statistical analyses.

Statistical Analyses

Independent samples $t$-tests were used to confirm demographics were not significantly different between groups with respect to height, mass, and age. Independent samples $t$-tests were used to identify group differences in closed-chain dorsiflexion and physical activity and CAI questionnaire scores ($p \leq .05$). A two-way ANOVA was used to determine squat depth magnitude differences by group (CAI, healthy) and squat task (normal, elevated rearfoot). A series of factorial ($2 \times 2 \times 3$) ANOVAs were used to determine joint angular displacement variability differences by group (CAI, healthy) and squat task (normal, elevated rearfoot) for all three anatomical planes at the ankle, knee, and hip joints separately. Separate factorial ANOVAs were determined necessary to identify if the task altered variability in specific planes at each joint. Sagittal plane differences were expected due to hypothesized increased change in sagittal ankle range of motion with the elevated rearfoot. Also, the mechanism of injury for the index sprain includes ankle frontal and sagittal plane movement and changes in more than one plane may be possible. If a statistically significant interaction effect was present, then simple main effects were determined. If the interaction was not statistically significant, then main effects for group were assessed.
**Figure 4.3.** CONSORT flow diagram of group allocation. *Processing issues included inability to fill marker trajectory gaps due to long windows of upper extremity marker missing data (n=1) and inability to accurately model the rearfoot (n=5).
Results

There were no statistically significant differences between groups with respect to height, mass, age, or physical activity levels ($p>.05$). Significant mean differences between groups on all ankle questionnaires ($p<.01$) confirmed the CAI group reported greater perceived ankle instability compared to healthy controls. Test limb closed chain dorsiflexion identified with the WBLT distance was not different between groups, $t(26)=1.62, p=.09, d=0.67, (1-\beta)=0.50$. See Table 4.1 for a summary of group demographics. Group means for joint angular displacements, means of standard deviation time series, and summated joint kinematic variability and for the ankle, knee, and hip joint in all three anatomical planes are reported in Tables 4.2 and 4.3, respectively. The task outcome, squat depth percentage of leg length, was not significantly different between groups for either task ($p>.05$).

No significant interaction effects were identified between group, task, and anatomical plane (direction). There was a significant main effect of anatomical plane on amount of summated kinematic variability for the knee and hip joints; see Table 4.4 for summary of results. Contrasts for the knee joint revealed that sagittal, $F(1,26)=81.22, p<.001, \eta^2=0.76, (1-\beta)=1.00$, and transverse plane $F(1,26)=60.67, p<.001, \eta^2=0.70, (1-\beta)=1.00$ summated kinematic variability were significantly higher than in the frontal plane for both tasks. Similarly, contrasts for the hip revealed that sagittal, $F(1,26)=70.56, p<.001, \eta^2=0.73, (1-\beta)=1.00$, and transverse plane $F(1,26)=9.13, p=.006, \eta^2=0.26, (1-\beta)=0.83$, summated kinematic variability were also significantly higher than in the frontal plane for both tasks, see Figure 4.4. Task did not have a significant main effect on amount of summated kinematic variability ($p>.05$).
### Table 4.1. Summary of Participant Characteristics (Mean and SD)

<table>
<thead>
<tr>
<th></th>
<th>CAI (n=14) (5F, 9M)</th>
<th>CON (n=14) (5F, 9M)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td><strong>Matching Criteria</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Height (cm)</td>
<td>172.3</td>
<td>9.5</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>71.1</td>
<td>10.2</td>
</tr>
<tr>
<td>Age (years)</td>
<td>23.9</td>
<td>3.6</td>
</tr>
<tr>
<td>GSLTPAQ (physical activity level)</td>
<td>52.4</td>
<td>14.6</td>
</tr>
<tr>
<td><strong>Ankle Related Measures</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IdFAI*</td>
<td>20.5</td>
<td>5.8</td>
</tr>
<tr>
<td>CAIT*</td>
<td>15.7</td>
<td>6.2</td>
</tr>
<tr>
<td>FAAM (%)*</td>
<td>86.8</td>
<td>11.2</td>
</tr>
<tr>
<td>FAAM-Sport Subscale (%)*</td>
<td>78.8</td>
<td>15.9</td>
</tr>
<tr>
<td>WBLT distance (cm)</td>
<td>11.4</td>
<td>2.8</td>
</tr>
<tr>
<td><strong>Normalized Squat Depth Magnitude</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normal (% leg length)</td>
<td>59.0</td>
<td>6.0</td>
</tr>
<tr>
<td>Elevated Rearfoot (% leg length)</td>
<td>59.0</td>
<td>5.0</td>
</tr>
</tbody>
</table>

*Significant at \( p < .05 \).

**Note.** F=Female; M=Male; GSLTPAQ=Godin-Shephard Leisure-Time Physical Activity Questionnaire; IdFAI=Identification of Functional Ankle Instability; CAIT=Cumberland Ankle Instability Tool; FAAM=Foot and Ankle Ability Measure; WBLT=Weight Bearing Lunge Test.

### Table 4.2. Group Means(SD) of Involved Limb Joint Angular Displacement (degrees) for the Ankle, Knee, and Hip in All Three Anatomical Planes for Compiled Squat Trials

<table>
<thead>
<tr>
<th></th>
<th>CAI (n=14)</th>
<th>CON (n=14)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Normal</td>
<td>Elevated Rearfoot</td>
</tr>
<tr>
<td><strong>Ankle</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sagittal</td>
<td>26.6(4.9)</td>
<td>31.7(5.5)</td>
</tr>
<tr>
<td>Frontal</td>
<td>7.4(3.6)</td>
<td>6.2(2.7)</td>
</tr>
<tr>
<td>Transverse</td>
<td>7.3(2.9)</td>
<td>8.5(3.4)</td>
</tr>
<tr>
<td><strong>Knee</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sagittal</td>
<td>114.0(15.7)</td>
<td>126.1(11.4)</td>
</tr>
<tr>
<td>Frontal</td>
<td>8.1(3.4)</td>
<td>7.6(2.9)</td>
</tr>
<tr>
<td>Transverse</td>
<td>17.0(6.9)</td>
<td>20.5(9.1)</td>
</tr>
<tr>
<td><strong>Hip</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sagittal</td>
<td>88.9(8.5)</td>
<td>85.6(8.4)</td>
</tr>
<tr>
<td>Frontal</td>
<td>8.8(4.0)</td>
<td>8.9(4.0)</td>
</tr>
<tr>
<td>Transverse</td>
<td>18.7(8.9)</td>
<td>22.8(8.9)</td>
</tr>
</tbody>
</table>
Table 4.3. Group Means(SD) of Summated Kinematic Variability$^a$ of the Involved Limb Across Compiled Squat Trials for the Ankle, Knee, and Hip in All Three Anatomical Planes

<table>
<thead>
<tr>
<th></th>
<th>CAI (n=14)</th>
<th></th>
<th>CON (n=14)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Normal</td>
<td>Elevated Rearfoot</td>
<td>Normal</td>
<td>Elevated Rearfoot</td>
</tr>
<tr>
<td>Ankle</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sagittal</td>
<td>169.4(43.8)</td>
<td>222.5(65.5)</td>
<td>175.3(64.77)</td>
<td>184.1(50.6)</td>
</tr>
<tr>
<td>Frontal</td>
<td>117.8(37.1)</td>
<td>130.6 (40.1)</td>
<td>107.9 (65.5)</td>
<td>117.2(24.6)</td>
</tr>
<tr>
<td>Transverse</td>
<td>107.6(24.6)</td>
<td>137.1(42.9)</td>
<td>117.5 (40.87)</td>
<td>135.9(74.3)</td>
</tr>
<tr>
<td>Knee</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sagittal$^b$</td>
<td>345.4(67.5)</td>
<td>504.4(235.8)</td>
<td>514.6(298.65)</td>
<td>423.6(121.8)</td>
</tr>
<tr>
<td>Frontal</td>
<td>174.2(37.5)</td>
<td>101.7(37.6)</td>
<td>118.0 (44.54)</td>
<td>112.2(40.7)</td>
</tr>
<tr>
<td>Transverse$^b$</td>
<td>190.6(47.5)</td>
<td>168.6(57.9)</td>
<td>191.3(56.62)</td>
<td>185.8(73.0)</td>
</tr>
<tr>
<td>Hip</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sagittal$^c$</td>
<td>475.6(133.4)</td>
<td>376.7(165.6)</td>
<td>405.6(221.55)</td>
<td>324.6(86.7)</td>
</tr>
<tr>
<td>Frontal</td>
<td>104.6(33.3)</td>
<td>184.3(68.5)</td>
<td>186.2 (51.11)</td>
<td>180.9(46.1)</td>
</tr>
<tr>
<td>Transverse$^c$</td>
<td>166.8(53.0)</td>
<td>201.9(83.2)</td>
<td>214.3 (73.16)</td>
<td>209.7(66.3)</td>
</tr>
</tbody>
</table>

Note. $^a$Units of summated joint kinematic variability = deg·%squat.
$^b$Significantly higher summated variability compared to frontal plane for the knee joint.
$^c$Significantly higher summated variability compared to frontal plane for the hip joint.

Table 4.4. Summary of Main Effects on Summated Joint Kinematic Variability

<table>
<thead>
<tr>
<th></th>
<th>F(df)</th>
<th>$p$-value</th>
<th>Partial $\eta^2$</th>
<th>Power (1-\beta)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Task</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ankle</td>
<td>0.77(1.0, 26.0)</td>
<td>0.39</td>
<td>0.03</td>
<td>0.14</td>
</tr>
<tr>
<td>Knee</td>
<td>0.50(1.0, 26.0)</td>
<td>0.49</td>
<td>0.02</td>
<td>0.11</td>
</tr>
<tr>
<td>Hip</td>
<td>0.22(1.0, 26.0)</td>
<td>0.65</td>
<td>0.01</td>
<td>0.07</td>
</tr>
<tr>
<td>Plane</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ankle</td>
<td>1.63(1.0, 26.3)</td>
<td>0.20</td>
<td>0.06</td>
<td>0.33</td>
</tr>
<tr>
<td>Knee</td>
<td>105.96(1.1, 29.2)</td>
<td>&lt;.001*</td>
<td>0.80</td>
<td>1.00</td>
</tr>
<tr>
<td>Hip</td>
<td>66.66(1.8, 30.6)</td>
<td>&lt;.001*</td>
<td>0.72</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Note. *Significant at $p$<.05.
Figure 4.4. Summated lower extremity joint kinematic variability by group (columns; CAI = Left and CON = Right) and task (rows; Elevated Rearfoot = top and Normal = bottom).

*Denotes significant main effect of anatomical plane on summated kinematic variability for the joint.
Discussion

The present study, to our knowledge, is the first to determine summated joint kinematic variability by finding the area under the joint angle standard deviation time series throughout a repeated squat task. First, we predicted CAI individuals would have less joint kinematic variability in the sagittal plane throughout the normal squat with a different task outcome (squat depth) than healthy controls. This hypothesis was not supported. Less sagittal plane variability for CAI individuals was observed in the normal squat compared to the elevated rearfoot but was not statistically significantly different. Our second hypothesis predicted CAI and healthy controls would have similar joint kinematic variability in the sagittal plane throughout the elevated rearfoot squat and a similar task outcome. This hypothesis was partially supported by the non-significant results for task by group interaction on summated joint kinematic variability. However, neither hypothesis was supported by the lack of squat depth difference between groups for either task.

The greatest summated joint kinematic variability appears to be in the sagittal plane for both groups at all joints. Our observations support previous findings of significantly greater ankle and knee sagittal-plane motion in those with greater closed chain dorsiflexion during squat tasks.\(^{31}\) Conversely, sagittal hip displacement and summated kinematic variability of both groups seem to decrease with rearfoot elevation. We found similar increased frontal plane knee angular displacement during a squat in those with CAI as previously identified in healthy individuals with limited closed chain dorsiflexion when compared to controls.\(^{32}\) This may suggest compensation in the frontal plane when inadequate sagittal ankle ROM is available in closed chain activities, particularly in the double-leg squat. Therefore, clinicians working with CAI, or other individuals, with limited closed chain dorsiflexion are encouraged to restore normal sagittal
ankle ROM following the index sprain to prevent kinematic changes proximal in the lower extremity.

The goal of the block under the rearfoot was to place the foot at a downward angle to allow more sagittal plane movement (e.g., dorsiflexion) by relaxing the posterior structures of Achilles Tendon and gastrocnemius tissue. Manipulation of sagittal ankle ROM with rearfoot elevation appears to increase sagittal knee angular displacement and decrease hip angular displacement in both groups. Macrum et al. found similar (but inversely related) results when limiting ankle dorsiflexion with a wedge during a squat. All of these results support the idea that changes in sagittal ankle ROM are directly related to changes in sagittal knee ROM. However, the observed increase in summated knee kinematic variability with elevating the rearfoot may raise concerns for the changes in the kinematic chain. Consistent elevation of the rearfoot to achieve greater sagittal ROM of the ankle and knee during squat performance is not recommended due to the unknown changes and potential adverse effects it could have on joint health.

Transverse plane summated kinematic variability was significantly larger than frontal plane summated kinematic variability for the knee and hip. The majority of CAI movement variability literature has identified increased frontal ankle kinematic variability during the stance phase following a jump landing or during gait and is a more intuitive result based on the mechanism of injury for the index sprain. However, we should note the transverse plane had greater kinematic variability compared to the frontal plane for all individuals. Previously, significantly less transverse knee kinematic variability was observed in those with functionally unstable ankles compared to controls during the stance phase following a single-leg landing. The difference in task constraints between the squat and single-leg landings may explain the
differences in transverse plane kinematic variability. Muscular tightness, anatomical restrictions, and/or the fixation of both feet to the floor throughout the multiple squat repetitions may result in a rotational component of the movement in an attempt to squat without the necessary sagittal ROM. However, the transverse plane is not routinely assessed in CAI movement variability literature. Further research is necessary to quantify and compare kinematic variability in normal and CAI individuals to better understand kinematic variability differences throughout various functional tasks. This evidence will help better determine if this form of variability is applicable in the posttraumatic osteoarthritis development.

There are limitations to the current study. The premise of using a block to elevate the heel was to restore adequate closed chain dorsiflexion to those with CAI who were assumed to have deficits compared to their healthy counterparts. We did this in order to determine how that specific intrinsic constraint altered kinematic variability throughout a squat. However, we did not have statistically significant closed chain dorsiflexion ROM differences between groups. Our observed WBLT distance mean for CAI individuals (11.4cm) was less than 2cm greater than previously published CAI group means and had a similar difference value between groups.\textsuperscript{49,50} Within these studies, sagittal knee displacement was less during single legged-landings\textsuperscript{50} and the Star Excursion Balance Test\textsuperscript{49} for those with CAI. Identification of squat start and end times with COM vertical trajectories was limited by the use of a 14-segment model and missing upper extremity marker trajectory gaps that were unresolvable. Lastly, many of our findings are underpowered due to the reduction of sample size from data processing issues. A different model should be considered to identify COM vertical trajectory, needed to identify squat start and end times.
In summary, summated joint kinematic variability was used to compare the standard deviations of joint angular displacement throughout an entire squat with the feet flat and rearfoot elevated. The sagittal plane had the greatest amount of summated kinematic variability across tasks and groups for each joint. The transverse plane had the second greatest amount of summated kinematic variability across tasks for all individuals. The comparison of angular displacements and summated kinematic variability has suggested a need to further understand angular displacement with respect to total variability within a trial. The collective use of these two measures may help identify a trade-off between angular displacement and summated kinematic variability to better understand neuromuscular control changes in CAI.
References


CHAPTER 5

INTRA-LIMB COORDINATION DURING NORMAL AND ELEVATED REARFOOT SQUAT IN INDIVIDUALS WITH CHRONIC ANKLE INSTABILITY ²

² Samson CO, Simpson KJ, Newell KM, Brown CN. To be submitted to Clinical Biomechanics
Introduction

Chronic Ankle Instability (CAI) affects approximately 1 in 5 high school and collegiate athletes\(^1\) and 1 in 5 adults (18-65 years)\(^2\). CAI is characterized by a history of at least one significant ankle sprain and at least one of the following: history of the previously injured ankle ‘giving way’, recurrent sprains (2 or more), or ‘feelings of instability’ during physical activities.\(^3\) Mechanical insufficiencies associated with CAI include increased lateral ankle ligament complex laxity and restricted arthrokinematics of the talocrural, subtalar and/or distal tibiofibular joints.\(^4\) Functional insufficiencies, such as impaired neuromuscular control and poor balance, are associated with perceived feelings of instability associated with CAI.\(^5\) Those with functional ankle instability and articular cartilage alterations present with unequal loading of the talocrural joint.\(^6\) This may result in a greater percentage of articular contact surface stress due to an increased number and magnitude of rapid impact loadings\(^7,8\) which could explain the higher rate of posttraumatic ankle osteoarthritis in those with CAI\(^9,10\) compared to uninjured controls. Potentially detrimental movement patterns throughout functional activities (e.g., increased ankle plantarflexion and ankle and rearfoot inversion during walking and running\(^11\) and decreased knee flexion upon landing\(^12\) compared to healthy controls) may be driven by mechanical and/or functional insufficiencies. Abnormal movement pattern identification and definition throughout various functional tasks is needed to better understand why chronic instability of the ankle is the main cause for developing ligamentous posttraumatic osteoarthritis of the ankle.\(^10\)

Coordination assessment provides awareness to how segments within a kinematic chain move relative to one another throughout a task and provides a method to quantify the quality of movement abilities of those with CAI. Consideration of adjacent segment coordination may provide insight. Abnormal movements between two adjacent segments throughout tasks, defined
as translational or rotational, may predispose certain CAI individuals to develop posttraumatic osteoarthritis. These abnormal movements with unknown causes (e.g., impaired neuromuscular control following the index sprain) could elicit altered loading magnitudes and areas of the articular cartilage throughout motion, such as increased shear and compressive forces. Differences in contact areas within healthy in-vivo talocrural joints were identified as the greatest in ankle neutral (midstance) and least in ankle dorsiflexion (heel strike) during simulated (static) walking events. These differences in contact areas with different joint angles throughout walking may result from changes in segment coordination throughout the movement. Coordination assessment methods provide a means to identify abnormal inter-segmental movements by quantifying the spatio-temporal movement (e.g., in-phase or anti-phase) of one segment relative to another throughout multiple repetitions of a task. Vector coding determines the angular distance between the two segments on an angle-angle diagram between two adjacent time points to assess the spatio-temporal coordination throughout a task. Inter-segment coordination throughout task completion is needed to better understand if CAI individuals display abnormal rotational movements during functional tasks that may cause cartilage degeneration. Most CAI movement literature to date has focused on single joint kinematics in one plane (i.e., sagittal or frontal) at a single point in time. However, these analyses do not provide a comprehensive picture of how those with CAI move nor does it identify how two segments move relative to one another, which may be more important to identify abnormal rotational movement presence.

Segment coordination throughout various functional tasks in those with CAI is not well understood due to the few studies quantifying shank-rearfoot and hip-ankle relative coordination during walking and jogging in those with CAI, and not in other functional tasks.
Identifying the shank movement relative to rearfoot is the most intuitive because the ankle is defined by the interaction of these two segments, which are involved in the mechanism of injury and complaints of giving way. Studies have identified altered knee neuromuscular control, kinematics, and kinematic variability. Therefore, starting with consideration of the shank movement relative to the femur is a necessary starting point to further understand changes proximal in the kinematic chain resulting from CAI due to limited proximal segment coordination information. While other studies have looked at the effects of CAI and ankle restriction on lower extremity “coordination” during a vertical jump task, quantification of spatio-temporal segment pair movement relative to one another was not determined. Identification of adjacent segments (e.g., shank-rearfoot or shank-femur) moving in-phase or out-of-phase (anti-phase) cannot be determined without relative spatio-temporal coordination assessments. Anti-phase movement of adjacent segments can be described as the segments moving in opposite directions. If the rearfoot externally rotates as the shank internally rotates in CAI individuals only, then anti-phase movement of adjacent segments may define an abnormal rotational movement representing articular surface grinding. There is a need to consider other weight bearing functional tasks other than walking and jogging to determine if differences in inter-segment coordination between CAI and healthy individuals are consistent in all closed chain tasks.

The double-leg squat has not been effectively utilized in ankle instability research despite the ease of test standardization, applicability across activities of daily living, sports and strength training. A squat task is commonly utilized clinically to assess bilateral active range of motion (ROM) and strength of the lower extremity, and to increase strength for functional improvement. The task demands of the squat require adequate closed chain dorsiflexion range
of motion (ROM). Considering a lack of active closed-chain dorsiflexion ROM is prevalent and well documented in those with CAI\textsuperscript{26}, identification of squat performance with and without this intrinsic constraint may provide insight to how CAI insufficiencies alter movement abilities that contribute to the development of sequelae. There is no current evidence of double-leg squat intra-limb coordination assessment with and without the presence of inadequate closed chain dorsiflexion for CAI individuals.

Thus, the overall purpose of this study was to determine shank-rearfoot and shank-femur relative coordination throughout a squat with and without adequate closed chain dorsiflexion in CAI individuals compared to healthy controls. We hypothesized CAI individuals will spend less total time in-phase for the shank-rearfoot and shank-femur throughout the normal squat compared to healthy controls. CAI individuals have less in-phase shank-rearfoot motion throughout stance than their healthy counterparts in walking and jogging.\textsuperscript{14,17,18} Additionally, isolated rearfoot movement in the frontal plane causes the index sprain and recurrent sprains, which may suggest more rearfoot movement during activity and, therefore, less in-phase movement of the shank-rearfoot. The squat is a closed chain task similar to the stance portion of gait and previous findings are hypothesized to be translatable across closed chain tasks with the intrinsic constraint present. Less in-phase shank-femur coordination time is expected in the transverse plane throughout the normal squat in those with CAI because of previously observed knee and ankle joint displacement reduction in the sagittal and frontal planes due to anatomical\textsuperscript{27} or study-induced\textsuperscript{28} limited closed-chain dorsiflexion during a squat.
Methods

Participants

An a-priori power analysis using G*Power™ (Version 3.0.10, Kiel University, Germany) was completed to determine the appropriate sample size necessary to detect significant differences between groups for coordination variables as reported in the literature. For differences in intralimb coordination pair variability during walking, an estimated 17 participants per group was determined necessary to obtain a similar effect size of 0.89 with power (1-β) =0.80 and α≤0.05.14 for a total of 34 participants in the study.

A total of 64 recreationally active participants were recruited, active identified as ≥24 on Godin-Shephard Leisure-Time Physical Activity Questionnaire (GSLTPAQ).3,29 CAI individuals were identified according to recommended International Ankle Consortium guidelines using the Identification of Functional Ankle Instability or the combined results the Cumberland Ankle Instability Tool and Ankle Instability Instrument.3 Controls were matched based on gender and limb dominance and within 10% of age, height and mass. Exclusion criteria for all groups included: history of surgery or fracture in either lower extremity, acute musculoskeletal injury in the previous 3 months resulting in at least one day of interrupted physical activity, and current pain, swelling or discoloration of either limb.3

Instrumentation

Kinematic data were captured using 61 retro-reflective markers (14 mm) and a 7-camera motion capture system (VICON-MX40, 240Hz; Vicon Motion Systems Ltd., UK).30 A customized body and foot marker set was used based on the Plug-in-Gait31 and Oxford foot32 models. Right-handed orthogonal global and segment coordinate systems were defined as +X
projecting to the right, +Y in the anterior direction, and +Z in the upward direction (see Figure 5.1).³³

**Figure 5.1.** Retro-reflective marker placement and orientation of segment and global coordinate systems.

**Data collection**

Informed consent was obtained prior to data collection, as approved by the university institutional review board. Participants completed ankle and physical activity questionnaires to determine eligibility. Anthropometric data and closed chain dorsiflexion as described by Bennell et al.³⁴ were collected. Excellent intra-rater reliability for all measures was established prior to all participant testing (ICCs (2,1) = 0.90-0.99).

Participants completed a five-minute warm-up on a stationary bike at a comfortable speed with no resistance and were given the opportunity to complete any self-selected dynamic warm-
up exercises or stretches as desired. Participants wore non-reflective compression shorts, a sports bra if female and compression shirt or shirtless if male, and no shoes to allow marker placement following the warm-up task.

Standardized instructions were given prior to each of the squatting tasks. For the normal squatting task, participants were instructed to stand with toes facing forward, feet parallel, shoulder width a part, and with each foot on a force platform (Figure 2). For the modified squatting task, participants were instructed to maintain the same starting position with the addition of a 4cm wooden block under the rearfoot. This set up mimics the block modification used during the deep squat test of the Functional Movement Screen (FMS)\textsuperscript{25}, a commonly used clinical assessment tool. Both squat tasks were completed with shoulders flexed, elbows extended, and arms parallel to the ground.\textsuperscript{35} Participants were instructed to squat as low as possible for each repetition maintaining the previous alignment instructions and their balance throughout the entire trial, failure to maintain alignment resulted in a bad trial. Because the participants were instructed to squat to the lowest depth comfortable while maintaining balance throughout the trial, if a noticeable difference of the squat depth was observed for any repetition within a trial or between trials then the trial was stopped, not used for analyses, and started over after the duration of a 2 minute rest period. Additionally, if the participant lost their balance at any point in the trial, the trial was stopped immediately, not used for analyses, and started over.

Participants completed 4 trials of 10 repetitions at a comfortable pace for each of the squatting tasks (i.e., normal squat and modified squat with rearfoot elevated) with at least two-minutes rest between each task for a total of 4 completed trials (or 40 squats) per condition. The first squat task was randomized among participants and counterbalanced throughout the
remaining of the testing session. Matched CAI and healthy participants performed the squat tasks in the same order.

Data processing

Marker trajectory gaps in the dynamic trials were filled with rigid body or pattern fill as determined appropriate in VICON Nexus (v2.4, Vicon Motion Systems Ltd., UK) prior to exporting the raw marker data. Minor gaps (≤10 frames) were manually filled with a cubic spline interpolation. Raw marker coordinate data were filtered with a low-pass fourth-order Butterworth filter. A 4 Hz cutoff frequency was determined based on visual inspection of a spectrum analysis for marker trajectories in all three anatomical planes for the first 5 CAI and healthy participants.

Model construction was completed with filtered marker trajectories and anthropometric data in Visual 3D (Version 5.02.22, C-Motion, Inc., Germantown, MD). Segment angles were calculated using an x-y-z Cardan sequence of rotations and the lab identified as the reference segment. The whole body COM position and velocity in the vertical axis was determined in Visual 3D as the weighted sum of the segmental COM for based on a 14-segment model.

Temporal normalization of each squat to percentage of squat time (101 points per squat for each of the 10 squats per trial) was completed in MATLAB (R2017b, Mathwork Inc., Natick, MA) with the start and end of each squat determined by COM vertical position. The middle eight squats of the 10 squats captured for each trial were used in the vector coding analysis (32/40 total squats per condition).

Data analysis

Of the 64 participants, 40 were included in the initial data analysis, see CONSORT (Figure 5.2). An additional 12 participants (6 CAI, 6 CON) were removed following data
processing due to inability of the 14-segment model used to estimate COM trajectory to identify
the start and end times of the middle 8 squats for one of the participants in the CAI-CON pairs.
Prior to statistical analysis no participant outliers were identified with time spent in major
coordination patterns >3SD from the CAI and control group means of their group. Therefore, a
total of 28 participants (14 CAI and 14 CON) were included in the statistical analyses.

Vector coding as specified by Needham et al.\textsuperscript{40} was used to identify spatial coordination
patterns of two adjacent segments throughout the squat descent and ascent phases. On the angle-
angle diagram of the inferior and superior segments (horizontal and vertical axis, respectively), a
vector was created between two consecutive time points of the normalized squat (see Figure 5.3).
The coupling angle was then calculated between the vector and the horizontal axis. Mean
coupling angle was calculated across the 32 squat repetitions of both conditions for each
participant then within groups using circular statistics as previously described.\textsuperscript{40,41}

Coordination patterns for each condition were determined based on ranges of mean
coupling angle to identify the coordination of the two segments. Four coordination patterns were
considered: in-phase (both segments moving in the same direction at the same time), anti-phase
(both segments moving in opposite directions at the same time), superior-segment dominant
(superior segment displacing while inferior minimally displaces) and inferior segment dominant
(inferior segment displacing while superior minimally displaces). See Figure 5.3 for ranges.\textsuperscript{42,43}
The magnitude of change in the horizontal direction of the vector between consecutive time
points on the angle-angle diagram represents the inferior segment’s angular displacement change
whereas the magnitude of change in the vertical direction represents the superior segment’s
angular displacement change. Angles within ±5° degrees of the horizontal axis define the inferior
segment moving while there is little to no angular displacement of the superior segment. This is
termed a “major coordination pattern of inferior segment only”. Similarly, angles within ±5° of the vertical axis define the superior segment moving while there is little to no angular displacement of the inferior segment. This is termed a “major coordination pattern of superior segment only.” Coupling angles within quadrants one and three were identified as in-phase, or both segments displacing in the same direction at the same time. This major coordination pattern was further divided into three sub-coordination patterns. A window of 5° on either side of 45° and 225° was used to identify the in-phase equal phase, or the same amount of displacement in the same direction of both segments. Superior dominant only was defined as greater change in the vertical than horizontal direction for the vector between two consecutive points, representing the superior segment displacing with minimal displacement of the inferior segment. Conversely, inferior dominant only was defined as greater change in the horizontal than the vertical direction, representing the inferior segment displacing with minimal displacement of the superior segment. Coupling angles within quadrants two and four were identified as anti-phase, or the segments displacing in opposite directions at the same time. Similar sub-coordination patterns were defined for this major coordination pattern.

The total time spent in each coordination pattern throughout the squat descent and ascent phases of the normal and elevated squat was calculated for each individual. Times were based on the percentage of squat time (1 point equal to 1% of squat time). Lastly, all variables were calculated for one test limb. The test limb of CAI individuals was identified as the limb with lower perceived ankle stability identified with the ankle questionnaires. The test limb of the control was determined based on the limb used for the CAI matched participant.
Figure 5.2. CONSORT flow diagram of group allocation.

*Processing issues included long marker trajectory gaps for the upper extremity (n=1) required for COM trajectory calculations with 14-segment model and inability to accurately model the rearfoot (n=5) for all squats.
### Coordination Pattern

<table>
<thead>
<tr>
<th>Coordination Pattern</th>
<th>Coupling Angle (CPA) Range</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>In-phase</strong></td>
<td></td>
</tr>
<tr>
<td>Equal</td>
<td>$40^\circ \leq \text{CPA} \leq 50^\circ$; $220^\circ \leq \text{CPA} \leq 230^\circ$</td>
</tr>
<tr>
<td>Superior dominant</td>
<td>$5^\circ \leq \text{CPA} \leq 40^\circ$; $185^\circ \leq \text{CPA} \leq 220^\circ$</td>
</tr>
<tr>
<td>Inferior dominant</td>
<td>$50^\circ \leq \text{CPA} \leq 85^\circ$; $230^\circ \leq \text{CPA} \leq 265^\circ$</td>
</tr>
<tr>
<td><strong>Anti-phase</strong></td>
<td></td>
</tr>
<tr>
<td>Equal</td>
<td>$130^\circ \leq \text{CPA} \leq 140^\circ$; $310^\circ \leq \text{CPA} \leq 320^\circ$</td>
</tr>
<tr>
<td>Superior dominant</td>
<td>$140^\circ \leq \text{CPA} \leq 175^\circ$; $320^\circ \leq \text{CPA} \leq 355^\circ$</td>
</tr>
<tr>
<td>Inferior dominant</td>
<td>$95^\circ \leq \text{CPA} \leq 130^\circ$; $275^\circ \leq \text{CPA} \leq 310^\circ$</td>
</tr>
<tr>
<td><strong>Superior only</strong></td>
<td>$0^\circ \leq \text{CPA} \leq 5^\circ$; $175^\circ \leq \text{CPA} \leq 185^\circ$; $355^\circ \leq \text{CPA} \leq 360^\circ$</td>
</tr>
<tr>
<td><strong>Inferior only</strong></td>
<td>$85^\circ \leq \text{CPA} \leq 95^\circ$; $265^\circ \leq \text{CPA} \leq 275^\circ$</td>
</tr>
</tbody>
</table>

**Figure 5.3.** Coordination patterns visual representation based on mean coupling angles. [42, 44] Red arrow defines the orientation of the vector between two consecutive points on the angle-angle diagram (inferior and superior segments along the horizontal and vertical axes, respectively). Major coordination patterns (in-phase, anti-phase, superior segment only and inferior segment only) are defined by solid gray lines. Superior and inferior dominant sub-coordination patterns within each major coordination phase are defined on either side of the gray dashed lines identifying the phase of equal segment displacement. The area between the dashed lines represent the equal sub-coordination pattern for in-phase or anti-phase depending on quadrant.
Statistical analysis

Independent samples t-tests were used to identify group differences in closed-chain dorsiflexion and physical activity and CAI questionnaire scores \((p \leq .05)\). Independent samples t-tests were used to confirm similar demographics with respect to height, mass, and age between groups. A series of factorial \((2 \times 2 \times 4)\) analyses of variance (ANOVA) were used to determine mean differences in time spent in the four coordination patterns between tasks (normal, modified) and between groups (CAI, CON) for the shank-rearfoot and shank-femur for each anatomical plane separately \((\alpha=.05)\). This was necessary to discern if time spent in-phase compared to other major coordination patterns differed between groups and tasks for each anatomical plane. If a statistically significant interaction effect was present, then simple main effects were determined. If the interaction was not statistically significant, then main effects for group were assessed.

Results

No statistically significant differences between groups with respect to height, mass, age, or physical activity levels were identified \((p > .05)\). Healthy controls and CAI individuals reported significantly different levels of perceived ankle stability on all ankle questionnaires \((p < .01)\). Groups had similar closed chain dorsiflexion identified with the WBLT distance \((t(26) = 1.62, p = .09, d = 0.67, (1-\beta) = 0.50)\). Mean group characteristics are summarized in Table 5.1.

There were no statistically significant interactions for group by task by coordination pattern, group by coordination pattern, or task by coordination pattern for the shank-rearfoot in any plane \((p > .05)\). However, time spent in the four major coordination patterns for the shank-rearfoot was significantly different regardless of task or group for the sagittal \((F(1.49, 38.63) = 158.51, p < .001, \eta^2 = 0.86, (1-\beta) = 1.00)\), frontal \((F(1.09, 28.44) = 108.18, p < .001,\)
\[ \eta^2 = 0.81, \ (1-\beta) = 1.00 \), and transverse \( F(1.43, 37.25) = 111.89, \ p < .001, \ \eta^2 = 0.81, \ (1-\beta) = 1.00 \)

planes, see Table 5.3 and Figure 5.4.

There were no statistically significant interactions for group by task by coordination pattern for the shank-femur in any plane. Significant interactions and simple main effects for group by coordination and task by coordination of the shank-femur are summarized in Table 5.2. Significant group differences for time spent in transverse plane anti-phase versus in-phase are highlighted in Figure 5.5.

**Table 5.1.** Group Means and Standard Deviations for Participant Characteristics

<table>
<thead>
<tr>
<th></th>
<th>CON (n=14) (5F, 9M)</th>
<th>CAI (n=14) (5F, 9M)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Matching Criteria</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Height (cm)</td>
<td>171.9 (9.4)</td>
<td>172.3 (9.5)</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>69.6 (10.5)</td>
<td>71.1 (10.2)</td>
</tr>
<tr>
<td>Age (years)</td>
<td>23.9 (3.7)</td>
<td>23.9 (3.6)</td>
</tr>
<tr>
<td>GSLTPAQ (physical activity level)</td>
<td>58.7 (20.1)</td>
<td>52.4 (14.6)</td>
</tr>
<tr>
<td><strong>Ankled Related Measures</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IdFAI*</td>
<td>1.5 (2.2)</td>
<td>20.5 (5.8)</td>
</tr>
<tr>
<td>CAIT*</td>
<td>29.5 (1.2)</td>
<td>15.7 (6.2)</td>
</tr>
<tr>
<td>FAAM (percent)*</td>
<td>96.3 (4.9)</td>
<td>86.8 (11.2)</td>
</tr>
<tr>
<td>FAAM-Sport Subscale (percent)*</td>
<td>100.0 (0.0)</td>
<td>78.8 (15.9)</td>
</tr>
<tr>
<td>WBLT distance (cm)</td>
<td>31.5 (8.1)</td>
<td>26.6 (6.5)</td>
</tr>
</tbody>
</table>

*Significantly different at \( p < .05 \).
<table>
<thead>
<tr>
<th></th>
<th>Group X Coordination</th>
<th>Task X Coordination</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Transverse</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anti-phase vs. In-phase</td>
<td>3.78 (2.18, 56.64)</td>
<td>12.34 (1.54,40.07)</td>
</tr>
<tr>
<td></td>
<td>0.03</td>
<td>&lt;.001</td>
</tr>
<tr>
<td></td>
<td>0.13</td>
<td>0.32</td>
</tr>
<tr>
<td></td>
<td>0.69</td>
<td>0.98</td>
</tr>
<tr>
<td><strong>Frontal</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shank-only vs. In-phase</td>
<td>13.76 (1,26)</td>
<td>4.22 (1.74,45.10)</td>
</tr>
<tr>
<td></td>
<td>0.001</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>0.35</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>0.95</td>
<td>0.67</td>
</tr>
<tr>
<td>Transverse</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shank-only vs. In-phase</td>
<td>6.71 (1,26)</td>
<td>5.72 (1,26)</td>
</tr>
<tr>
<td></td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>0.21</td>
<td>0.18</td>
</tr>
<tr>
<td></td>
<td>0.70</td>
<td>0.63</td>
</tr>
<tr>
<td>Femur-only vs. In-phase</td>
<td>6.39 (1,26)</td>
<td>13.76 (2.00,52.06)</td>
</tr>
<tr>
<td></td>
<td>0.02</td>
<td>0.003</td>
</tr>
<tr>
<td></td>
<td>0.21</td>
<td>0.21</td>
</tr>
<tr>
<td></td>
<td>0.90</td>
<td></td>
</tr>
<tr>
<td>Anti-phase vs. In-phase</td>
<td>8.86 (1,26)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.82</td>
<td></td>
</tr>
</tbody>
</table>
Table 5.3. Group Means(SD) of Percent Time Spent in Each Coordination Pattern for Shank-Rearfoot for the Normal and Elevated Rearfoot Squats

<table>
<thead>
<tr>
<th></th>
<th>Elevated Rearfoot</th>
<th>Normal Rearfoot</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sagittal</td>
<td>Frontal</td>
<td>Transverse</td>
</tr>
<tr>
<td><strong>In-Phase</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Equal</td>
<td>1.1(1.7)</td>
<td>1.5(1.1)</td>
<td>4.5(3.8)</td>
</tr>
<tr>
<td>Shank dominant</td>
<td>3.7(4.1)</td>
<td>2.2(1.5)</td>
<td>7.6(5.4)</td>
</tr>
<tr>
<td>Rearfoot dominant</td>
<td>9.8(6.6)</td>
<td>53.9(22.1)</td>
<td>37.9(12.7)</td>
</tr>
<tr>
<td><strong>Anti-Phase</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Equal</td>
<td>6.6(4.7)</td>
<td>1.2(1.5)</td>
<td>4.0(3.1)</td>
</tr>
<tr>
<td>Shank dominant</td>
<td>18.9(14.8)</td>
<td>2.4(1.9)</td>
<td>11.2(6.4)</td>
</tr>
<tr>
<td>Rearfoot dominant</td>
<td>47.7(13.4)</td>
<td>8.5(7.4)</td>
<td>21.7(5.9)</td>
</tr>
<tr>
<td><strong>Single Segment</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shank only</td>
<td>2.9(3.4)</td>
<td>0.4(0.6)</td>
<td>2.9(2.6)</td>
</tr>
<tr>
<td>Rearfoot only</td>
<td>9.3(6.9)</td>
<td>29.9(14.4)</td>
<td>10.2(8.7)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Elevated Rearfoot</th>
<th>Normal Rearfoot</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sagittal</td>
<td>Frontal</td>
<td>Transverse</td>
</tr>
<tr>
<td><strong>In-Phase</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Equal</td>
<td>1.0(1.2)</td>
<td>2.1(3.1)</td>
<td>7.2(8.6)</td>
</tr>
<tr>
<td>Shank dominant</td>
<td>4.6(3.2)</td>
<td>2.4(2.4)</td>
<td>13.1(8.8)</td>
</tr>
<tr>
<td>Rearfoot dominant</td>
<td>14.5(12.5)</td>
<td>61.5(21.3)</td>
<td>36.3(12.9)</td>
</tr>
<tr>
<td><strong>Anti-Phase</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Equal</td>
<td>4.9(4.5)</td>
<td>0.3(0.5)</td>
<td>3.4(1.7)</td>
</tr>
<tr>
<td>Shank dominant</td>
<td>10.1(6.2)</td>
<td>1.6(1.5)</td>
<td>8.4(5.0)</td>
</tr>
<tr>
<td>Rearfoot dominant</td>
<td>47.0(14.0)</td>
<td>6.3(5.9)</td>
<td>19.2(10.0)</td>
</tr>
<tr>
<td><strong>Single Segment</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shank only</td>
<td>1.9(2.0)</td>
<td>0.3(0.5)</td>
<td>2.9(2.6)</td>
</tr>
<tr>
<td>Rearfoot only</td>
<td>16.1(11.7)</td>
<td>25.6(15.4)</td>
<td>10.0(6.8)</td>
</tr>
</tbody>
</table>
Table 5.4. Group Means (SD) of Percent Time Spent in Each Coordination Pattern for Shank-Femur for the Normal and Elevated Rearfoot Squats

**Shank-Femur: CAI**

<table>
<thead>
<tr>
<th></th>
<th>Elevated Rearfoot</th>
<th>Normal Rearfoot</th>
<th>Normal Rearfoot</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sagittal</td>
<td>Frontal</td>
<td>Sagittal</td>
</tr>
<tr>
<td><strong>In-Phase</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Equal</td>
<td>0.1(0.4)</td>
<td>1.0(1.5)</td>
<td>0.6(1.9)</td>
</tr>
<tr>
<td>Femur dominant</td>
<td>0.4(0.5)</td>
<td>2.4(1.9)</td>
<td>2.4(3.2)</td>
</tr>
<tr>
<td>Shank dominant</td>
<td>6.2(13.0)</td>
<td>7.1(5.7)</td>
<td>17.7(14.2)</td>
</tr>
<tr>
<td><strong>Anti-Phase</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Equal</td>
<td>6.7(4.3)</td>
<td>1.7(2.3)</td>
<td>1.6(2.1)</td>
</tr>
<tr>
<td>Femur dominant</td>
<td>3.6(4.4)</td>
<td>2.6(2.1)</td>
<td>4.4(4.3)</td>
</tr>
<tr>
<td>Shank dominant</td>
<td>36.1(13.3)</td>
<td>80.7(6.0)</td>
<td>27.5(13.3)</td>
</tr>
<tr>
<td><strong>Single Segment</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Femur only</td>
<td>0.0(0.0)</td>
<td>0.4(0.6)</td>
<td>0.5(1.0)</td>
</tr>
<tr>
<td>Shank only</td>
<td>47.8(10.2)</td>
<td>6.2(4.4)</td>
<td>43.1(13.2)</td>
</tr>
</tbody>
</table>

**Shank-Femur: CON**

<table>
<thead>
<tr>
<th></th>
<th>Elevated Rearfoot</th>
<th>Normal Rearfoot</th>
<th>Normal Rearfoot</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sagittal</td>
<td>Frontal</td>
<td>Transverse</td>
</tr>
<tr>
<td><strong>In-Phase</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Equal</td>
<td>0.1(0.4)</td>
<td>0.8(1.4)</td>
<td>0.9(1.4)</td>
</tr>
<tr>
<td>Femur dominant</td>
<td>0.8(1.3)</td>
<td>3.1(2.6)</td>
<td>0.9(1.8)</td>
</tr>
<tr>
<td>Shank dominant</td>
<td>4.4(5.5)</td>
<td>7.3(3.9)</td>
<td>27.2(13.4)</td>
</tr>
<tr>
<td><strong>Anti-Phase</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Equal</td>
<td>3.9(4.1)</td>
<td>2.3(1.4)</td>
<td>0.8(1.3)</td>
</tr>
<tr>
<td>Femur dominant</td>
<td>0.4(0.9)</td>
<td>5.5(3.7)</td>
<td>2.3(5.6)</td>
</tr>
<tr>
<td>Shank dominant</td>
<td>48.9(10.7)</td>
<td>78.1(6.9)</td>
<td>15.6(9.7)</td>
</tr>
<tr>
<td><strong>Single Segment</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Femur only</td>
<td>0.3(0.5)</td>
<td>0.9(1.2)</td>
<td>0.3(0.5)</td>
</tr>
<tr>
<td>Shank only</td>
<td>41.4(12.7)</td>
<td>3.6(3.0)</td>
<td>52.1(14.4)</td>
</tr>
</tbody>
</table>
Figure 5.4. Time Spent in Sub-coordination Patterns for the Shank-Rearfoot by Group (columns) and Task (rows) for All Three Anatomical Planes.
Figure 5.5. Time Spent in Sub-coordination Patterns for the Shank-Femur by Group (columns) and Task (rows) for All Three Anatomical Planes.

*Significant difference of time spent in anti-phase versus in phase between groups in the transverse plane.
Discussion

The present study, to our knowledge, is the first to compare the shank-rearfoot and shank-femur coordination throughout squat tasks between those with and without CAI. Additionally, it is the first to compare time spent in major and sub-coordination patterns throughout a squat as defined by previous studies.\textsuperscript{42,44} In general, we hypothesized less in-phase movement of the shank-rearfoot and shank-femur for the transverse plane in those with CAI compared to healthy controls, based on previous literature\textsuperscript{14,18} and as potential explanation for the increased risk of developing posttraumatic osteoarthritis in those with CAI. The shank-rearfoot hypothesis was not supported, but the shank-femur hypothesis was supported with significant differences between groups for time spent in anti-phase versus in-phase for the transverse plane regardless of task.

Those with CAI spent less time in-phase than anti-phase for the shank-femur than their healthy counterparts. The greater amount of time spent in transverse plane anti-phase relative motion between the shank and femur may suggest altered neuromuscular control because the shank spends more time moving in the opposite direction of the femur in CAI individuals versus in similar directions as seen in the controls. This supports and may provide a macroscopic representation of previous neuromuscular alterations identified at the knee with electromyography during double-leg vertical stop-jump tasks in those with CAI compared to controls.\textsuperscript{12} The anti-phase movement of the shank-femur may suggest abnormal rotational movement between the two segments during closed chain activities that could lead to articular cartilage changes of the tibiofemoral joint.\textsuperscript{7} Clinicians treating those with CAI should consider therapeutic interventions to improve neuromuscular control of all joints in the lower extremity. Further research is needed to better understand if altered shank-femur coordination is found in
CAI individuals across various functional tasks with closed and open chain considerations to identify potential sequelae at the knee due to the presence of CAI.

CAI and healthy individuals did not spend significantly different amounts of time in coordination patterns by group or task for the shank-rearfoot. Previous studies identifying significant differences between CAI and controls of the shank-rearfoot during closed chain phases of motion have paired transverse motion of the shank with frontal plane motion of the rearfoot to determine coupling angles.\textsuperscript{14,17,18} Our comparisons of same plane motion for the rearfoot and shank (e.g., frontal rearfoot and frontal shank) may explain the lack of significant results observed for the shank-rearfoot throughout the squat. The frontal rearfoot relative to transverse shank motion of previously conducted studies mimics the index sprain mechanism of injury and perhaps identifies instabilities of the ankle complex throughout movement. However, our comparisons of same plane relative motion between the shank-rearfoot aimed to identify abnormal rotational or translational movements between the articular surfaces. It is also possible that the double-leg squat is more constraining on the shank-rearfoot relative motion due to the fixation of both feet throughout the entirety of the squat versus the planting and removal of each foot throughout the stance and swing phases of gait in previous studies.\textsuperscript{14,17,18} The absence of significant differences in the shank-rearfoot for all anatomical planes between tasks for both groups suggests elevating the rearfoot in certain short-term therapeutic interventions may not put those with CAI at increased risk of giving way due to the increased plantarflexion angle.

Significant differences for time spent in coordination patterns in the sagittal, frontal, and transverse planes differed between tasks for all individuals regardless of CAI presence. For all three anatomical planes, the elevation of the rearfoot caused the shank to move more relative to the femur (shank only) than the change in time spent in shank-femur in-phase. The
implementation of the block altered the coordination of all individuals and is noteworthy for all clinicians who choose to elevate the rearfoot for rehabilitative or performance training purposes. This change needs to be further investigated to determine if it is beneficial or detrimental to the patient and clinicians should use caution when elevating the rearfoot during squats.

There are limitations to this study. Similar amounts of closed chain dorsiflexion between groups as identified with the WBLT distance measure. The amount of available dorsiflexion may influence the percent time spent in certain major and sub-coordination patterns but without significant differences between groups it is unknown if manipulating the dorsiflexion ROM with a block implement alters lower extremity coordination. Consideration for the amount of ROM gained with a block relative to the individual should be further studied in future lower extremity coordination studies. The reduction in sample size due to data processing issues with the COM model may contribute to the observed low power and small effect sizes.

Intra-limb coordination patterns were presented for those with and without CAI in two squat tasks. No differences in coordination patterns for the shank-rearfoot were identified between groups or task in any anatomical plane. CAI individuals spend significantly greater amounts of time spent in transverse anti-phase shank-femur relative motion than in-phase compared to their healthy counterparts. Subtle movements, particularly those of anti-phase relative movement, may provide insight to altered knee neuromuscular control and potential development of sequelae at the knee following the onset of CAI.
References


CHAPTER 6
SUMMARY

Chapter four assessed the joint angular kinematic variability presented as the integrated standard deviation time series to determine summated joint kinematic variability between groups and tasks. Chapter five identified the time spent in major and sub-coordination patterns for the shank-rearfoot and shank-femur throughout the normal and elevated rearfoot squat tasks. Chapter six will address the alternative methodological considerations for the research questions answered in chapters four and five in addition to kinetic analyses.

Closed Chain Dorsiflexion

No differences were found in WBLT distance between groups when determining closed chain dorsiflexion. Consideration for the “moving” dorsiflexion as defined by the movement of the shank relative to the femur during the WBLT should be made due to similarities of shank movement in the squat task. The moving angle is determined as the difference between 90 degrees neutral and the WBLT inclination angle.

Similarly, the angle of ankle when the rearfoot is placed on the block may have differed between individuals depending on foot length. There were no statistically significant differences between groups in ankle plantarflexion created with rearfoot elevation, $t(26)=-1.82, p=0.08, [-9.48,0.58]$.

Use of Plug-In-Gait Foot versus Oxford Rearfoot

Segment model definition will directly influence the joint kinematics generated for interpretation. Multiple individuals were identified as having “drift” in frontal ankle kinematics
with the Plug-In-Gait foot at the beginning of the 10 squat trial (see Figure below). Individuals were instructed to start the squat with feet parallel but would often externally rotate the feet as the trial progressed. The drift identifies the models inability to remove the forefoot motion from the rearfoot. Further consideration for multi-segment foot models should be made in the CAI kinematic literature.

**Figure 6.1.** Representative internal/external rotation of the foot relative to the rearfoot motion and vertical COM position.

**COM Trajectory to Identify Squat Start and End Points**

The critical time points to identify the start, lowest depth, and end of squat presented a challenge across individuals. The participants were instructed to perform the 10 squats at a comfortable speed. Some chose to complete the squats as quickly as possible, others paused while standing or resting at the bottom, while a few performed the squats as slow as possible. Consideration should be made for variables to describe the time between squats and the
“bounce” effect of the COM trajectory in the vertical direction to better understand the participant’s selection of squat performance temporal parameters.

**Summated Joint Kinematic Variability with Respect to Trials**

Summated joint kinematic variability similarities that were identified in chapter four may be due to the removal of the temporal component of how the fast or slow the participant chose to complete the 10 squats within a trial. Identification of the start of the trial would be the frame before the COM trajectories lowers below standing height and the end of the trial as the last instance of returning to standing height. Temporal normalization to total trial time at 100% with 1010 points (101 points for 10 squats within one trial) would keep the frequency content of how the squats were initially performed. When exploring the four trials within a condition, a few CAI participants appeared to have less variability between trials for squats 6-10 compared to the first half. Sets, or trials, of 10 repetitions is commonly used in rehabilitation programs but it is possible there is an ideal number of repetitions within a trial for those with CAI to complete before falling into a more rigid pattern.

**Vector Coding**

In order to better compare coupling angles across squatting and walking/jogging tasks with previous CAI coordination literature, vector coding should be considered to align with the transverse plane of the shank and frontal plane of the femur. The use of circular statistics to generate time series data for the mean coupling angle, magnitude and variability with curve analysis will be necessary to truly compare shank-rearfoot coordination across tasks. 29,30,42

**Kinetic Assessment**

There was no assessment of the ground reaction forces collected in chapter four or five. Due to the cyclic nature of completing 10 repetitions within a trial, it may be worthwhile to
consider nonlinear measures to analyze COP data for the normal squat. Adjustment
c onsiderations to the COP data would need to be made to account for the two wedges placed
under the feet.
REFERENCES


APPENDIX A:

PHYSICAL ACTIVITY LEVEL QUESTIONNAIRE

Godin Leisure-Time Exercise Questionnaire

1. During a typical 7-Day period (a week), how many times on the average do you do the following kinds of exercise for more than 15 minutes during your free time (write on each line the appropriate number).

   a) STRENUOUS EXERCISE
      (HEART BEATS RAPIDLY)
      (e.g., running, jogging, hockey, football, soccer, squash, basketball, cross country skiing, judo, roller skating, vigorous swimming, vigorous long distance bicycling)

   b) MODERATE EXERCISE
      (NOT EXHAUSTING)
      (e.g., fast walking, baseball, tennis, easy bicycling, volleyball, badminton, easy swimming, alpine skiing, popular and folk dancing)

   c) MILD EXERCISE
      (MINIMAL EFFORT)
      (e.g., yoga, archery, fishing from river bank, bowling, horseshoes, golf, snow-mobiling, easy walking)

2. During a typical 7-Day period (a week), in your leisure time, how often do you engage in any regular activity long enough to work up a sweat (heart beats rapidly)?

   OFTEN       SOMETIMES       NEVER/RARELY
   1.  ☐         2.  ☐         3.  ☐
APPENDIX B:

CAI REGION SPECIFIC PROs

<table>
<thead>
<tr>
<th>IDFAI</th>
<th>Identification of Functional Ankle Instability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Instructions: This form will be used to categorize your ankle stability status. A separate form should be used for the right and left ankles. Please fill out the form completely and if you have any questions, please ask the administrator. Thank you for your participation.</td>
</tr>
<tr>
<td></td>
<td>&quot;Giving way&quot; is described as a temporary uncontrolled sensation of instability or rolling over of one's ankle.</td>
</tr>
<tr>
<td></td>
<td>I am completing this form for my RIGHT/LEFT ankle (circle one).</td>
</tr>
<tr>
<td></td>
<td>1.) Approximately how many times have you sprained your ankle? ________</td>
</tr>
<tr>
<td></td>
<td>2.) When was the last time you sprained your ankle?</td>
</tr>
<tr>
<td></td>
<td>□ Never □ &gt; 2 years □ 1-2 years □ 6-12 months □ 1-6 months □ &lt; 1 month</td>
</tr>
<tr>
<td></td>
<td>□ 0 □ 1 □ 2 □ 3 □ 4 □ 5</td>
</tr>
<tr>
<td></td>
<td>3.) If you have seen an athletic trainer, physician, or healthcare provider how did he/she categorize your most serious ankle sprain?</td>
</tr>
<tr>
<td></td>
<td>□ Have not seen someone □ Mild (Grade I) □ Moderate (Grade II) □ Severe (Grade III)</td>
</tr>
<tr>
<td></td>
<td>□ 0 □ 1 □ 2 □ 3</td>
</tr>
<tr>
<td></td>
<td>4.) If you have ever used crutches, or other device, due to an ankle sprain how long did you use it?</td>
</tr>
<tr>
<td></td>
<td>□ Never used a device □ 1-3 days □ 4-7 days □ 1-2 weeks □ 2-3 weeks □ &gt;3 weeks</td>
</tr>
<tr>
<td></td>
<td>□ 0 □ 1 □ 2 □ 3 □ 4 □ 5</td>
</tr>
<tr>
<td></td>
<td>5.) When was the last time you had &quot;giving way&quot; in your ankle?</td>
</tr>
<tr>
<td></td>
<td>□ Never □ &gt; 2 years □ 1-2 years □ 6-12 months □ 1-6 months □ &lt; 1 month</td>
</tr>
<tr>
<td></td>
<td>□ 0 □ 1 □ 2 □ 3 □ 4 □ 5</td>
</tr>
<tr>
<td></td>
<td>6.) How often does the &quot;giving way&quot; sensation occur in your ankle?</td>
</tr>
<tr>
<td></td>
<td>□ Never □ Once a year □ Once a month □ Once a week □ Once a day</td>
</tr>
<tr>
<td></td>
<td>□ 0 □ 1 □ 2 □ 3 □ 4</td>
</tr>
<tr>
<td></td>
<td>7.) Typically when you start to roll over (or 'twist') on your ankle can you stop it?</td>
</tr>
<tr>
<td></td>
<td>□ Never rolled over □ Immediately □ Sometimes □ Unable to stop it</td>
</tr>
<tr>
<td></td>
<td>□ 0 □ 1 □ 2 □ 3</td>
</tr>
<tr>
<td></td>
<td>8.) Following a typical incident of your ankle rolling over, how soon does it return to 'normal'?</td>
</tr>
<tr>
<td></td>
<td>□ Never rolled over □ Immediately □ &lt; 1 day □ 1-2 days □ &gt; 2 days</td>
</tr>
<tr>
<td></td>
<td>□ 0 □ 1 □ 2 □ 3 □ 4</td>
</tr>
<tr>
<td></td>
<td>9.) During &quot;Activities of daily life&quot; how often does your ankle feel UNSTABLE?</td>
</tr>
<tr>
<td></td>
<td>□ Never □ Once a year □ Once a month □ Once a week □ Once a day</td>
</tr>
<tr>
<td></td>
<td>□ 0 □ 1 □ 2 □ 3 □ 4</td>
</tr>
<tr>
<td></td>
<td>10.) During &quot;Sport/or recreational activities&quot; how often does your ankle feel UNSTABLE?</td>
</tr>
<tr>
<td></td>
<td>□ Never □ Once a year □ Once a month □ Once a week □ Once a day</td>
</tr>
<tr>
<td></td>
<td>□ 0 □ 1 □ 2 □ 3 □ 4</td>
</tr>
</tbody>
</table>

Version 1.0
APPENDIX C

CUMBERLAND ANKLE INSTABILITY TOOL

<table>
<thead>
<tr>
<th>Question</th>
<th>LEFT</th>
<th>RIGHT</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. I have pain in my ankle</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Never</td>
<td></td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>During sport</td>
<td></td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>Running on uneven surfaces</td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Running on level surfaces</td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Walking on uneven surfaces</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Walking on level surfaces</td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>2. My ankle feels UNSTABLE</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Never</td>
<td></td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>Sometimes during sport (not every time)</td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Frequently during sport (every time)</td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Sometimes during daily activity</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Frequently during daily activity</td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>3. When I make SHARP turns, my ankle feels UNSTABLE</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Never</td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Sometimes when running</td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Often when running</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>When walking</td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>4. When going down the stairs, my ankle feels UNSTABLE</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Never</td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>If I go fast</td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Occasionally</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Always</td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>5. My ankle feels UNSTABLE when standing on ONE leg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Never</td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>On the ball of my foot</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>With my foot flat</td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>6. My ankle feels UNSTABLE when</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Never</td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>I hop from side to side</td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>I hop on the spot</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>When I jump</td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>7. My ankle feels UNSTABLE when</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Never</td>
<td></td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>I run on uneven surfaces</td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>I jog on uneven surfaces</td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>I walk on uneven surfaces</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>I walk on a flat surface</td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>8. TYPICALLY, when I start to roll over (or &quot;twist&quot;) on my ankle, I</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>can stop it</td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Immediately</td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Often</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Sometimes</td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Never</td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>9. After a TYPICAL incident of my ankle rolling over, my ankle</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>returns to &quot;normal&quot;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Almost immediately</td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Less than one day</td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>1-2 days</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>More than 2 days</td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>I have never rolled over on my ankle</td>
<td></td>
<td></td>
<td>3</td>
</tr>
</tbody>
</table>