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ABSTRACT OF DISSERTATION

Matthew C. Hoch

The Graduate School
University of Kentucky
2011

THE EFFECT OF JOINT MOBILIZATION ON FUNCTIONAL OUTCOMES
ASSOCIATED WITH CHRONIC ANKLE INSTABILITY

ABSTRACT OF DISSERTATION

A dissertation submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy in the College of Health Sciences
at the University of Kentucky

By
Matthew C. Hoch

Lexington, Kentucky

Co-Directors: Dr. Patrick O. McKeon, Assistant Professor of Athletic Training and
Dr. Richard D. Andreatta, Associate Professor of Communication Sciences & Disorders

Lexington, Kentucky

2011

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ABSTRACT OF DISSERTATION

THE EFFECT OF JOINT MOBILIZATION ON FUNCTIONAL OUTCOMES ASSOCIATED WITH CHRONIC ANKLE INSTABILITY

Ankle sprains are among the most common injuries sustained by physically active individuals. Although ankle sprains are often considered innocuous in nature, a large percentage of individuals experience repetitive sprains, residual symptoms, and recurrent ankle instability following a single acute sprain; otherwise known as chronic ankle instability (CAI). In addition to repetitive ankle trauma, those with CAI experience reductions in functional capacity over the life span. This indicates that current intervention strategies for CAI are inadequate and require further investigation.

The objective of this dissertation was to explore differences in walking and running gait parameters between individuals with and without CAI; as well as, examine the effects of a 2-week Maitland Grade III anterior-to-posterior talocrural joint mobilization intervention on self-reported function, ankle mechanics, postural control, and walking and running gait parameters in a cohort of individuals with CAI. It was hypothesized that individuals with CAI would exhibit different gait kinematics and joint coupling variability patterns compared to healthy individuals and the joint mobilization intervention would improve patient-oriented, clinician-oriented, and laboratory-oriented measures of function in those with CAI.

Several observations were made from the results. In the first study, alterations in single joint kinematics and joint coupling variability were found between those with CAI and healthy individuals. In the second study, it was determined that the joint mobilization intervention improved patient-oriented and clinician-oriented measures of function as indicated by improved Foot and Ankle Ability Measure scores, increased weight-bearing dorsiflexion range of motion, and increased reach distances on the Star Excursion Balance Test. However, there were no changes in measures of instrumented ankle arthrometry or laboratory measures of postural control. In the third study, there were no changes in single joint kinematics or joint coupling variability during walking and running associated with the joint mobilization intervention. It can be concluded that joint mobilizations had a significant positive impact on patient-, and clinician-oriented measures of function. Though the laboratory measures did not detect any improvements, joint mobilizations did not produce deleterious effects on function. Therefore, future investigation on the effects of joint mobilization in conjunction with other, more active, rehabilitation strategies is warranted.

KEY WORDS: ankle instability, ankle sprains, gait, manual therapy, rehabilitation

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THE EFFECT OF JOINT MOBILIZATION ON FUNCTIONAL OUTCOMES
ASSOCIATED WITH CHRONIC ANKLE INSTABILITY

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DISSERTATION

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TABLE OF CONTENTS

ACKNOWLEDGEMENTS	iii
List of Figures	viii
List of Tables	ix
Chapter 1: Introduction	1
Background	1
The Problem	6
Purposes	8
Experimental Aims and Hypotheses	8
Clinical Implications	9
Operational Definitions	10
Assumptions	12
Delimitations	12
Chapter 2: Review of the Literature	14
Introduction	14
Chronic Ankle Instability	14
Functional Impairments Associated with Chronic Ankle Instability	15
Static Postural Control	16
Dynamic Postural Control	18
Gait Biomechanics	21
Mechanical Impairments Associated with Chronic Ankle Instability	25
Ligamentous Laxity of the Ankle Complex	25
Alterations in Arthrokinematics of the Ankle Complex	27
Talocrural Joint Mobilization Techniques for Chronic Ankle Instability	29
Range of Motion	30
Sensory Stimulation and Sensorimotor System Function	32
Summary	34
Contemporary Models of Motor Control and Disablement as it Relates to Sensorimotor Control and Function in Chronic Ankle Instability	35
The Dynamical Nature of Sensorimotor System Organization	36
The Dynamic Nature of Function	39

Integrating the Dynamic Systems Theory and ICF Model of Health for Chronic Ankle Instability	42
Chapter 3: Kinematic Alterations in Walking and Running Gait in Those with Chronic Ankle Instability.....	44
Introduction.....	44
Methods.....	46
Experimental Design and Subjects	46
Instrumentation and Data Capture.....	47
Procedures	48
Data Reduction	48
Statistical Analysis	50
Results.....	51
Discussion.....	52
Kinematics	52
Joint Coupling Relationships.....	55
Limitations and Future Directions.....	57
Conclusion	58
Chapter 4: Effect of Joint Mobilization on Self-Reported Function, Range of Motion, and Postural Control in Those with Chronic Ankle Instability	66
Introduction.....	66
Methods.....	68
Design	68
Subjects.....	68
Instrumentation.....	69
Testing Procedures	70
Dorsiflexion Range of Motion.....	70
Instrumented Arthrometry	71
Dynamic Postural Control	72
Static Postural Control.....	72
Joint Mobilization Intervention	73
Minimal Detectable Change Scores	74
Statistical Analysis	74

Results.....	75
Self-Reported Function.....	75
Dorsiflexion Range of Motion.....	76
Ankle Arthrometry	76
Dynamic Postural Control	76
Static Postural Control.....	77
Discussion.....	78
Limitations and Future Research.....	82
Conclusion	84
Chapter 5: Effect of Joint Mobilization on Gait Kinematics and Joint Coupling Variability in Those with Chronic Ankle Instability	95
Introduction.....	95
Methods.....	97
Design.....	97
Subjects.....	97
Instrumentation and Data Capture	98
Procedures	99
Data Reduction	100
Joint Mobilization Intervention	101
Statistical Analysis	102
Results.....	103
Discussion.....	103
Limitations and Future Directions.....	107
Conclusion	109
Chapter 6: Summary	112
Synthesis and Application of Results	114
Appendix A.....	120
Appendix B.....	121
Appendix C.....	122
Appendix D.....	134
Bibliography	146

Vita..... 155

List of Figures

Figure 4.1: Study timeline.....	90
Figure 4.2: Weight-bearing lunge test.....	91
Figure 4.3: Ankle/subtalar arthrometric assessment	92
Figure 4.4: Position for static postural control assessment.....	93
Figure 4.5: Star Excursion Balance Test (anterior, posteromedial, posterolateral).....	94

List of Tables

Table 3.1: Group differences in walking kinematics.	60
Table 3.2: Group differences in walking joint coupling variability.	61
Table 3.3: Group statistics for the average vector coding coefficient during walking.	62
Table 3.4: Group differences in running kinematics.	63
Table 3.5: Group Differences in running joint coupling variability.	64
Table 3.6: Group statistics for the average vector coding coefficient during running.	65
Table 4.1: Mean \pm SD and MDC for the FAAM and FAAM-S.	85
Table 4.2: Mean \pm SD and MDC for DF ROM and ankle arthrometry.	86
Table 4.3: Mean \pm SD and MDC for normalized reach distances on the SEBT.	87
Table 4.4: Mean \pm SD and MDC for eyes open TTB measures.	88
Table 4.5: Mean \pm SD and MDC for eyes closed TTB measures.	89
Table 5.1: Mean \pm SD for the average vector coding coefficients of the walking stride.	110
Table 5.2: Mean \pm SD for the average vector coding coefficient of the running stride.	111

Chapter 1: Introduction

Background

Ankles sprains are the most frequently occurring injury sustained by physically active individuals participating in sport¹⁻², on active-duty in the military³, and within the general population.⁴ It is estimated that 23,000 ankle sprains occur daily in the United States with an estimated 4.2 billion dollars spent annually on treatment for these injuries.⁴⁻⁵ Although often considered innocuous in nature, ankles sprains demonstrate the highest recurrence rate of any musculoskeletal injury.⁶⁻⁷ Up to 70% of people experience repetitive sprains, residuals symptoms, and recurrent ankle instability following a single acute sprain; otherwise known as chronic ankle instability (CAI).⁸ In addition to repetitive incidents of joint trauma, those with CAI experience reductions in functional capacity and health-related quality of life.⁹⁻¹⁰ The factors contributing to CAI have traditionally been separated into mechanical and functional impairments.⁸ Mechanical impairments include range of motion deficits, arthrokinematic alterations, ligamentous laxity, and degenerative changes.⁸ Functional impairments are sensorimotor deficits that affect stability during functional activities including deficits in postural control and alterations in gait.^{8, 11} Therefore, ankle sprains are frequently occurring injuries and the development of CAI is multi-factorial in nature.

Alterations in ankle joint mechanics have been a frequently studied area to explain the pathology and etiology of CAI.¹² Previous research¹³ has identified structural changes in extra-articular structures including ruptures or elongation of the lateral and medial ankle ligaments; as well as, intra-articular cartilage damage in those with CAI. Several investigations¹⁴⁻¹⁷ have identified that those with CAI exhibit increased anterior

translation of the talus as a result of ligamentous laxity. Other mechanical impairments include alterations in boney alignment or arthrokinematics of the distal tibiofibular and talocrural joints; specifically positional faults (malalignment) of the distal fibula and talus.¹⁸⁻²⁴ The direction of fibular positional faults are contradictory in the literature with some reports^{18-19, 25} concluding the distal fibula is anteriorly positioned while other studies²⁰⁻²¹ report the distal fibula is posteriorly positioned following ankle sprain. This suggests that investigating alterations in other arthrokinematics such as those at the talocrural joint may provide greater insight into meaningful mechanical changes associated with CAI.

Despite the contradictory findings associated with changes in fibular position, recent studies²³⁻²⁴ have identified an anterior talar positional fault in individuals with CAI using radiographic imaging. Anterior talar positional faults can be described as an abnormal anterior displacement of the talus in a neutral position of the talocrural joint and may be the result of increased anterior ligamentous laxity and restrictions in posterior noncontractile articular structures.²³⁻²⁴ Currently, no prospective investigations have been conducted to determine if changes in talar positioning are the result of repetitive ankle sprains or merely a predisposing factor to injury. Despite the paucity of information regarding the origination of anterior talar positional faults, this impairment has been supported in the literature by previous studies which have identified decreased posterior talar glide²⁶ and improvements in posterior talar glide following anterior-to-posterior joint mobilization in individuals with a history of ankle sprain.²⁷⁻²⁹ These studies advocate for further examination of the effects of altered talocrural arthrokinematics on the mechanical and functional impairments associated with CAI.

Anterior talar positional faults are likely associated with restrictions in posterior talar glide^{24, 30} which indicate this change in arthrokinematics may also be responsible for purported reductions in dorsiflexion range of motion (DF ROM).³¹⁻³⁵ DF ROM restrictions have been exhibited during walking and running gait^{31, 35} and may be responsible for deficits in certain aspects of dynamic postural control in those with CAI.³⁶⁻³⁸ Reductions in DF ROM and posterior talar glide from restrictions in joint capsular and ligamentous tissues may affect the transmission of afferent information.⁸ This suggests these mechanical impairments may be contributing factors to deficits in sensorimotor system function and the functional impairments experienced by those with CAI.

Postural control deficiencies have been a long studied impairment in individuals with a history of ankle sprain.³⁹⁻⁴³ Several investigators⁴²⁻⁴³ have determined that individuals with CAI exhibit deficits in static and dynamic postural control. These deficits have been highlighted in a series of systematic reviews and meta-analyses which have critically appraised the available research associated with postural control and individuals with a history of recurrent ankle sprains.⁴¹⁻⁴⁶ These reports indicate that those with CAI exhibit impairments in the limb with a history of ankle sprain but also in the uninvolved limb. Additionally, alterations in postural control are plastic and can be manipulated through rehabilitation.⁴⁶ Therefore, when accounting for all of the available evidence, individuals with a history of recurrent ankle sprains demonstrate modifiable impairments in instrumented single-limb stance postural control as well as various dynamic postural control assessments including the Star Excursion Balance Test (SEBT).⁴¹⁻⁴⁶

The most common method of assessing single-limb stance postural control is by evaluating center of pressure (COP) excursions using an instrumented forceplate.⁴¹ Traditional COP measurements include spatial variables such as area and range; as well as, temporal variables such as velocity.⁴¹ However, a spatiotemporal COP analysis technique referred to as time-to-boundary (TTB) appears to detect postural control deficits in those with CAI more consistently compared to traditional COP measures.⁴⁷⁻⁴⁹ TTB measures the amount of time to make a postural correction and the level of constraint experienced by the sensorimotor system while maintaining balance around a base of support.⁵⁰⁻⁵¹ Thus, individuals with CAI have demonstrated less time and fewer movement solutions to maintain single-limb stance compared to healthy individuals.⁴⁸

To compliment laboratory measures of postural control, several investigators have examined dynamic postural control using a non-instrumented, clinical measure known as the SEBT.^{42, 44} The SEBT is a battery of lower extremity maximal reach tests while the contra-lateral limb attempts to maintain single-limb balance.⁵² Of the 8 reach directions, the anterior, posteromedial, and posterolateral directions appear to be the most independent for reducing the amount of redundant information during this assessment.⁵³ Individuals with CAI have demonstrated shorter reach distances; particularly in the anterior direction, when standing on the injured limb and compared to healthy individuals.^{38, 52, 54} Shorter reach distances suggests those with CAI portray decreased sensorimotor system function.⁵² Therefore, using the most recent recommendations for administering the SEBT appears to provide a good indication of the ability of those with CAI to organize various components of sensorimotor function and range of motion to accomplish a movement goal.

Alterations in gait biomechanics have also been investigated in those with CAI. Alterations which have been identified include increased rearfoot inversion and shank external rotation during the terminal swing phase; as well as, decreased DF ROM during the stance phase of walking and running.^{31, 35, 55} Also, when examining the joint coupling relationship between rearfoot inversion-eversion and shank external-internal rotation, those with CAI demonstrated less coordinated movement patterns.⁵⁵ Less coordinated movement between the shank and rearfoot, greater rearfoot inversion and shank external rotation, and decreases in DF ROM during indicates that those with CAI may be in a more precarious, open-pack position at the time of initial ground contact which could increase the susceptibility of sustaining additional ankle sprains.³⁵

Based on the multi-factorial nature of CAI, interventions for addressing both the mechanical and functional impairments exhibited by those with CAI are necessary to reduce ankle sprain reoccurrence, restore functional loss, and prevent degenerative joint disease.⁵³ A manual therapy technique known as joint mobilization has been used to successfully address several mechanical impairments in those with a history recurrent ankle sprains by increasing DF ROM and posterior talar glide.²⁷⁻²⁹ In addition to restoring range of motion and arthrokinematics, there is evidence to suggest that joint mobilization may enhance sensorimotor system function by stimulating articular afferent receptors located in the ligaments and joint capsule surrounding the ankle.⁵⁶ Despite the alleged ability of joint mobilization to stimulate articular afferent receptors, limited evidence is available to support these claims.

To provide preliminary evidence of the capability of joint mobilization to enhance sensorimotor system function, a recent investigation²⁷ determined that a single

application of anterior-to-posterior talocrural joint mobilizations was able to enhance TTB postural control in the anteroposterior direction and concurrently increase DF ROM in those with CAI. Despite these findings, no significant improvements occurred in performance on the SEBT and no significant changes occurred in posterior talar glide or posterior ankle stiffness.²⁷ Additionally, this study was unable to evaluate changes in patient-oriented measures of self-reported function such as the Foot and Ankle Ability Measure (FAAM) to determine if subjects perceived meaningful changes in function following treatment application. Therefore, further investigating the effects of joint mobilization following more than a single intervention period may reveal more systematic improvements in the mechanical, functional, and self-perceived impairments in function exhibited by those with CAI.²⁷

The Problem

At least 1 of 3 individuals develops CAI following an acute ankle sprain.⁶ Several contributing factors for CAI have been identified including alterations in gait biomechanics.⁵⁵ Few studies have provided a comprehensive examination of distal and proximal lower extremity kinematics in those with CAI. Additionally, the sensorimotor organization of lower extremity joints and segments during gait has not been examined beyond the relationship between rearfoot inversion-eversion and shank rotation. This indicates that the current understanding of gait deviations in those with CAI may be incomplete. Examining the kinematics of the hip, knee, shank, ankle, and rearfoot along with the interaction of these joints in the same investigation may provide a more holistic rendering of the gait alterations displayed by those with CAI.

The large number of individuals who develops CAI also suggests the current

treatment strategies might be inadequate. Most interventions (strengthening, balance training) focus on motor aspects of rehabilitation. While this aspect of rehabilitation may be important, interventions which target sensory pathways may be beneficial; however, this has not been extensively explored. Joint mobilization offers an intervention with the potential to target sensory pathways at the articular level by manipulating noncontractile tissues and concurrently stimulating the mechanoreceptors within these structures.²⁷ Previous research has focused primarily on the mechanical benefits for talocrural joint mobilization, but there is limited information regarding its effects on sensorimotor system function.

The current evidence indicating joint mobilization may have sensorimotor benefits is based on a single bout of treatment. It is unknown whether multiple joint mobilization treatments offer any potential sensorimotor benefits. Although it has been speculated that joint mobilization can enhance the transmission of afferent information from articular receptors, the exact mechanism by which these changes occur and their impact on global measures of sensorimotor function has not been established. Examining joint mobilization in this way may elucidate how stimulating articular mechanoreceptors can influence the information and action fields of the sensorimotor system in those with CAI. Therefore, systematically exploring the capabilities of joint mobilization to address local and global sources of impairment associated with CAI is necessary to determine the utility of this intervention. Before rigorous randomized clinical trials can be employed to examine the efficacy of joint mobilization for the outcomes associated with CAI, it would be beneficial to examine the effects of joint mobilization in a prospective cohort design to gain information on the effects of multiple joint mobilization treatments over time.

Therefore, this study proposes investigating the effects of joint mobilization on self-reported function, ankle mechanics, and sensorimotor system function in those with CAI following multiple bouts of joint mobilization treatment using a repeated-measures design.

Purposes

There were 3 purposes of this dissertation. The first purpose was to provide a comprehensive examination of gait parameters in those with CAI compared to individuals without CAI. The second purpose is to examine the effect of a 2-wk talocrural joint mobilization intervention on self-reported function measured by the FAAM and FAAM-S, measures of ankle arthrokinematics with an instrumented arthrometer, DF ROM measured on the weight-bearing lunge test (WBLT), and static and dynamic postural control assessed by TTB measures and the SEBT. The third purpose was to assess the effects of joint mobilizations on walking and running gait parameters captured with 3-dimensional motion analysis using a repeated-measures design.

Experimental Aims and Hypotheses

Specific Aim 1: Explore differences in walking and running gait parameters in those with and without CAI.

Specific Aim 2: Investigate the effect of a 2-wk talocrural joint mobilization intervention on:

- 1) patient-oriented measures of self-reported function.
- 2) clinician-oriented measures of range of motion and dynamic postural control.
- 3) laboratory-oriented measures of static postural control.

Specific Aim 3: Examine the effects of the joint mobilization intervention on laboratory-

oriented walking and running gait parameters.

Hypothesis for Specific Aim 1: Those with CAI will demonstrate kinematic differences in rearfoot, shank, and ankle motion; as well as, different shank-rearfoot coupling variability patterns during walking and running gait when compared to the group without CAI.

Hypotheses for Specific Aim 2: Following the 2-wk talocrural joint mobilization intervention subjects will demonstrate significant improvements in:

- 1) patient-oriented measures of function as indicated by increased FAAM and FAAM-S scores.
- 2) clinician-oriented measures of function as indicated by increased DF ROM, increased posterior talar glide, and increased reach distances on the SEBT.
- 3) laboratory-oriented measures of function as indicated by increased TTB magnitude and variability.

Hypothesis for Specific Aim 3: Joint mobilizations will result in alterations of various gait parameters such as DF ROM, rearfoot inversion, and joint coupling relationships of the lower extremity.

Clinical Implications

Providing a comprehensive analysis of walking and running gait in those with CAI may expose additional contributing factors for the development of CAI that can aid in the development of potential therapeutic interventions. The equipment intensive laboratory approach of this study will hopefully provide clinically meaningful results by examining the data through the context of clinically recognizable phases of the gait cycle and by making potential connections between gait deviations (kinematics and sensorimotor system organization) and self-reported measures of function. This approach

will enable laboratory-oriented measures of gait to take on more meaningful clinical applications.

The purpose of the other studies in this dissertation is to assess the effects of a 2-wk talocrural joint mobilization intervention on self-reported function, ankle range of motion, static and dynamic postural control, and gait parameters in individuals with self-reported CAI. Joint mobilization is a common manual therapy technique for addressing local restrictions in range of motion and offers an affordable and non-equipment intensive intervention which is readily accessible to clinicians. Despite the accessibility of this intervention, there is a lack of evidence to support its use in those with CAI beyond the mechanical benefits associated with a limited number of treatments. To systematically evaluate the effects of multiple joint mobilization treatments in those with CAI, this study will use patient-, clinician-, and laboratory-oriented measures (PCL Model) to capture function at the level of the person in their environment, as well as, local impairments in range of motion and global impairments in sensorimotor system function. By using the PCL Model, the aim is to provide a deeper understanding of the interaction between mechanical impairments, sensorimotor system impairments, and self-perceived changes in function which may lead to the development of effective rehabilitation strategies for addressing the recurrent episodes of ankle trauma and reductions in functional capacity experienced by those with CAI.

Operational Definitions

Arthrokinematics: The involuntary movement occurring between articular surface (roll, spin, glide) which is also synonymous with the term accessory motion.

Center of Pressure (COP): Two dimensional coordinate of the origin of the three-

dimensional forces arising from the action-reaction between the foot and forceplate during stance.

Chronic Ankle Instability (CAI): A health condition characterized by repetitive bouts of ankle instability resulting in recurrent ankle sprains and functional loss following the occurrence of one or more acute ankle sprains.

Dorsiflexion: Type of motion within the sagittal plane representative of the talocrural joint in which the angle between the dorsum of the foot and the leg is decreased.

Dynamic Postural Control: Maintaining the body's center of mass within a given base of support while performing a functional activity.

Joint Coupling: The kinematic coordination of motion between 2 joints or 2 segments.

Joint Mobilization: A form of manual therapy that aims to increase physiologic and accessory motion by increasing the extensibility of joint capsule and ligamentous tissues, promoting the alignment and tracking of articular surfaces, and improving the transmission of afferent information by passively moving the joint into areas of soft-tissue restriction.

Osteokinematics: Gross, voluntary movements of bones at joints (dorsiflexion, plantar flexion).

Plantar Flexion: Type of motion within the sagittal plane representative of the talocrural joint in which the angle between the dorsum of the foot and the leg is increased.

Posterior Talar Glide: Arthrokinematic motion of the talus in the ankle mortise during dorsiflexion (or movement of the tibia anteriorly over the talus on a fixed foot).

Static Postural Control: Maintaining the body's center of mass within a given base of support while attempting to limit movement or keep the body at rest.

Time-to-boundary (TTB): A spatiotemporal analysis of COP which estimates the time it would take every two consecutive COP points to reach the boundary of the base of support if the trajectory and velocity were to remain constant.

Vector Coding: A spatiotemporal analysis of the coupling of 2 joints over a specific period of time visualized using angle-angle plots.

Assumptions

It will be assumed that:

1. Subjects with a self-reported history of CAI will have the condition of interest.
2. Subjects will understand the FAAM and FAAM-S and will provide answers which reflect their functional capacity to the best of their ability.
3. Subjects will demonstrate their best effort during data collection.
4. Subjects will not receive other forms of rehabilitation and will maintain their current level of physical activity between data collection sessions.

Delimitations

1. Subjects will be males and females between the ages of 18 - 45.
2. Subjects will be physically active.
 - a. Qualified by a score of 4 or higher on the NASA Physical Activity Scale.
3. Subjects will have self-reported CAI.
 - a. Qualified by < 90% on the FAAM, < 80% on the FAAM-S, and answering “yes” to at least 4 questions on the Ankle Instability Instrument (AII).
4. Subjects will be free from peripheral neuropathies or other health conditions which may influence postural control or gait.
5. All subjects will not have sustained an ankle sprain in at least 6 wks and no other

lower extremity injuries in at least 6 months.

6. All subjects will have no history of lower extremity surgery.
7. All assessments will be performed barefoot.
8. Joint mobilizations will be performed by a certified athletic trainer with 5 years of experience.

Chapter 2: Review of the Literature

Introduction

The purpose of this literature review is to: 1) describe the health condition known as chronic ankle instability (CAI), 2) discuss the current evidence regarding functional impairments in static postural control, dynamic postural control, and gait biomechanics associated with CAI, 3) discuss the research regarding mechanical impairments associated with CAI, 4) discuss the research examining the effects of joint mobilization on functional outcomes in those with CAI, 5) discuss the dynamical systems theory of motor control and the International Classification of Health, Disability, and Function (ICF) model of health as it relates to sensorimotor control and function in those with CAI.

Chronic Ankle Instability

Lateral ankle sprains are the most common injuries incurred by the physically active.¹⁻⁴ It has been estimated that lateral ankle sprains occur at a daily injury rate of 23,000 or 1 in 10,000 people in the United States.⁴ Reports associated with the National Collegiate Athletic Association indicate that ankle sprains accounted for 15% of all athletic injuries sustained between 1988 and 2003.¹ Additionally, a recent study which included all active-duty members of the United States military, determined that ankle sprains are sustained at a rate of approximately 35 sprains per 1,000 person-years with nearly a half million sprains reported over an 8-year period.³ The most common predisposing factor to sustaining an ankle sprain is a previous history of ankle sprain.⁵⁷⁻⁵⁸ In addition to the frequency of ankle sprains, it has been reported that up to 73% of individuals who incur a single acute ankle sprain will experience negative sequelae in the form of repeated episodes of self-perceived ankle instability and repetitive ankle sprains.

Therefore, ankle sprains are common in physically active people from an array of backgrounds and the presence of residual ankle sprain symptoms and recurring ankle sprains are a commonly occurring phenomenon associated with an initial ankle sprain injury.

This clinical phenomenon, referred to as CAI, has been associated with two predominant areas of impairment; mechanical and functional instability.⁸ Previous research has identified that aspects of mechanical and functional instability can occur independently; however, a majority of individuals with CAI exhibit a combination of both mechanical and functional impairments.⁸ This suggests that rather than viewing mechanical and functional instability as dichotomous entities, it may be more accurate and significant to view these areas of impairment as synergists that work together to promote the etiology of CAI, augment functional loss, and progress the development of degenerative joint disease.⁸

Functional Impairments Associated with Chronic Ankle Instability

Functional instability is any impairment of the sensorimotor system that influences dynamic joint stability during functional movement.^{8, 11} Functional instability has been evaluated using multiple techniques designed to assess proprioception, strength, neuromuscular control, postural control, and gait.^{8, 53} Despite the wide range of techniques which have been employed to examine functional instability in those with CAI, the most contemporary methods which may provide the best indication of local and global changes in sensorimotor system function are static postural control⁴³, dynamic postural control⁴², and gait biomechanics.^{31, 55, 59}

Static Postural Control

Instrumented measures of postural control have been a commonly used method for assessing the sensorimotor deficits in those with CAI.⁴¹ Temporal and spatial measures of center of pressure (COP) have been common measures for assessing static postural control during single-limb stance on a forceplate. The most common dependent measures derived from COP include area, range, % of range used, standard deviation of COP, and velocity.⁴¹ Many of these measures are further separated into the anteroposterior and mediolateral directions. McKeon and Hertel⁴¹ performed a systematic review with a specific aim of determining if postural control deficits can be detected in those with CAI using instrumented measures of static postural control. Based on the effect size point estimates, it appeared postural control was adversely affected in those with CAI when compared to a healthy control group; however, the extent of these findings could not be determined because of inconsistent results, small effect sizes, and large confidence intervals. Additionally, the evidence was not conclusive that the affected limb of those with unilateral CAI had poorer postural control when compared to the unaffected limb. Following these results, the authors suggested that the traditional methods of assessing COP may not be sensitive enough to detect the subtle deficits displayed by those with CAI.⁴¹

To further synthesize the literature associated with postural control impairments in those with CAI, a series of meta-analyses⁴²⁻⁴⁵ were conducted to determine if postural control deficits were present in those with CAI compared to healthy control groups and to determine if bilateral deficits were present in those with CAI. Wikstrom et al.⁴³ determined that pooling the effect sizes across 15 studies (subjects = 324) examining

static postural control or the SEBT using a random effects model meta-analysis demonstrated a moderate effect size (0.6 ± 0.1) indicating postural control impairments were present in those with CAI. The results of this meta-analysis were confirmed by a similar meta-analysis of postural sway in single-limb stance (standardized mean difference = 0.6 ± 0.2) performed by Munn et al.⁴⁴ Additionally, a separate meta-analysis⁴⁵ examining bilateral static postural control deficits determined that the involved limb was impaired but not the uninvolved limb in those with CAI. These meta-analyses confirmed that static postural control is impaired in the involved limb of those with CAI; however, bilateral impairments were not detected.

The results of these systematic reviews and meta-analyses have generated some important insight regarding the static postural control impairments demonstrated by those with CAI. First, the postural control deficits experienced by those with CAI are likely subtle.^{41,43} Second, the traditional COP measures are likely not sensitive enough to consistently detect subtle postural control deficits in those with CAI using sensible sample sizes.^{41,43} Last, it appears the uninvolved limb of those with CAI could be used as a control limb; however, this recommendation should be considered with caution because of the first and second points presented.⁴⁵ To overcome these methodological considerations, postural control measures which are more sensitive than the traditional COP measures would be useful for consistently detecting postural control impairments in relatively small sample sizes.

To address these methodological limitations, investigators⁵¹ have developed an innovative data reduction method which combines the spatial and temporal aspects of COP referred to as time-to-boundary (TTB). TTB combines the spatial and temporal

aspects of COP by concurrently measuring the direction and speed of each COP data point in the anteroposterior and mediolateral directions based on its relative location to the boundaries of the base of support created by the borders of the foot.⁵⁰⁻⁵¹ This technique identifies a series of specific points during each trial, referred to as minimas, which represent instances where a person has the least amount of time to make postural corrections because the COP is moving at a high velocity and/ or the COP excursion is moving closer to its respective boundary.⁵⁰⁻⁵¹ Additionally, examining the standard deviation of the magnitude of minima points, provides insight into the amount of constraint experienced by the sensorimotor system or the amount of solutions used to make postural corrections.⁵⁰⁻⁵¹ Although TTB is a somewhat novel technique for analyzing COP, it has consistently detected single-limb stance postural control deficits in those with CAI.^{47-49, 60-61} Additionally, TTB measures have been sensitive in detecting improvement following rehabilitation in those with CAI^{27, 36} and detecting laboratory induced impairments in somatosensory function in health individuals.⁶²⁻⁶³ Collectively, these findings suggest that TTB may provide greater insight into the subtle impairments in sensorimotor system function and provide a valuable global measure for re-examining sensorimotor function following rehabilitation.

Dynamic Postural Control

Dynamic postural control assessments measure the ability to regain stability following perturbation or maintain center of gravity within the boundaries of the base of support during functional activities.⁵³ Although several laboratory and clinical measures of dynamic postural control have been used to identify or determine the magnitude of postural control impairments associated with CAI, a clinical measure known as the SEBT

has been used most commonly.^{42, 53} The SEBT evaluates the ability to maintain a stable base of support in single-limb stance while the opposite limb performs maximal reach excursions in a battery of reach directions.^{52, 64} Hertel⁵³ recommends simplifying the SEBT by only performing the anterior, posteromedial, and posterolateral direction to eliminate the redundant information captured when all 8 directions are assessed. During the trial, the subject is to keep their hands on the hips, the heel of the stance limb in contact with the ground, perform a light toe touch at the point of maximal reach, and return to double limb stance without falter.⁵² Shorter reach distances (normalized by leg length) or more errors throughout the assessment are indicative of poorer postural control and sensorimotor system constraint.⁵³⁻⁵⁴

Several studies have examined SEBT reach distances in those with CAI compared to healthy control subjects.^{38, 54, 65-67} To synthesize these studies, recent meta-analyses^{42, 44} were conducted and determined that those with CAI display significantly shorter reaches distances when compared to healthy control subjects. When pooling the data across all reach directions from all included studies, Arnold et al.⁴² and Munn et al.⁴⁴ identified moderate between group effect sizes (0.3 ± 0.1 ; 0.4 ± 0.3). Unlike static measures of postural control, there is no evidence of bilateral impairments in individuals with unilateral CAI.⁵³ Despite these findings, bilateral improvements have been demonstrated following the rehabilitation of only the involved limb.⁶⁶ This indicates that although bilateral impairments have not been detected, central mediating factors may play a role in sensorimotor system function during rehabilitation which could be identified using this assessment.⁶⁶

Shorter reach distances may be the result of global alterations in sensorimotor

system function; however, deficits in the SEBT may also be a consequence of local impairments in muscle strength or range of motion.^{27, 65, 68} Those with CAI have demonstrated shorter reach distances in the anterior, posteromedial, and posterolateral directions.^{54, 67} Following 4-wks of a comprehensive rehabilitation program or progressive dynamic balance training program, significant improvements have been identified in the posterior reach directions but not in the anterior.^{36, 66} This suggests that maximal anterior reach distance may be dependent on contributions from specific articulations or muscle groups which are not as critical for achieving maximal posterior reach distances. Furthermore, it is apparent that if a local deficiency is playing a role in limiting anterior reach distances it has not been specifically addressed by the previously studied rehabilitation programs.^{36, 66} Identifying characteristics which make the anterior reach direction unique may elucidate what is limiting reach in this direction.

Several studies have examined motion of the ankle, knee, and hip in relation to performance on the SEBT in healthy individuals.⁶⁸⁻⁶⁹ These studies determined anterior reach performance is significantly related to sagittal plane motion from the ankle, knee, and hip while the posterior directions were only related to sagittal plane motion of knee and hip.⁶⁸⁻⁶⁹ It was later determined that weight-bearing DF ROM explained over twice the amount of variance in anterior reach performance in healthy individuals ($r^2 = 0.40$) compared to those with CAI ($r^2 = 0.16$).⁷⁰ Because of the coupling relationship between ankle dorsiflexion and knee flexion in a weight-bearing position⁷¹, it is reasonable to speculate that arthrokinematic restrictions in posterior talar glide may limit dorsiflexion and subsequently knee flexion during anterior reach in those with CAI.⁷⁰ This is supported by a separate investigation³⁷ which found significantly greater amounts of

movement in the proximal lower extremity joints and spinal rotation during SEBT performance in those with CAI. In both studies^{37, 70}, no significant differences were detected in SEBT performance despite different organizational strategies to complete the task. This suggests local impairments in DF ROM may require those with CAI to develop more proximal strategies to achieve maximal reach.^{37, 70}

Interventions which attempt to restore DF ROM may increase anterior reach distances in those with CAI.^{27, 69} To examine this hypothesis Hoch and McKeon²⁷ examined SEBT performance following a single treatment of joint mobilization to improve DF ROM. Although significant increases in DF ROM occurred, no changes were detected in anterior reach. This indicates that it may take additional time or supplemental rehabilitation to re-incorporate the freed range of motion into SEBT strategies. Also, increases in DF ROM and increases in anterior reach may not be linear in nature suggesting greater improvements in DF ROM may be required to elicit change in the SEBT.²⁷

Gait Biomechanics

In comparison to studies investigating postural control deficiencies, considerably fewer studies have investigated gait alterations associated with CAI. However, several of the investigations which have examined the kinematics and kinetics associated with walking and running have identified alterations which are expected to be deleterious to dynamic stability during gait.^{31, 35, 55, 72-73} Drewes et al.⁵⁵ identified increased rearfoot inversion and shank external rotation during the terminal swing phase in those with CAI. Additionally, increased rearfoot inversion and inversion velocity have been specifically identified immediately pre- and post heel strike suggesting additional stress may be

applied to the ankle at the time of ground contact.⁷²⁻⁷³ Furthermore, those with CAI have displayed a more plantar flexed position at the time of initial ground contact and decreased DF ROM during the late stance phase of walking and running.^{31,35} Several studies⁷⁴⁻⁷⁶ have determined those with CAI exhibited altered plantar pressure distributions characterized by a laterally oriented, slower velocity COP profile during stance with an abrupt medial shift in COP leading to toe off. These kinetic alterations are consistent with dorsiflexion deficits and increased inversion kinematics.⁷⁴ Despite differences in distal lower extremity joints and segments, no differences have been detected in knee or hip kinematics⁷²; however, proximal changes in the lower extremity gait function have not been examined as extensively as distal kinematic alterations.

When examined collectively, the biomechanical alterations identified in those with CAI mimic the most common mechanism of ankle sprains; hypersupination.⁷⁷ Greater rearfoot inversion, greater shank external rotation, and decreases in DF ROM during walking and running suggest that those with CAI may be in a more precarious, open-pack position at the time of initial ground contact which could increase the susceptibility for sustaining additional ankle sprains.^{35,55,77} Many of these identified alterations have been demonstrated during the absorption phases of stance and swing. This suggests that the gait alterations associated with CAI may have greater clinical implications if viewed through the context of the foot and ankle rocker system. As described by Perry⁷⁸, the stance phase can be divided into 3 rockers based on ankle and foot position: heel-rocker (initial heel contact to initial forefoot contact, e.g. absorption phase), ankle-rocker (forefoot contact to maximum tibial progression over the ankle, e.g. absorption-to-propulsion phase), and forefoot-rocker (heel lift to toe off, e.g. propulsion

phase). Examining kinematic alterations which occur in conjunction with absorption and propulsion associated with the rocker system could aid in providing meaningful clinical interpretation in future studies.

Despite several identified differences between those with and without CAI, few studies have attempted to correct gait alterations associated with CAI. Currently, separate investigations have examined the ability of external bracing orthotics³⁵ or dynamic balance training⁷⁷ to manipulate kinematic alterations of the rearfoot, shank, or ankle. Neither intervention significantly altered the gait kinematics of those with CAI. This indicates additional interventions should be investigated to address gait alterations in those with CAI.

In addition to identifying gait alterations associated with individual lower extremity joints and segments, examining the lower extremity joint coupling relationships may provide an indication of the sensorimotor system's ability to spontaneously self-organize multiple joints and segments during gait.⁷⁹ The variability of joint coupling relationships may provide insight into the flexibility of the sensorimotor system to cope with perturbation and dissipate stress at specific points of transition throughout across the gait cycle.⁷⁹⁻⁸⁰ This dynamic systems approach to examine joint coupling variability has not been systematically evaluated throughout the lower extremity in those with CAI; however, less coordinated movement patterns during the last 10% of the stride cycle have been displayed when examining the relationship between rearfoot inversion-eversion and shank external-internal rotation.⁵⁵ This evidence suggests that the organization of shank and rearfoot kinematics may be affected during the transition from unloaded to loaded position creating a less stable condition for force absorption in those with CAI.⁵⁵

Although the joint coupling relationships associated with other combinations of lower extremity joints and segments has not been explored in those with CAI, similar decreases in joint coupling variability have been identified in those with patellofemoral pain syndrome during running.⁸¹ This suggests decreases in joint coupling variability may represent a decreased complexity or reduction in the number of strategies to perform activities such as gait which may present a contributing factor to chronic overuse, future injuries, or a decreased ability to cope with perturbation.^{55, 80-81}

Past studies have mainly used a technique known as continuous relative phase to assess joint coupling variability patterns associated with lower extremity injury.⁷⁹ The continuous relative phase technique does have several identified limitations which include the assumption that the behavior of interest is sinusoidal in nature (which is often not the case), the degree of required normalization is controversial, and the resultant continuous relative phase angle is difficult to interpret as it relates to changes in mechanical or sensorimotor system function.⁸² Future studies should explore the use of a technique known as vector coding.⁸³⁻⁸⁴ Vector coding may be regarded as a more proficient technique because it provides continuous relative motion analysis with less normalization and thereby preserving true spatial information.⁸³

Vector coding quantifies the variability in vector angles between each consecutive point on an angle–angle plot.⁸³ More specifically, it may be advantageous to use the vector coding technique described by Tepavac and Field-Fote⁸³ because it directly accounts for variability in magnitude of vector length in addition to variability in vector angles which is unaddressed in other vector coding techniques. Using the Mullineaux and Uhl⁸⁵ presentation technique, vector coding coefficients are presented on a range from 0

(no variability) to 1 (maximum variability) for each consecutive point-to-point vector. Employing these types of analyses when examining lower extremity kinematics associated with CAI may provide a more comprehensive understanding of sensorimotor system alterations extending beyond the kinematics of individual joints during gait.

Mechanical Impairments Associated with Chronic Ankle Instability

Mechanical instability is caused by numerous factors which alter the mechanics of the talocrural, subtalar, and tibiofibular joints.^{8, 12} This group of impairments typically creates either hypomobility or hypermobility in range of motion which includes ligamentous laxity, arthrokinematic restrictions, or degenerative changes in anatomical structure.^{8, 12} These impairments have been identified using a combination of various clinical and laboratory assessments of ligamentous stability and ankle arthrokinematics including diagnostic imaging^{16, 23}, manual stress tests^{16, 26}, and ankle arthrometry.⁶⁷

Ligamentous Laxity of the Ankle Complex

Examining the integrity of the ankle ligaments have been the focus of studying mechanical impairments following ankle sprain.¹² The anterior talofibular ligament (ATFL) is typically the first ligamentous support to be injured followed by the calcaneofibular ligament (CFL) in the event of a lateral ankle sprain.^{8, 12} Hinterman et al. performed arthroscopic evaluations of 148 patients with CAI and reported that rupture or elongation of the ATFL and CFL was present in 86% and 64% of cases respectively.¹³ Ligamentous laxity can decrease the overall stability of the ankle joint and may have implications for alterations in arthrokinematics and eventually degenerative joint disease.^{8, 12} Therefore, the implications of damage to these ligaments has been a

fundamental area of study for examining mechanical contributions to the development of CAI.

The integrity of the ligamentous stabilizers surrounding the ankle have been studied since the work of Freeman¹⁷ who determined that varus laxity caused by damage to the CFL was likely related to the development of residual symptoms one year following ankle sprain. Since the work of Freeman, several investigators^{14-16, 26, 86-90} have examined the presence of pathologic laxity in the anterior direction or sagittal plane caused by damage to the ATFL and in frontal plane rearfoot inversion caused by damage to the CFL following ankle sprain. Several studies have detected increased anterior talar translation and inversion rotation in individuals with a history of lateral ankle sprain using common manual stress tests including the anterior drawer test and talar tilt test^{16-17, 26}; as well as, through the use of diagnostic imaging.⁸⁷⁻⁸⁹ To provide an objective measurement of ligamentous laxity and joint stiffness that would be feasible for both the clinical and laboratory setting, ankle arthrometers have been developed which provide a reliable and valid measure of static ankle stability in multiple planes of movements.⁹¹⁻⁹²

The ankle arthrometer provides an indication of ligamentous laxity and joint stiffness in multiple planes by measuring the amount of movement occurring with a specific amount of force applied to each of the directions evaluated.⁹² Ligamentous laxity in the anteroposterior and mediolateral planes has been evaluated using the ankle arthrometer in individuals with a history of ankle sprain.^{14-15, 67, 77, 86, 93-94} Several investigations^{14-15, 67} have identified increased anterior talar translation and/ or increased degrees of inversion rotation representing ligamentous laxity in those with CAI. Individuals with CAI have displayed up to 5 mm of greater anterior translation and up to

4.5 degrees of greater inversion rotation compared to either the uninvolved limb or a control group.^{15, 67} Additionally, when increased inversion rotation and increased anterior displacement were combined with failed balance trials and lower plantar flexion to dorsiflexion peak torque ratio, CAI group membership was able to be correctly predicted in 86.7% of subjects.⁶⁷

Alterations in Arthrokinematics of the Ankle Complex

Although ligamentous laxity has been speculated to be one of the main contributing factors to the development of CAI, other mechanical impairments in ankle arthrokinematics may occur independently or concurrently with ligamentous laxity to contribute to CAI.⁸ Normal arthrokinematics of the talocrural joint include anterior-posterior glide of the talus during sagittal plane motion.^{8, 12} More specifically, during ankle dorsiflexion, the talus must glide posteriorly and externally rotate in relation to the ankle mortise. During plantar flexion, the talus must glide anteriorly and internally rotate in relation to the ankle mortise.^{8, 12} These motions of the talus in relation to the mortise are coupled with involuntary movement of the distal fibula in relation to the tibia. During ankle dorsiflexion, the distal fibula will glide superiorly and laterally. During plantar flexion, the distal fibula will glide inferiorly.^{8, 12} Disruptions in normal arthrokinematics may restrict osteokinematic ranges of motion such as ankle dorsiflexion.^{8, 12} The alterations in arthrokinematics which have been specifically explored in those with CAI include positional changes in the distal fibula and talus.^{18, 23}

Mulligan⁹⁵ originally proposed that alterations in distal fibular arthrokinematics occur in the anterior direction following lateral ankle sprain. Since Mulligan's hypothesis, several studies^{18-21, 25, 96-97} have investigated the presence of distal fibular positional faults

in individuals with acute ankle sprains and those with CAI. The results of these studies have been split whether distal fibular positional faults occur in the anterior^{18-19, 96} or the posterior direction.^{20-21, 97} The conflicting findings are likely the result of the methods used to evaluate fibular position.¹⁸ Several studies^{20-21, 97}, which identified a posterior positional fault, used the talus as the reference for anatomic position which makes the assumption talar positioning is unaltered following ankle sprain. Studies^{18-19, 96} which identified anterior positional faults used the tibia as the anatomic reference for fibular positioning. The conflicting findings in this literature make it difficult to determine the clinical significance of changes in distal fibular arthrokinematics suggesting other changes in arthrokinematics should be investigated.

Another arthrokinematic impairment which has been hypothesized to occur in those with CAI is restricted posterior talar glide during DF ROM.^{31, 36} This arthrokinematic alteration could limit the available DF ROM causing functional alterations in gait and dynamic postural control.^{69, 98} Restrictions in posterior talar glide have been examined clinically using a test referred to as the posterior glide test.²⁶ Those with a history of ankle sprain have demonstrated inconsistent results on this test in a study by Denegar et al.²⁶ suggesting posterior talar glide restrictions are present while Hubbard et al.¹⁵ were unable to detect deficits. Despite these findings, the hypothesis that alterations in posterior talar glide occur in those with CAI is supported by studies^{31, 36} which identified DF ROM deficits in the late stance phase of gait and in the anterior direction of the SEBT; both activities which have been correlated to weight-bearing DF ROM.^{69, 98} Additionally, several studies²⁷⁻²⁹ have successfully used joint mobilization

techniques to increase posterior talar glide and DF ROM in those with CAI suggesting impairments may be present in these measures prior to treatment.

Until recently, most of the evidence supporting the idea of restricted posterior talar glide has been based on circumstantial evidence. However, two recent investigations²³⁻²⁴ have identified anterior talar displacement using radiographic images in individuals with CAI. The results of these studies²³⁻²⁴ suggest that ligamentous laxity coupled with posterior noncontractile or contractile tissues restrictions may be responsible for changes in posterior talar glide. Because these studies²³⁻²⁴ had retrospective study designs, it is unclear if anterior talar displacement is the result of a single ankle sprain, repeated ankle trauma, or was a predisposing factor to sustaining an initial ankle sprain. Despite the dearth of information regarding the origination of anterior talar displacement, the evidence is consistent that this impairment can be addressed using manual therapy techniques such as joint mobilization and manipulation which target the posterior noncontractile tissues of the talocrural joint.⁹⁹⁻¹⁰⁰

Talocrural Joint Mobilization Techniques for Chronic Ankle Instability

A common treatment strategy to restore diminished DF ROM when accompanied by talocrural arthrokinematic restrictions following ankle sprain are manual therapy techniques known as joint mobilization.¹⁰¹ Joint mobilization aims to increase osteokinematic and arthrokinematic range of motion by increasing the extensibility and flexibility of joint capsular and ligamentous tissues, promote the alignment and tracking of bony surfaces, and increase sensory input, reduce pain, and reduce muscle spasm by stimulating articular sensory receptors.¹⁰² These techniques include Maitland's joint mobilizations¹⁰², Mulligan's mobilization with movement (MWM)⁹⁵, and high-velocity

low amplitude (HVLA) thrusts.¹⁰⁰ Maitland's joint mobilizations use different grades of passive joint oscillations through a specific arthrokinematic range to achieve therapeutics effects which range from pain relief, to gradual increases in range of motion, and finally joint manipulation.¹⁰² Mulligan's MWM is a combination of actively or passively moving a joint through an osteokinematic range of motion (commonly in a loaded position) while passively moving the same joint through the agonist arthrokinematic range of motion.⁹⁵ HVLA thrusts are joint manipulation techniques which incorporate strategic patient positioning with short, quick thrusts (high velocity) applied over short distances (low amplitude) across areas of tissue restriction.¹⁰³⁻¹⁰⁵ The application of these techniques to the rehabilitation for ankle sprains include restoring osteokinematic and arthrokinematic range of motion and stimulating sensory receptors for the purposes of reducing pain, enhancing proprioception, and restoring joint position sense.¹⁰¹

Range of Motion

Following ankle sprain, anterior talar displacement has been identified which is likely associated with restricted posterior talar glide and DF ROM.^{23, 26, 28} To address a talar positional fault and restore these ranges of motion, several manual therapy techniques suggest increasing the extensibility of the posterior noncontractile tissue of the ankle by gliding or rolling the talus in the anterior-to-posterior direction (or tibia in the posterior-to-anterior direction).^{56, 95, 102} To provide support for this approach, there is an emerging body of evidence advocating the use of joint mobilization techniques for restoring normal talocrural arthrokinematics and osteokinematics.^{28-29, 33, 100-101, 103-110} The results of a critically appraised topic⁹⁹ and systematic reviews of the literature¹⁰⁰⁻¹⁰¹ indicate that the previously mentioned joint mobilization techniques demonstrate trends

in effect size which signifies they have the ability to enhance DF ROM in individuals with a history of ankle sprain and promote a closed-pack position which is thought to maximize the bony congruency of mortise and talus, enhancing the overall stability of the joint.⁸

Several investigators^{33, 104-106, 108-110} have examined the effects of these manual therapy techniques on DF ROM in individuals with acute ankle sprains. Green et al.³³ conducted a randomized controlled trial which examined the effects of mid grade Maitland anterior-to-posterior talocrural joint mobilization along with conservative treatment (rest, ice, compression, elevation) compared to conservative treatment alone for the rehabilitation of acute lateral ankle sprains. This investigation³³ determined that the group receiving joint mobilization needed approximately 4 treatment sessions to restore pain-free DF ROM which was significantly fewer treatments than the control group. Following the results of Green et al.³³, additional studies^{104-106, 108-109} determined MWM and HVLA thrusts were able to achieve a similar restitution of DF ROM in individuals with acute ankle sprains.

The ability of joint mobilization to restore DF ROM and increase posterior talar glide has also been investigated in individuals with a history of recurrent ankle sprains or CAI.^{27-29, 103-104} Two cross-over investigations²⁸⁻²⁹ have examined the effect of a single treatment of either weight-bearing or non-weight bearing MWM on the weight-bearing DF ROM of individuals with recurrent ankle sprains. The findings from these studies²⁸⁻²⁹ suggest that when a 2cm weight-bearing DF ROM deficit is present, MWM can increase posterior talar glide and weight-bearing DF ROM in the upwards of 55% and 26%, respectively. It should be noted that these results did not greatly differ between the

weight-bearing and non-weight-bearing interventions suggesting either strategy can achieve similar therapeutic effects.²⁸ Other investigations¹⁰³⁻¹⁰⁴ have examined the effect of a 4-wk intervention of HLVA ankle mortise separation on individuals with recurrent ankle sprains and determined this intervention could also significantly increase DF ROM. Most recently, Hoch & McKeon²⁷ identified significant increases in weight-bearing DF ROM and statistical trends towards increases in instrumented posterior talar glide following a single Maitland Grade III anterior-to-posterior talocrural joint mobilization treatment in individuals with CAI. Collectively, the results of these investigations^{27-29, 33, 103-106, 108-109} indicate that talocrural joint mobilization has therapeutic benefits for increasing osteokinematic and arthrokinematic range of motion in those with a history of ankle sprain despite the number of studies investigating only a single treatment.^{27-29, 105-106, 108}

Sensory Stimulation and Sensorimotor System Function

In addition to the purely mechanical effects of joint mobilization, utilizing these techniques to enhance sensorimotor system function has also been proposed.^{56, 102} Employing joint mobilization for these purposes implies that sensory receptors located primarily in the ligaments and joint capsule are excited while moving the joint through arthrokinematic and osteokinematic ranges of motion.^{56, 102} The primary receptors located in the noncontractile tissues surrounding a joint are Pacinian corpuscles and Ruffini's end organs which transmit information regarding proprioception, joint position, collagen stretching, vibration detection, and deep pressure.¹¹¹ These receptors transmit afferent information to the medulla and eventually to the opposite ventroposterior-lateral nucleus of the thalamus via the dorsal column medial-lemniscus ascending pathway.¹¹² Although

this ascending pathway has been linked to the sensory receptors in the lower extremity, it can only be speculated that joint mobilization can stimulate these receptors and induce changes in sensorimotor system function using this pathway.

Although using joint mobilization for enhancing sensorimotor system function is a relatively novel concept in research literature, three recent investigations^{27, 103, 108} have examined functional alterations following joint mobilization. In a blinded, placebo-controlled study, Lopez-Rodriguez et al.¹⁰⁸ determined that a single treatment HVLA caudal thrust along with MWM was able to immediately redistribute foot loading patterns during stance in individuals with acute grade II ankle sprains. Although changes were found in baropodometrics, no changes were detected in stabilometric measures. Köhne et al.¹⁰³ determined that 6 treatments of HVLA long axial thrust treatments could significantly improve proprioception by decreasing the absolute error during joint re-position sense testing. While these investigations^{103, 108} provide preliminary evidence that change occurs in sensorimotor system function following joint mobilization, these studies provide little indication of changes in the sensorimotor system's ability to cope with constraint during movement goal execution.

Examining goal oriented measures of postural control following joint mobilization may provide greater insight into functional changes in the sensorimotor system following joint mobilization. To explore this concept, Hoch and McKeon²⁷ systematically explored changes in static and dynamic postural control following joint mobilization in individuals with CAI. The results of this randomized, cross-over study indicate that a single Maitland Grade III anterior-to-posterior joint mobilization treatment significantly increased eyes open TTB measures in the anteroposterior direction. Despite

identifying changes in static postural control, there were no changes in the reach distances on the SEBT. The findings of this study suggest that although joint mobilization may be able to enhance sensorimotor system function after a single treatment, more time is likely required to incorporate the freed range of motion and ancillary sensory input into coordinated movements.²⁷

Summary

There is an emerging body of evidence supporting the use of joint mobilization for the rehabilitation of acute ankle sprains and CAI.¹⁰¹ The majority of the evidence indicates these techniques have mechanical benefits for restoring range of motion and normal arthrokinematics. While evidence exists that joint mobilization may produce functional changes^{27, 103, 108} in sensorimotor system function because of increased proprioception, enhanced joint position sense, and increased postural control, this needs further exploration to identify the mechanism by which these changes occur, the potential magnitude of these changes, and the dosage of treatment required to create lasting changes in sensorimotor system function. The current limitations associated with this body of knowledge is the lack of investigations using multiple treatments, no evidence of the most efficient treatment parameters, and the influence of these techniques on dynamic activity such as gait kinematics remains unknown. These limitations do not detract but rather support the need for further systematic exploration of the effects of joint mobilization on the mechanical and functional impairments; as well as, the self-reported functional loss associated with CAI.

Contemporary Models of Motor Control and Disablement as it Relates to Sensorimotor
Control and Function in Chronic Ankle Instability

The factors currently thought to contribute to CAI include mechanical and functional deficits which focus on impairment as a direct result of pathology.⁸ This view of CAI provides an explicit and thorough illustration of the arthrokinematic, structural, neuromuscular, and proprioceptive deficits thought to contribute to this condition, but not necessarily the functional loss or disability experienced by the individual.⁸ The study of impairment has been valuable for advancing knowledge directly associated with CAI; however, it places no emphasis on function as a dynamic and fluctuating continuum. This is evident because the impairments associated with CAI have been detected through objective measures of function in the form of proprioception, postural control, and neuromuscular control; however, little evidence has investigated the relationship between measures of local instability and self-reported disability.¹¹³

Function is not solely the cumulative effect of structural/functional impairments directly associated with a health condition. Function must also take into account an individual's perception of ability or disability.¹¹⁴ Examining CAI through the integration of the most contemporary theory of motor control and most contemporary model of health may provide a comprehensive assessment of a person's overall functional ability and elucidate the link between disability and health in this population.¹¹³ Applying the framework described in these models may provide a more accurate representation of alterations in functional capacity which may re-direct rehabilitation goals to satisfy patient needs and ultimately diminish the recurrence of injury and functional loss.¹¹³⁻¹¹⁴

Recent advancement in motor control theory may help interpret how sources of

functional loss and disability are manifestations of impaired sensorimotor coordination.^{50,}
⁸⁰ This theory, known as dynamic systems, views movement from a context-specific perspective which aims to explain how we utilize the freedom of the sensorimotor system to develop strategies in order to cope with changes in health, task complexity, and the environment.⁸⁰ Similarly, the International Classification of Functioning, Disability, and Health (ICF) examines the effect of injury and illness on the dynamic nature of function based on quality of life, overall health status, and impairment associated with societal and environmental factors.¹¹⁴ The theoretical framework set forth by dynamic systems theory corresponds with many of the fundamental concepts proposed by the ICF model.¹¹³ Applying framework from both theories can aid in making healthcare decisions that focus on the unique needs of individual patients. Specifically, this integration can help to understand the relationship among many of the contributing factors identified in those who suffer from CAI with self-reported decreases in function.¹¹³

The Dynamical Nature of Sensorimotor System Organization

In the past, movement variability was viewed as error, noise, or deviation from optimal movement patterns.⁵⁰ However, more recent theories of motor control recognize movement variability as a beneficial subconscious compensatory mechanism for coping with change, maintaining stability, preventing injury, and attaining higher levels of skill.⁸⁰ This theory known as dynamic systems, views sensorimotor coordination as constantly changing and fluctuating based on the interaction of multiple external and internal stimuli. The foundation of dynamic systems theory is that movement coordination is shaped by constraints originating from the organism, environment, and task.⁸⁰ Examples of constraints include injury and illness, complexity of the task, and unpredictable terrains.⁸⁰

Constraints placed upon the sensorimotor system shape the functional variability, or available solutions, to complete a movement goal.⁸⁰ This suggests that rather than having a single, rigid method of achieving a movement goal, the sensorimotor system spontaneously adapts its sensory and motor components to the demands from task and environmental factors. The notion of having multiple ways to achieve movement goals has been referred to as invariant results through variant means.¹¹⁵ Essentially, if a component of the movement system introduces error to the motor output, other parts of the system will re-organize their contribution to correct the fault.⁸⁰ This demonstrates the essential role of movement solution variability when attempting to cope with change and adapt movement solutions to accomplish a movement goal. As constraints on the sensorimotor system increase, the probability of successfully coping with change and completing the movement goal decreases.⁸⁰

Injury and disease place additional constraints on the sensorimotor system.⁸⁰ As rehabilitation professionals, athletic trainers aim to restore the ability to effectively cope with perturbation during movement goal execution. This can be accomplished through the purposeful manipulation of organismic, task, or environmental constraints during rehabilitation.³⁶ This theoretical approach is useful for examining those with CAI because it can explain how the diminished ability to cope with change can create a model for recurrent injury and instability if not appropriately addressed.⁵⁰ Individuals with CAI have demonstrated a reduction in the ability to freely cope with changes in the task and environment.^{36, 47-48, 54, 116} This is most evident through measures of postural control including TTB, the balance error scoring system (BESS), and SEBT. Those with CAI have demonstrated less TTB magnitude and variability compared to healthy subjects.⁴⁷⁻⁴⁸

In addition, they failed a greater number of trials compared to the healthy control group. These alterations indicate that individuals with CAI have a greater amount of constraint acting on the sensorimotor system which is associated with a diminished ability to successfully execute the movement goal. In addition to TTB, sensorimotor system function has been evaluated with clinical postural control measures such as the BESS and SEBT. Those with CAI have demonstrated greater errors on the BESS and shorter reach distances on the SEBT indicating the presence of diminished sensorimotor function.^{36, 38, 52, 54, 116} When the postural control deficits demonstrated on these assessments are examined as a group, it is evident that the constraint created by the presence of CAI decreases movement solution variability to complete these tasks.

By dynamically progressing task and environmental constraints, we can bolster the sensorimotor system's ability to dynamically cope with change.³⁶ This concept is supported by evidence indicating balance training programs effectively improve postural control and increase functional capacity in individuals with CAI.³⁶ Using the dynamic systems model, McKeon et al.³⁶ developed a randomized control trial that employed a static and dynamic balance training progression that consisted of static single-limb stance activities, single-limb hops to stabilization, single-limb hops to stabilization and reach, and unanticipated hops to stabilization. As subjects performed the balance training program and progressed error-free on the BESS, the task and environmental constraints were increased. Each exercise was progressed by changing the surface, task requirements, and visual input. Following cessation of the program, participants with CAI demonstrated significant improvement in TTB and increased reach on the SEBT from their baseline testing compared to the control group.³⁶ In addition to improved postural control, CAI

participants reported improved self-reported function. This investigation supports purposefully manipulating task and environmental constraints to improve self-reported function and functional variability.⁸⁰ This investigation is unique in the sense it related motor control to measures of self-reported function. In doing so, connections were made between alterations in global sensorimotor system function and its impact on overall self-reported health status.

The Dynamic Nature of Function

The ICF developed by the World Health Organization provides a scientific basis for assessing health and disability.¹¹⁷ Unlike previous models of disability which view health and disability as two separate conditions, the ICF defines function as the dynamically fluctuating continuum of disability and health.¹¹⁸ In essence, function refers to the level of freedom an individual experiences through personal and societal interactions.¹¹⁴ Health conditions and rehabilitation interventions can ramp up or down this freedom. This then translates into the changing experiences of health and disability on the continuum of function. The goal of the ICF is to capture the dynamic nature of function through the integration of the body or body part, the person as a whole, and the person as a whole in societal and environmental contexts.¹¹⁷ This is accomplished by examining the influences of health conditions, environmental factors, and personal factors on the domains of body structure and function, activity, and participation.^{114, 117}

Accounting for structural/functional impairments, activity limitations, and/or participation restrictions in these respective domains can assess how health conditions and other contextual factors influence the changing nature along the continuum of function.¹¹⁷ Contextual factors encompass environmental elements that are physical,

social, and attitudinal; as well as, personal elements such as age, sex, coping styles, social background, education, self-efficacy, and overall behavior patterns.¹¹⁴ As the domains and contextual factors interact, the results on the continuum of function can be quite different between individuals.¹¹³ For example, 2 patients suffer from acute ankle instability (health condition). Both patients may have decreased range of motion (structural/functional alteration) and both may lack the ability to run at full speed. However, when examining their participation restrictions, one may not be restricted at all (playing soccer with his 3 year old son) while the other may have significant restrictions (playing competitive soccer). The ICF identifies these factors as potential influences on an individual's continuum of function; therefore, as discussed in the example above it is possible to have structural\ functional impairment with no manifestation of activity limitation or participation restrictions.¹¹³

The ICF stresses the importance of using patient self-reported outcome measures to gauge the patient's overall perception of health status.^{114, 117} This information becomes essential when identifying patient needs and developing rehabilitation goals. Patient self-report forms can compliment objective evaluation techniques to provide a means of assessing a person's functional capacity from the patient's point of view. Functional capacity represents the level in which an individual is able to perform activities and participate in desired life experiences. Applying self-report forms can identify specific sources of functional loss and disability which can be useful when determining the appropriate intervention strategies.¹¹⁴

Individuals with CAI may exhibit structural impairment of the ankle in the form of ligamentous laxity, decreased range of motion, arthrokinematic restrictions, and

degenerative changes.⁸ These individuals also experience functional impairments in postural control⁴¹, proprioception¹¹⁹, and neuromuscular control.¹²⁰ The culmination of these impairments results in an ankle which is prone to sensations of “giving way” and bouts of joint instability, creating a predisposing factor for future ankle injuries.⁸ A reduction in functional capacity manifests, resulting in limitations in a person’s ability to perform certain activities and participate in desired life situations.¹²¹

Individuals with CAI often report heightened activity limitation when moving on uneven surfaces, stairs, and during lateral movements.¹²² Additionally, personal factors such as poor coping mechanisms, social support, medical assistance, and education can add to reductions in functional capacity. Contributions from these factors can cause activity limitations because certain tasks are unable to be executed to their original or expected level of performance and participation restrictions because these individuals may refrain from activities that produce greater levels of risk for sustaining future injuries.¹¹³ To identify factors that influence functional capacity, athletic trainers need valid and reliable instruments for determining sources of functional loss through patient self-report evaluations.

Several patient self-report forms are available to identify sources of functional loss and disability in the foot and ankle. Based on the evidence from the most recent systematic review of several self-report measures, the Foot and Ankle Disability Index (FADI) and Foot and Ankle Ability Measure (FAAM) provide the most appropriate global ratings of function for assessing ability in patients with CAI.¹²³ This conclusion was reached because these instruments have high content and construct validity, readability, reliability, internal consistency, and interpretability. The validity and

sensitivity of these instruments have deemed them reliable for detecting self-reported functional alterations related to CAI.¹²⁴⁻¹²⁵ The FADI and the FAAM contain 26 and 21 items respectively pertaining to activities of daily living. Additionally, these instruments have a supplementary 8 item index related to sport activities and participation.¹²⁴⁻¹²⁵ The FADI and FAAM support the goals of the ICF because they attempt to recognize functional capacity based on the perspective of the patient which provides clinicians with additional support for developing intervention strategies that address patient needs.

Integrating the Dynamic Systems Theory and ICF Model of Health for Chronic Ankle Instability

Addressing deficits associated with CAI can be accomplished by identifying patient-centered self-reported function assessments to identify areas of activity limitation and participation restriction. These identified alterations can then be addressed through purposeful manipulation of environmental and task constraints during rehabilitation.¹¹³ Throughout the rehabilitation process, progress can then be tracked by identifying error in movement goal execution during rehabilitation tasks and reassessing self-reported function. Finally, functional capacity and movement solution variability provide useful concepts to aid in the interpretation of identified deficits as they relate to an individual's perception of their functional ability using a whole person approach to healthcare.¹¹³ Although the ICF model and dynamic systems theory have different structure and terminology, both are multi-factorial models that emphasize the need to understand functioning as a complex system with many interacting components. This shared view allows the ICF model and dynamic systems theory to complement each other in many circumstances. This is evident by the similarity in impairment, activity limitation, and

participation restriction in the ICF model and the sources of constraint in the dynamic systems theory.¹¹³

Participation restriction in the ICF model and environmental constraints of the dynamic systems theory both examine the interaction and freedom a person has in his/her physical and social environments.¹¹³ A similar relationship is exhibited between activity limitations in the ICF model and task constraints in the dynamic systems theory. Finally, structural and functional impairment associated with ICF model and organismic constraints in the dynamic systems theory both examine how health influences function.¹¹³ Although the ICF aims at restoring functional capacity and the dynamical system theory aims at restoring functional variability in movement goal execution, the fundamental principles of both concepts allow them to achieve a homogenous goal of promoting overall function. The ICF model and dynamic systems theory are able to achieve similar goals because their basic framework is centered around a holistic examination of functioning rather than placing the emphasis directly on pathology.¹¹³

Chapter 3: Kinematic Alterations in Walking and Running Gait in Those with Chronic Ankle Instability

Introduction

Ankle sprains are among the most common orthopedic injuries sustained within the general population.⁵ Recent estimates indicate at least 628,026 ankle sprains are treated annually in United States emergency rooms.¹²⁶ Approximately 1 in 3 individuals who sustain a single acute ankle sprain develop a health condition known as chronic ankle instability (CAI) which is characterized by bouts of recurrent ankle instability resulting in multiple future ankle sprains.^{6, 53} In addition to the trauma associated with acute bouts of ankle instability and sprains, CAI has been linked to the development of post-traumatic ankle osteoarthritis¹²⁷ and functional loss⁹ indicating this health condition is associated with long term negative sequela over the life span.

The development of CAI is thought to be a multi-factorial phenomenon based on alterations in the mechanical and functional aspects of the ankle complex and surrounding structures.⁸ The interaction between mechanical alterations in joint laxity, arthrokinematics, and degenerative structural changes with functional impairments in proprioception, neuromuscular control, and postural control are likely responsible for the repetitive ankle trauma sustained by those with CAI.^{8, 53} The negative consequences of this interaction may be most eminent during dynamic activities such as gait which require spontaneous spatiotemporal coordination of several joints and segments during cyclic transitions from loaded to unloaded conditions while maintaining a base of support.^{53, 55}

Several alterations in walking and running gait kinematics have been identified in those with CAI.^{31, 35, 55, 72-73} These alterations include increased rearfoot inversion at heel

strike^{55, 72-73}, increased shank external rotation during terminal swing phase⁵⁵, and decreased ankle dorsiflexion in the stance phase.^{31, 35} Cumulatively, these findings indicate those with CAI may incur additional stress to the ankle complex and be in a more precarious, opened-pack position at the time of initial ground contact which could decrease the ability to attenuate ground reaction forces and increase the susceptibility to experiencing episodes of instability and additional ankle sprains.^{35, 72-73}

Although previous investigations have identified mechanical alterations associated with rearfoot, talocrural, and shank kinematics during gait in those with CAI, examining the contextual relationship of the multiple segments or joints of the lower extremity may provide additional insight into sensorimotor system alterations which may be exhibited in this group.⁸⁰ Drewes et al.⁵⁵ examined the joint coupling relationship between shank rotation and rearfoot inversion-eversion during walking and running gait and determined those with CAI demonstrated greater joint coupling variability during terminal swing compared to those without CAI. This indicates those with CAI were more out-of-phase and less coordinated as the foot was being positioned for initial contact.⁵⁵ These findings suggest that the sensorimotor system of those with CAI may be searching for stable or functional states of coordination during terminal swing when compared to healthy subjects. Despite these findings, the joint coupling relationships of other lower extremity joints remain unclear in those with CAI.⁸⁰

Examining movement system variability through joint coupling relationships may provide insight into the flexibility of the sensorimotor system to cope with perturbation and dissipate stress at specific points of transition throughout the gait cycle.^{55, 81} Performing an inclusive examination of lower extremity joint coupling variability

patterns may elucidate additional kinematic alterations which predispose those with CAI to repetitive joint trauma. Therefore, the purpose of this study is to systematically explore the kinematics and joint coupling relationships of the rearfoot, ankle, shank, knee, and hip throughout the walking and running gait cycle in those with and without CAI.

Methods

Experimental Design and Subjects

This study employed a case-control design in which subjects in the CAI group and healthy control group reported to the research laboratory for a single data collection session. Subjects were recruited from a large university and surrounding community using advertisements posted throughout the university over a 6 month period. A total of 14 males and 10 females volunteered to participate in the study. Subjects were classified into either the CAI group (7 males, 5 females; age: 25.9 ± 3.4 years; height: 176.5 ± 8.8 cm; weight: 80.3 ± 13.6 kg) or the healthy control group (7 males, 5 females; age: 26.7 ± 4.7 years; height: 171.8 ± 5.8 cm; mass: 72.5 ± 9.7 kg). Subjects in both groups were matched by side and gender. Prior to participation, all subjects provided written informed consent which was approved by the University's Institutional Review Board.

Previously described inclusion criteria were used to designate subjects to either the CAI group or control group.²⁷ To be included in the CAI group, subjects reported a history of at least 1 ankle sprain. Additionally, subjects had to report at least 2 episodes of “giving way” within the past 3 months. This was quantified by answering “yes” to question 1 and “yes” for a total of at least 5 questions on the Ankle Instability Instrument.¹²² An ankle sprain was defined as an incident in which the rearfoot was inverted or supinated and resulted in a combination of swelling, pain, and time lost or

modification of normal function for at least one day.⁸ An episode of giving way was described as an incident in which the rearfoot suddenly rolled, felt weak, or lost stability; however, the individual did not sustain an ankle sprain and was able to continue with normal function.⁸ Subjects also had to report functional loss as a result of their ankle sprain history by reporting disability scores of $\leq 90\%$ on the Foot and Ankle Ability Measure (FAAM) and a score of $\leq 80\%$ on the FAAM Sport Scale.¹²⁵ In the event subjects reported a bilateral history of ankle sprains, the limb with the greatest reported functional loss on the FAAM Scales was included in the study. Subjects reported an average of 9.2 ± 5.5 total ankle sprains. The average number of reported episodes of giving way over the previous 3 months was 5.7 ± 5.4 . The average FAAM score was $83.5 \pm 10.9\%$ and the average FAAM Sport score was $66.5 \pm 16.5\%$.

Inclusion criteria for the healthy control group included no history of ankle sprains or ankle instability, answering “no” to all questions on the Ankle Instability Instrument, and no self-reported functional loss on the FAAM and FAAM Sport. Exclusion criteria for both groups consisted of an acute ankle sprain within the past 6 wks, a previous history of lower extremity surgeries or fracture, other lower extremity injuries within the past 6 months that resulted in time lost or modification of normal function for at least one day, or other health conditions known to affect gait.

Instrumentation and Data Capture

To assist in accurately placing the retroreflective markers used for three-dimensional motion analysis, all participants were barefoot, wore close-fitting shorts, and females wore tank tops and males wore no tops. A total of 48, 10 mm retroreflective spherical markers were placed on subjects using adhesive tape over specific landmarks on

the lower extremities (Appendix A) using a modified marker set adapted from Pohl et al.¹²⁸ Subjects performed barefoot walking and running, during which the three-dimensional kinematics of the markers were recorded at 150 Hz using 15 Eagle motion capture cameras and Cortex v1.0 software (Motion Analysis Corporation, Santa Rosa, CA, USA). The cameras were positioned in a circle around a dual belt treadmill customized with embedded forceplates (Model TM-09-P, Bertec Corp; Columbus, OH, USA) which provided standardized gait speeds, ground reaction forces, and instants of initial contact and toe off. Kinetic data were sampled at 750 Hz and were recorded using Cortex software. The motion analysis system was calibrated using the Cortex software parameters prior to each data collection session.

Procedures

After being outfitted with retroreflective markers, a static trial was recorded in which subjects stood in the anatomic position with their feet positioned shoulder width apart. All subjects completed a warm-up and performed a 10-min walk at speeds which were gradually increased from 0.5 to 1.5 m/s to allow subjects to adjust to the treadmill before data collection. A walking and running trial was recorded with the option of rest in between. For walking trials, once the target speed of 1.5 m/s was achieved and maintained for 1 min, a 30 s trial was recorded. For running trials, subjects were gradually progressed from a walking to a running speed of 3.0 m/s and a 30 s trial was recorded after at least 1 min of running.

Data Reduction

From the 30 seconds of data capture, approximately 20 strides of the involved limb were available for walking and 40 strides of the involved limb were available for

running. From the available walking and running strides, mean ensemble curves were created for each variable of interest along with confidence intervals of 2 standard deviations. Strides which contained data points for any of the 6 kinematics variables that were outside the confidence interval were removed from analysis. Upon removal of all outliers, the first 5 nonconsecutive strides for walking and running in which all kinematics variables were available were entered into the analysis. Each stride was resampled to 101 frames to represent each percent of stride. This was done individually for each subject using a force plate threshold of 30 N to identify initial contact for each limb. Stride selection and the interpolation to 101 frames were completed through a custom program in Matlab 7.9.0 (Mathworks Inc, Natick, MA). For each subject, a reference angle for each kinematic variable of interest was determined from the recorded static trial and was subtracted from the angles recorded during walking and running.^{55, 72} Data were smoothed using a 2nd-order Butterworth filter with a cut-off frequency of 6 Hz which was determined by visually inspecting the raw data against the data at different cut-off frequencies.

Kinematic variables included 3-dimensional angles for 1) rearfoot inversion/eversion, 2) shank internal/external rotation, 3) ankle plantar flexion/dorsiflexion, 4) knee flexion/extension, 5) hip flexion/extension, 6) and hip abduction/adduction and were defined based on the anatomic locations of retro-reflective markers (Appendix B). Using vector-coding assessment techniques⁸³, the joint coupling variability of 1) shank rotation and rearfoot inversion/eversion, 2) knee flexion/extension and ankle plantar flexion/dorsiflexion, 3) knee flexion/extension and shank rotation, 4) hip abduction/adduction and rearfoot inversion/eversion, 5) hip flexion/extension and

ankle plantar flexion/dorsiflexion, and 6) hip flexion/extension and knee flexion/extension angle–angle was determined. This technique quantifies the variability in vector angles and magnitudes between each consecutive point on an angle–angle plot across multiple strides.⁸³ The calculation is the same as Tepavac and Field-Fote's⁸³, which is based on circular statistics and corrects for trial size, but the coefficient has been reversed to present a range from 0 (no variability) to 1 (maximum variability) for each consecutive point-to-point vector.⁸⁵ Therefore, a vector coding coefficient was analyzed for each percent of stride. Additionally, the average of the vector coding coefficients for the entire stride (VCoverall) was calculated to provide a summary measure for each joint coupling relationship.

Statistical Analysis

To determine meaningful differences in lower extremity kinematics and joint coupling relationships, a curve analysis^{55, 72} using the mean±SE for each of the 101 data points were calculated across the entire stride cycle (0% representing initial contact, 100% representing the same limb prior to the next contact). Group differences were determined as at least 5 consecutive points where the SEs for each group did not overlap. In the presence of non-overlapping points, the mean was calculated across the points for each subject. Group differences found on the curve analyses and in the VCoverall for each joint coupling relationship were examined using independent samples *t*-tests. For all analyses with the level of significance set *a priori* at $p \leq 0.05$. No correction for multiple comparison was performed on the alpha level to protect against making a type II error.¹²⁹ Instead, effect sizes (ES) were calculated based on the mean and pooled standard deviation of group differences using a bias-corrected *Hedge's g* with corresponding 95%

confidence intervals (CI).¹³⁰ ES were interpreted as weak (0 – 0.39), moderate (0.40 – 0.69) and strong (≥ 0.70).¹³¹ All statistical analyses were conducted using Excel 2007 (Microsoft, Redmond, WA, USA).

Results

For walking, the stance phase was defined as 0-66% whereas swing phase was defined as 67-100% of stride. For walking kinematics, potentially meaningful differences were identified in stance phase for rearfoot inversion/eversion, in swing phase for shank rotation, and in stance and swing phases for ankle dorsiflexion/plantar flexion, knee flexion/extension, and hip flexion/extension. No differences were identified in hip abduction/adduction kinematics. Group differences in walking kinematics are summarized in Table 3.1. For walking joint coupling variability, potentially meaningful differences were identified during the stance and swing phases of the knee flexion/extension-ankle dorsiflexion/plantar flexion, knee flexion/extension-shank rotation, hip abduction/adduction–rearfoot inversion/eversion, hip flexion/extension-ankle dorsiflexion/plantar flexion, and hip flexion/extension–knee flexion/extension coupling relationships. No differences were identified in the coupling relationship of shank rotation-rearfoot inversion/eversion. A summary of the group differences in walking joint coupling variability are displayed in Table 3.2. No differences were identified in VCoverall for any of the joint coupling relationships (Table 3.3).

In running, the stance phase was defined as 0-46% and swing phase as 47-100% of stride. Potentially meaningful differences were identified during the stance and swing phases in shank rotation and during the swing phase of knee flexion/extension. No differences were identified in rearfoot inversion/eversion, ankle dorsiflexion/plantar

flexion, hip flexion/extension, or hip abduction/adduction kinematics. Group differences in running kinematics are displayed in Table 3.2. For running joint coupling variability, potentially meaningful differences were identified during the stance and swing phases of knee flexion/extension-ankle dorsiflexion/plantar flexion, knee flexion/extension-shank rotation, hip abduction/adduction–rearfoot inversion/eversion, and hip flexion/extension-ankle dorsiflexion/plantar flexion coupling relationships. Potentially meaningful differences were also identified in the stance phase of shank rotation-rearfoot inversion/eversion and the swing phase of the hip flexion/extension–knee flexion/extension coupling relationships. Group differences in running joint coupling variability are displayed in Table 3.5. No differences were identified in VCoverall for any of the joint coupling relationships (Table 3.6). Visual representations of all walking and running kinematics and joint coupling variability patterns are displayed in Appendix C.

Discussion

Kinematics

The primary finding of this investigation is that those with CAI demonstrated alterations in distal and proximal lower extremity joint kinematics during gait. These alterations were more prominent during walking with fewer differences identified in running. These alterations may be best interpreted through the context of the foot and ankle rocker system and specific phases of swing.^{78, 132} Walking gait is associated with three rockers during stance phase including the heel-rocker (0-8%, initial heel contact to initial forefoot contact, e.g. absorption phase), ankle-rocker (9-46%, forefoot contact to maximum tibial progression over the ankle, e.g. absorption-to-propulsion phase), and forefoot-rocker (47-66%, heel lift to toe off, e.g. propulsion phase).^{78, 132} Running gait is

associated with the ankle-rocker (0-23%) and forefoot-rocker (24-46%). The swing phase for walking and running can be separated into initial-swing (toe off to maximal knee flexion), mid-swing (maximal knee flexion to a vertically positioned tibia) and terminal-swing (vertically positioned tibia to initial contact).⁷⁸

In regards to distal kinematic alterations, those with CAI demonstrated increased rearfoot inversion during the ankle-rocker and increased shank external rotation during terminal-swing during walking. These findings are supported by previous studies which identified similar alterations in those with CAI.^{55, 72-73} In this investigation, those with CAI demonstrated an abrupt shift into inversion during the transition from the heel-rocker to ankle-rocker which likely supports previous studies⁷⁴⁻⁷⁵ which identified increased plantar pressure along the lateral border of the foot in those with CAI. The positioning of the rearfoot and shank around the time of initial contact is thought to be critical for successfully maintaining a base of support during stance phase in order to prevent hypersupination or inversion.^{8, 55}

While significant differences were detected in rearfoot and shank kinematics, no significant differences were detected in ankle dorsiflexion. Similar to the findings of Drewes et al.³¹, those with CAI demonstrated trends towards decreased dorsiflexion during the ankle-rocker and terminal-swing phases of walking. Although the analysis determined there were no statistically significant differences between groups, these data points were associated with moderate effect sizes indicating these trends may have clinical implications for force absorption, the transition to propulsion, and the transition to a loaded condition for those with CAI.^{31, 78}

In addition to distal alterations, this study identified proximal alterations in

sagittal plane motion of the hip and knee. During walking, those with CAI demonstrated more hip and knee extension during the heel-rocker, ankle-rocker, mid-swing, and terminal-swing. While statistically significant differences were not identified in every instance where preliminary differences were detected, all were associated with strong effect sizes suggesting clinically meaningful differences may be present. While several proximal deviations were identified in walking, few group differences were detected during running. The presence of proximal alterations in hip and knee kinematics contradict previous reports⁷²⁻⁷³ which indicated that no sagittal plane alterations were present in the hip and knee of those with CAI. Proximal kinematic alterations may not have been identified in previous studies because of different instrumentation to capture kinematics (electromagnetic), gait was assessed during overground walking, and the timeframe of data capture was a narrow window around initial contact. In the current study, many of the proximal alterations were identified during mid- and terminal-swing and during the heel and ankle-rockers which would not have been identified in the previously mentioned studies.

Overall, these proximal alterations in lower extremity gait kinematics suggest those with CAI may have a decreased ability to absorb ground reaction forces during the absorption phase of stance (heel and ankle-rocker). Decreasing the force absorption capabilities of the lower extremity has implications for the development of degenerative joint disease, the ability to successfully maintain a base of support, and cope with changes in the environment.^{78, 127} Future studies should systematically explore ground reaction forces and their relationship to kinematic alterations in those with CAI.

Joint Coupling Relationships

The amount of joint coupling variability exhibited across the multiple joints and segments of the lower extremity is thought to provide insight into the flexibility and self-organization capabilities of the sensorimotor system when examined within the context of the state of health, the activity, and the environment.⁸⁰⁻⁸¹ In this study, those with CAI demonstrated joint coupling variability patterns which were overall similar to their healthy counterparts during treadmill walking and running in a laboratory setting. However, explicit differences were identified in specific areas of stride which may provide an indication of changes in sensorimotor system function in those with CAI.

The primary trend in group differences was associated with increased joint coupling variability during mid- and terminal-swing in those with CAI. This pattern was exhibited in 8 of the 12 coupling relationships examined in this study. These differences were significant during walking in the hip flexion/extension–knee and knee–ankle coupling relationships and during running in the hip flexion/extension -ankle, knee-ankle, and knee-shank coupling relationships. These joint coupling differences in terminal swing were similar to the results of Drewes et al.⁵⁵ although no differences were detected in rearfoot-shank coupling in this study. Increased joint coupling variability during mid- and terminal-swing may be representative of the sensorimotor system of the CAI group searching for functional or stable behavior when approaching initial contact and preparing for force absorption.^{55, 133} These coupling alterations may be a predisposing factor to experiencing episodes of instability or additional sprains because the positioning of the foot at the time of initial contact is critical for maintaining a base of support and absorbing force during the heel and ankle-rockers.⁵⁵

The other trend associated with joint coupling differences was decreased variability associated of the ankle-rocker and forefoot-rocker in those with CAI. This trend was significant during walking and running in the knee-shank, knee-ankle, and hip abduction/adduction-rearfoot coupling relationships. These differences were associated with the late ankle-rocker or forefoot rocker indicating healthy individuals exhibit greater joint coupling variability during force generation and propulsion. Coupling alterations in this window may represent a decrease in the number of the available strategies to generate force in those with CAI and could potentially be linked to the kinematic and joint coupling differences identified during swing phase.^{80, 133}

The interpretation of increased or decreased joint coupling variability during gait has yet to be fully elucidated.⁸² There are conflicting reports that either decreased joint coupling variability⁸¹ or increased joint coupling variability⁵⁵ are linked to deleterious changes in sensorimotor system function in conjunction with lower extremity injury. The results of the current study indicate that alterations in joint coupling variability are contextually dependent on the health condition of interest and constraints placed on the sensorimotor system from the task and environment. This was demonstrated by the opposite trends in group differences exhibited during stance and swing phases in this study. Increased joint coupling variability during stance may be indicative of more flexibility for absorbing and generating forces in a closed-chain or weight-bearing condition. Conversely, decreased joint coupling variability during swing may be favorable in order to create a more stable behavior for foot positioning which may result in fewer errors when approaching initial contact. Gaining a better understanding of the

optimal joint coupling variability for each of the specific subtasks or phases of gait may help to elucidate additional clinical implications for these measures.

This study provides evidence of concurrent alterations in sensorimotor function and self-reported function which promotes the potential relationship between functional capacity and movement solution variability.¹¹³ While the deviations in gait kinematics and joint coupling variability observed in this study were often subtle, purposefully manipulating the task and environment could have elicited larger differences. This is supported by examining the individual components of the FAAM and FAAM-S. On the FAAM, the task or activity with the greatest reported disability in the CAI group was walking on uneven ground. Because the treadmill was a flat, predictable environment with no imposed perturbations, those with CAI may not have experienced the typical amount of sensorimotor constraint experienced in their normal environments. Also, when examining the items of the FAAM-S, the greatest disability was reported with landing and cutting. This may provide some explanation to the subtleties of gait deviations associated with walking and running in this study as this group of individuals with CAI report more difficulty with other activities. Using patient-reported deficits to create additional context for examining sensorimotor system function may enable clearer trends to be identified in laboratory-oriented measures of function.

Limitations and Future Directions

The origin of the kinematic and joint coupling variability alterations identified in this investigation is unknown. However, the presence of both proximal and distal kinematic alterations and differences in joint coupling variability suggests many of the gait alterations may be related to changes in the way the central nervous system organizes

motor output. Future studies should investigate the contributing factors associated with these alterations and the connection between local and global impairments. Additionally, studies which attempt to restore normal gait function should consider how interventions may affect both the proximal and distal lower extremity and sensorimotor system function.

The primary limitation of this study is the retrospective design which does not permit a causal link to be established between CAI and the identified alterations in gait. Future studies should prospectively examine gait following first time acute ankle sprains to determine if the alterations in this study are a manifestation of a history of ankle sprain or are present as a predisposing factor to injury. All subjects performed walking and running barefoot on a treadmill. Barefoot kinematics on a treadmill may not be directly generalized to the common injury mechanisms associated with episodes of giving way or recurrent ankle sprains in most instances. Examining shod or overground gait may elicit different results. Additionally, many of the identified kinematic alterations suggest that those with CAI have a decreased ability to absorb ground reaction forces. Future studies should further investigate the relationships between gait kinetics and kinematic analyses in order to provide additional insight into the pathophysiology for the long-term repercussions of this condition.

Conclusion

During walking and running gait, those with CAI exhibited kinematic differences in both proximal and distal articulations and segments of the lower extremity. These alterations were more prominent during walking and were associated with the phases of gait responsible for force absorption. Also, those with CAI demonstrated increased

variability in the terminal-swing phase of several joint coupling relationships during walking and running which may have implications for foot placement leading to initial contact. Overall, these findings may be representative of global alterations in sensorimotor system function in those with CAI. Future research should consider these gait alterations when designing prospective gait investigations and when designing interventions associated with addressing gait deviations in those with CAI.

Table 3.1: Group differences in walking kinematics.

Kinematic Variable	% of Stride	Healthy (Mean ± SD)	CAI (Mean ± SD)	p-value	Effect Size ± 95% CI
Hip Flexion (+)/ Extension (-)	0-43	7.71° ± 3.38°	5.54° ± 3.98°	0.16	0.57 ± 0.82
	70-100	16.62° ± 3.02°	13.41° ± 3.61°	0.008	0.93 ± 0.84
Knee Flexion (+)/ Extension (-)	7-38	15.63° ± 4.44°	13.41° ± 3.39°	0.18	0.54 ± 0.81
	68-100	41.57° ± 5.49°	36.39° ± 3.54°	0.01	1.08 ± 0.86
Shank Rotation Internal (+)/ External (-)	88-100	-2.80° ± 2.12°	-0.44° ± 1.82°	0.008	-1.15 ± 0.86
Ankle Dorsiflexion (+)/ Plantar flexion (-)	18-31	4.25° ± 2.62°	2.30° ± 3.58°	0.14	0.60 ± 0.82
	63-68	-19.30° ± 3.65°	-15.30° ± 8.05°	0.13	-0.61 ± 0.82
	90-97	0.72° ± 2.29°	-1.16° ± 2.97°	0.09	0.68 ± 0.82
Rearfoot Eversion(+)/ Inversion (-)	5-34	0.61° ± 1.21°	-0.34° ± 0.94°	0.04	-0.85 ± 0.84

Table 3.2: Group differences in walking joint coupling variability.

Joint Coupling Relationship	% of Stride	Healthy (Mean ± SD)	CAI (Mean ± SD)	p-value	Effect Size ± 95% CI
Hip Flexion/Extension-Knee Flexion/Extension	14-18	0.10 ± 0.03	0.13 ± 0.05	0.07	-0.75 ± 0.83
	33-37	0.19 ± 0.06	0.26 ± 0.12	0.09	-0.71 ± 0.82
	82-87	0.27 ± 0.10	0.37 ± 0.13	0.05	-0.83 ± 0.83
Hip Flexion/Extension-Ankle Dorsi/Plantar Flex	48-53	0.19 ± 0.03	0.16 ± 0.07	0.15	0.59 ± 0.82
	90-96	0.12 ± 0.04	0.16 ± 0.08	0.08	-0.64 ± 0.82
Hip Abd/Adduction-Rearfoot Inversion/Eversion	53-58	0.39 ± 0.12	0.30 ± 0.09	0.05	0.81 ± 0.83
Knee Flexion/Extension-Shank Roation	48-55	0.20 ± 0.06	0.16 ± 0.05	0.07	0.76 ± 0.83
	58-63	0.10 ± 0.02	0.08 ± 0.02	0.07	0.85 ± 0.84
	89-96	0.11 ± 0.04	0.15 ± 0.06	0.05	-0.74 ± 0.83
Knee Flexion/Extension-Ankle Dorsi/Plantar Flex	47-52	0.23 ± 0.09	0.19 ± 0.06	0.10	0.55 ± 0.82
	79-85	0.11 ± 0.03	0.14 ± 0.04	0.06	-0.79 ± 0.83
	90-99	0.23 ± 0.08	0.25 ± 0.08	0.05	-0.26 ± 0.80

Table 3.3: Group statistics for the average vector coding coefficient during walking.

Joint-Coupling Relationship	CAI	Healthy	p-value
Hip Flexion/Extension-Ankle	0.18±0.03	0.18±0.02	0.79
Hip Flexion/Extension -Knee	0.28±0.05	0.24±0.05	0.06
Hip Abd/Adduction-Rearfoot	0.44±0.06	0.46±0.06	0.44
Knee-Ankle	0.19±0.04	0.19±0.03	0.60
Knee-Shank	0.24±0.04	0.25±0.02	0.55
Shank-Rearfoot	0.40±0.12	0.36±0.13	0.55

Table 3.4: Group differences in running kinematics.

Kinematic Variable	% of Stride	Healthy (Mean ± SD)	CAI (Mean ± SD)	p-value	Effect Size ± 95% CI
Shank Rotation Internal (+)/ External (-)	31-36	6.44° ± 2.00°	4.68° ± 3.43°	0.14	0.61 ± 0.82
	95-100	1.96° ± 1.86°	0.09° ± 3.26°	0.10	0.68 ± 0.82
Knee Flexion(+)/ Extension (-)	80-100	38.68° ± 10.53°	32.00° ± 6.26°	0.07	0.69 ± 0.82

Table 3.5: Group Differences in running joint coupling variability.

Joint Coupling Relationship	% of Stride	Healthy (Mean ± SD)	CAI (Mean ± SD)	p-value	Effect Size ± 95% CI
Hip Flexion/Extension-Knee Flexion/Extension	78-83	0.22 ± 0.12	0.32 ± 0.17	0.11	-0.66 ± 0.82
Hip Flexion/Extension-Ankle Dorsi/Plantar Flexion	13-18	0.18 ± 0.07	0.24 ± 0.08	0.05	-0.81 ± 0.83
	23-28	0.18 ± 0.06	0.13 ± 0.07	0.10	0.67 ± 0.82
	92-100	0.17 ± 0.08	0.27 ± 0.10	0.01	-1.05 ± 0.85
Hip Abd/Adduction-Rearfoot Inversion/Eversion	40-46	0.30 ± 0.10	0.42 ± 0.19	0.06	-0.76 ± 0.83
	48-53	0.55 ± 0.16	0.41 ± 0.12	0.03	0.96 ± 0.84
Knee Flexion/Extension-Shank Rotation	0-4	0.46 ± 0.23	0.31 ± 0.14	0.07	0.75 ± 0.83
	23-30	0.23 ± 0.09	0.17 ± 0.05	0.05	0.81 ± 0.83
	58-71	0.14 ± 0.05	0.20 ± 0.10	0.09	-0.71 ± 0.83
	88-100	0.13 ± 0.06	0.23 ± 0.11	0.01	-1.09 ± 0.86
Knee Flexion/Extension-Ankle Dorsi/Plantar Flexion	23-32	0.19 ± 0.04	0.15 ± 0.3	0.03	0.92 ± 0.84
	90-100	0.22 ± 0.11	0.37 ± 0.10	0.003	-1.33 ± 0.84
Shank Rotation-Rearfoot Inversion/Eversion	28-32	0.29 ± 0.18	0.20 ± 0.05	0.10	0.73 ± 0.83

Table 3.6: Group statistics for the average vector coding coefficient during running.

Joint-Coupling Relationship	CAI	Healthy	p-value
Hip Flexion/Extension-Ankle	0.17±0.04	0.15±0.03	0.26
Hip Flexion/Extension -Knee	0.24±0.03	0.21±0.05	0.19
Hip Abd/Adduction-Rearfoot	0.39±0.05	0.40±0.04	0.79
Knee-Ankle	0.17±0.03	0.15±0.03	0.28
Knee-Shank	0.22±0.03	0.21±0.04	0.10
Shank-Rearfoot	0.41±0.06	0.46±0.06	0.10

Chapter 4: Effect of Joint Mobilization on Self-Reported Function, Range of Motion, and Postural Control in Those with Chronic Ankle Instability

Introduction

Lateral ankle sprains are often considered innocuous injuries, suggesting the dissipation of acute symptoms is representative of resolution of the overall health condition. However, more than 70% of individuals who sustain a single lateral ankle sprain experience residual symptoms, recurrent bouts of instability, additional ankle sprains, and reduced functional capacity.^{7, 9, 134} These negative sequelae associated with acute ankle sprains are the primary characteristics of chronic ankle instability (CAI).⁸ The prevalence of CAI combined with the associated decreased quality of life⁹ and risk of developing co-morbidities such as post-traumatic ankle osteoarthritis^{127, 135} advocates for further development of rehabilitation interventions to address this clinical phenomenon.

Several mechanical impairments have been identified as contributing factors for CAI.⁸ The primary mechanical impairments include increased anterior joint laxity¹⁴, reduced posterior talar glide²⁶, and reduced dorsiflexion range of motion (DF ROM).³¹⁻³² DF ROM deficits may be related to a disruption in normal talar arthrokinematic range of motion as a result of restrictions in noncontractile tissues and degenerative changes in ankle complex structure.⁸ This is supported by studies which identified either restrictions in posterior talar glide^{26, 28} or the presence of an anterior positional fault of the talus in relation to the ankle mortise.^{12, 23}

In addition to mechanical considerations, a loss of DF ROM which is arthrogenic in nature may contribute to the functional impairments associated with CAI by disrupting the normal transmission of afferent information available to the sensorimotor system.^{8, 27}

Deficits in postural control as well as other functional impairments are thought to be the result of a loss in somatosensory information from damaged ligamentous mechanoreceptors; however, alterations in sensory input may also be associated with changes in arthrokinematic function.^{23, 27, 62} This suggests there may be a synergistic relationship between the mechanical and functional alterations associated with CAI.

While the connection between impairments and reduced self-reported function is unclear, interventions which address multiple aspects of impairment are likely essential for restoring activity and participation in those with CAI.⁵³ To address mechanical impairments, previous studies have attempted to use joint mobilization manual therapy to address deficits in posterior talar glide and DF ROM.^{27-29, 100} Joint mobilization is used to increase osteokinematic and arthrokinematic motion by increasing the extensibility of noncontractile tissues.¹⁰² Previous studies have demonstrated a single joint mobilization treatment provides initial resolution of mechanical impairments associated with a history of ankle sprain.^{27-29, 100} Additionally, a single joint mobilization treatment has also been associated with increased postural control²⁷ and facilitation of soleus motoneuron pool excitability¹³⁶ suggesting there may be a link between arthrokinematic function and functional impairments in those with CAI.

The limitation of the research evidence associated with joint mobilization and CAI is the lack of studies examining multiple joint mobilization treatments. Examining the effect of multiple treatments would enhance the clinical application of this intervention and provide the opportunity to assess patient-oriented measures of function to compliment measures of impairment. Therefore, the purpose of this study is to examine the effect of a 2-wk anterior-to-posterior talocrural joint mobilization

intervention on weight-bearing DF ROM, ankle/subtalar arthrometrics, postural control, and self-reported function in those with CAI. It is hypothesized that the joint mobilization intervention will improve local and global impairments as well as self-reported function in those with CAI.

Methods

Design

This investigation employed a prospective cohort design. The independent variable was time (baseline, pre-intervention, post intervention, 1-wk follow-up). The dependent variables were DF ROM, instrumented ankle/subtalar arthrometrics, normalized reach distances on the Star Excursion Balance Test (SEBT), and TTB measures of postural control. Subjects reported to the research laboratory for 4 separate testing sessions and 6 joint mobilization treatments across a 4-wk period to complete the study.

Subjects

A power analysis was conducted based on the mean minima of TTB in the anterior-posterior (AP) direction from a previous study²⁷ indicating 7 subjects would be required to achieve a statistical power of 0.8 at a significance level of 0.05. Therefore, 12 subjects with self-reported CAI (6 M, 6 F; age = 27.4 ± 4.3 years; height = 175.4 ± 9.78 cm; mass = 78.4 ± 11.0 kg) were included to account for potential drop-out. Subjects were recruited using advertisements posted throughout a large university over a 4 month period. To be included in the study subjects reported a history of at least one ankle sprain. Additionally, subjects had to report at least two episodes of “giving way” within the past 3 months. This was quantified by answering “yes” to question 1 and for a total of at least 4 questions on the Ankle Instability Instrument.¹²² An ankle sprain was defined as an

incident in which the rearfoot was inverted or supinated and resulted in a combination of swelling, pain, and time lost or modification of normal function for at least one day.⁸ An episode of giving way was described as an incident in which the rearfoot suddenly rolled, felt weak, or lost stability; however, the individual did not sustain an ankle sprain and was able to continue with normal function.⁸ Subjects also had to report functional loss as a result of their ankle sprain history by reporting disability scores of $\leq 90\%$ on the Foot and Ankle Ability Measure (FAAM) and a score of $\leq 80\%$ on the FAAM Sport Scale.¹²⁵ In the event subjects reported a bilateral history of ankle sprains, the limb with the greatest reported functional loss on the FAAM was included in the study. Subjects reported an average of 5.3 ± 5.5 total ankle sprains. The average number of episodes of giving way over the previous 3 months was 8.4 ± 7.4 . Exclusion criteria consisted of the subject reporting an acute ankle sprain within the past 6 wks, a previous history of lower extremity surgeries or fracture, other lower extremity injuries within the past 6 months that resulted in time lost or modification of normal function for at least one day, and other health conditions known to affect balance. Prior to participation, all subjects provided written informed consent in compliance with the institutional review board.

Instrumentation

Static postural control was assessed with the Accusway Plus force plate (AMTI; Watertown, MA). Center of pressure data were sampled at 50 Hz. Instrumented measurements of posterior talar displacement and posterior stiffness was performed using a portable ankle arthrometer (Hollis Ankle Arthrometer, Blue Bay Research Inc., Navarre, FL, USA).

Testing Procedures

After being included into the study, subjects participated in the first data collection session (baseline). Following the baseline session, subjects were instructed to maintain normal physical activity and activities of daily living and report back to the laboratory in 1 wk for the second data collection session (pre-intervention). Immediately following the pre-intervention session, subjects received their first joint mobilization treatment and returned to the laboratory for 5 additional joint mobilization treatments over the next 2 wks. Subject underwent the third data collection session (post-intervention) within 1-2 days following the final joint mobilization treatment. After another wk, 1-wk follow-up data were collected (Figure 4.1). During each data collection session, the dependent measures including DF ROM, dynamic postural control, static postural control, instrumented ankle/subtalar arthrometry, and self-reported function on the FAAM and FAAM-S were collected in a counterbalanced order which was maintained across data collections for each subject. All dependent measures were collected barefoot using previously described protocols.²⁷

Dorsiflexion Range of Motion

The weight-bearing lunge test was performed using the knee-to-wall principle described by Vicenzino et al.²⁸ Previous investigators⁷¹ reported intraclass correlation coefficients of ≥ 0.97 SEM for the inter-tester and intersession reliability of this assessment of DF ROM in healthy adults. Subjects performed 3 practice trials and 3 analysis trials of the weight-bearing lunge test on the involved limb in which they kept their heel firmly planted on the floor while they flexed their knee to the wall.²⁷ The uninvolved limb was positioned alongside and behind the involved limb and was used to

maintain stability during the test. When subjects were able to maintain heel and knee contact, they were progressed backwards from the wall and repeated the modified lunge. All subjects started the test approximately 2 cm from the wall and initially progressed in 1 cm increments until the first lunge that the heel lifted from the floor or the knee failed to make contact with the wall. Following the first failed lunge attempt, foot placement of the involved limb was adjusted in smaller increments to achieve the maximum distance from the wall. Maximum DF ROM was measured to the nearest 0.1 cm by a tape measure secured to the floor to measure the distance of the great toe from the wall based on the furthest distance the foot was able to be placed without the heel lifting off the ground while the knee was able to touch the wall. After achieving maximum DF ROM, subjects stood, resumed a comfortable position, and performed the next trial from the original starting position. This measure of maximum DF ROM has been highly correlated to the number of degrees achieved during the weight-bearing lunge test in a previous study.⁷¹ This study⁷¹ also determined there is approximately 3.6° of DF ROM for every 1 cm in distance away from the wall.

Instrumented Arthrometry

Using an instrumented arthrometer (Hollis Ankle Arthrometer, Blue Bay Research, Navarel, FL), subjects underwent three trials for anterior displacement/ stiffness, posterior displacement/ stiffness, and inversion rotation/ stiffness based on previously established protocols.^{27, 77} Anterior and posterior displacement (mm) was considered the displacement at the time of maximal force. Anterior and posterior stiffness was determined by calculating the slope of the force-displacement relationship (N/mm). Inversion rotation was considered the degrees of rotation (°) at the time of maximal

torque. Inversion stiffness was determined by calculating the slope of the torque-rotation relationship ($N \cdot mm / ^\circ$). Arthrometer data were collected using a custom LabView software program (National Instruments Corp., Austin, TX, USA) and analyzed with a custom written Matlab code (Version R2009b, MathWorks Inc., Natick, MA, USA).

Dynamic Postural Control

The anterior, posteromedial (PM), and posterolateral (PL) directions of the SEBT were measured based on the recommendations of Hertel.⁵³ Subjects were positioned according to a series of tape measures secured to the floor. Equal halves of the length and width of the involved foot were in each quadrant of the SEBT instrument. Subjects were instructed to perform maximal reaches with the uninvolved limb followed by a single, light toe touch on the tape measure. During the trial, if the hands did not remain on the hips, the position of the stance foot was not maintained, the heel did not remain in contact with the floor, or the subject lost balance then the trial was discarded and repeated. Each subject performed 4 practice trials in each direction on the involved limb and 3 trials were performed in each direction for analysis.¹³⁷ Distances were measured in cm, normalized to each subject's leg length, and multiplied by 100.⁶⁴ Leg length was measured as the distance from the anterior superior iliac spine to the distal tip of the medial malleolus.⁶⁴

Static Postural Control

Subjects performed 1 practice trial and 3 analysis trials of single-limb stance on the involved limb with eyes open and eyes closed on a forceplate for 10 s.⁴⁸ Prior to testing, each subject's foot width and length were measured and used to center the foot on the forceplate. Subjects were instructed to remain as still as possible with arms folded

across the chest, and the uninvolved limb positioned at 45° of knee flexion and 30° of hip flexion. If the subjects touched down with the suspended limb, opened their eyes during eyes closed testing, or were unable to maintain the standing posture for the 10-s duration, the trial was discarded and repeated. Center of pressure data was separated into anterior-posterior (AP) and medial-lateral (ML) directions and analyzed as TTB variables (mean of TTB ML minima, mean of TTB AP minima, standard deviation of TTB ML minima, and standard deviation of TTB AP minima).⁵¹ The calculation of TTB variables was based on the previously described methods of Hertel et al.⁵¹ and computed using a custom written Matlab code (Version R2009b, MathWorks Inc., Natick, MA, USA). Mean of TTB minima provides an estimate of the average amount of time a person has to make postural corrections while the standard deviation (SD) of TTB minima indicates the number of solutions used to maintain single-limb stance based on the boundaries of the base of support for each individual. Higher mean of TTB minima values would indicate that on average a greater amount of time is available to make postural corrections. Higher SD of TTB minima values would indicate more solutions used to maintain single-limb stance, representing a less constrained sensorimotor system.⁵¹

Joint Mobilization Intervention

The joint mobilization intervention consisted of 6 separate visits to the laboratory in which each subject received 2, 2-min sets of Maitland Grade II talocrural joint traction and 4, 2-min sets of Maitland Grade III talocrural joint mobilization with 1 min of rest between sets. Traction was employed to distract the talus from the ankle mortise to promote posterior gliding of the talus for the joint mobilization treatments. The joint mobilization technique consisted of stabilizing the distal tibia and fibula and mobilizing

the talus in an anterior-to-posterior direction in accordance with a previously established protocol.²⁷ The joint mobilization was operationally defined as large-amplitude, 1-s rhythmic oscillations from the joint's mid-range to end range with translation taken to tissue resistance.^{56, 107} Compliance was 100%, meaning all subjects received all treatments within the designated treatment period. Each subject received an average of 1251 ± 40 oscillations over the 6 treatment periods. A grade III joint mobilization was selected in an attempt to increase the posterior capsular endpoint and provide stimulation of articular mechanoreceptors from oscillations which span the length of the available accessory motion. All joint mobilization treatments were conducted by the same Certified Athletic Trainer with 5 years of experience.

Minimal Detectable Change Scores

Because no control group was used in this study, minimal detectable change (MDC) scores were calculated to determine the minimal change required within our dependent variables to achieve changes beyond the error of the measurements. MDC scores were determined using intersession reliability (intraclass correlation coefficient (2, 1) and SE of measurement) from the data collected during the baseline and pre-intervention sessions. MDC scores were calculated using the following formula: $SE \text{ of measurement} * \sqrt{2}$.¹³⁸⁻
¹³⁹ Each MDC score is provided next to the respective dependent variable in Tables 4.1, 4.2, 4.3, 4.4 and 4.5.

Statistical Analysis

Separate one-way ANOVAs were used to examine differences in the FAAM, the FAAM-S, DF ROM, each arthrometry measure, each direction of normalized reach distance on the SEBT, and each TTB variable. The independent variable was time

(baseline, pre-intervention, post intervention, 1-wk follow-up). Post hoc comparisons were completed using Fisher's LSD in the presence of a time effect. The significance level for all analyses was set *a priori* at $p \leq 0.05$. No correction for multiple comparison was performed on the alpha level to protect against making a type II error.¹²⁹ Instead, effect sizes (ES) were calculated based on the mean difference, the standard deviation (SD) of the differences, and the correlation of repeated-measures using a bias-corrected *Hedge's g* with corresponding 95% confidence intervals (CI).¹³⁰ ES were interpreted as weak (0 – 0.39), moderate (0.40 – 0.69) and strong (≥ 0.70).¹³¹ Statistical analyses were conducted using PASW version 18.0 (Chicago, IL, USA) and Excel 2007 (Microsoft, Redmond, WA, USA).

Results

Self-Reported Function

Means (\pm SD) for the FAAM and FAAM-S measures are listed in Table 4.1. There was a significant time effect for the FAAM ($p = 0.001$) and the FAAM-S ($p = 0.001$) scores. There were no significant differences between the baseline and pre-intervention measures for the FAAM ($p = 0.88$, ES = 0.04 ± 0.80) and the FAAM-S ($p = 0.24$, ES = 0.20 ± 0.80). For the FAAM, significant differences were detected between baseline and post-intervention measures ($p = 0.01$, ES = 0.79 ± 0.83), baseline and 1-wk follow-up measures ($p = 0.01$, ES = 0.43 ± 0.81), pre-intervention and post-intervention measures ($p = 0.01$, ES = 0.76 ± 0.83), and pre-intervention and 1-wk follow-up measures ($p = 0.01$, ES = 0.43 ± 0.81). For the FAAM-S, significant differences were detected between baseline and post-intervention measures ($p = 0.01$, ES = 0.80 ± 0.83), baseline and 1-wk follow-up measures ($p = 0.01$, ES = 0.78 ± 0.83), pre-intervention and post-intervention measures ($p = 0.01$, ES

= 0.77 ± 0.83), and pre-intervention and 1-wk follow-up measures ($p = 0.01$, $ES = 0.78 \pm 0.83$). No significant differences were detected between the post-intervention and 1-wk follow-up measures for the FAAM ($p = 0.78$, $ES = -0.03 \pm 0.80$) or the FAAM-S ($p = 0.81$, $ES = 0.13 \pm 0.80$).

Dorsiflexion Range of Motion

Means (\pm SD) for DF ROM measures are listed in Table 4.2. A significant time effect was detected for DF ROM measures ($p < 0.001$). There were no significant differences between the baseline and pre-intervention measures ($p = 0.77$, $ES = -0.10 \pm 0.80$). Significant differences were detected between baseline and post-intervention measures ($p < 0.001$, $ES = 3.03 \pm 1.17$), baseline and 1-wk follow-up measures ($p < 0.001$, $ES = 1.83 \pm 0.95$), pre-intervention and post-intervention measures ($p < 0.001$, $ES = 2.97 \pm 1.16$), and pre-intervention and 1-wk follow-up measures ($p < 0.001$, $ES = 1.59 \pm 0.92$). No significant differences were detected between the post-intervention and 1-wk follow-up measures ($p = 0.53$, $ES = 0.16 \pm 0.80$).

Ankle Arthrometry

Means (\pm SD) for ankle arthrometry measures are listed in Table 4.2. There was no significant time effects detected for anterior displacement ($p = 0.21$), anterior stiffness ($p = 0.75$), posterior displacement ($p = 0.94$), posterior stiffness ($p = 0.33$), inversion rotation ($p = 0.22$), or inversion stiffness ($p = 0.59$).

Dynamic Postural Control

Means (\pm SD) for SEBT measures are listed in Table 4.3. There was a significant time effect for the anterior ($p < 0.001$), PM ($p = 0.003$) and PL ($p < 0.001$) directions. There were no significant differences between the baseline and pre-intervention measures for

the anterior ($p = 0.08$, $ES = 0.52 \pm 0.81$), PM ($p = 0.30$, $ES = -0.28 \pm 0.80$), or PL ($p = 0.50$, $ES = 0.19 \pm 0.80$) directions. For the anterior direction, significant differences were detected between baseline and post-intervention measures ($p = 0.001$, $ES = 1.26 \pm 0.87$), baseline and 1-wk follow-up measures ($p = 0.001$, $ES = 1.20 \pm 0.87$), pre-intervention and post-intervention measures ($p = 0.001$, $ES = 1.17 \pm 0.87$), and pre-intervention and 1-wk follow-up measures ($p = 0.006$, $ES = 0.89 \pm 0.84$). For the PM direction, significant differences were detected between baseline and 1-wk follow-up measures ($p = 0.01$, $ES = 0.79 \pm 0.83$), pre-intervention and post-intervention measures ($p = 0.001$, $ES = 1.10 \pm 0.86$), and pre-intervention and 1-wk follow-up measures ($p < 0.001$, $ES = 1.45 \pm 0.90$). However, there was no differences between the baseline and post-intervention measures ($p = 0.10$, $ES = 0.47 \pm 0.81$). For the PL direction, significant differences were detected between baseline and post-intervention measures ($p = 0.002$, $ES = 1.02 \pm 0.85$), baseline and 1-wk follow-up measures ($p = 0.002$, $ES = 1.03 \pm 0.85$), pre-intervention and post-intervention measures ($p = 0.002$, $ES = 1.08 \pm 0.85$), and pre-intervention and 1-wk follow-up measures ($p = 0.003$, $ES = 0.98 \pm 0.85$). No significant differences were detected between the post-intervention and 1-wk follow-up measures in the anterior ($p = 0.54$, $ES = 0.10 \pm 0.80$), PM ($p = 0.26$, $ES = 0.31 \pm 0.81$), or PL ($p = 0.49$, $ES = 0.19 \pm 0.80$) directions.

Static Postural Control

Means (\pm SD) for eyes open TTB measures are listed in Table 4.4. For eyes open trials, there were no significant time effects detected for mean of TTB AP minima ($p = 0.67$), mean of TTB ML minima ($p = 0.93$), SD of TTB ML minima ($p = 0.90$), or SD of TTB AP minima ($p = 0.91$). Means (\pm SD) for eyes closed TTB measures are listed in Table 4.5. For eyes closed trials, there were no significant time effects detected for mean of TTB AP

minima ($p = 0.86$), mean of TTB ML minima ($p = 0.60$), SD of TTB ML minima ($p = 0.90$), or SD of TTB AP minima ($p = 0.90$).

Discussion

It was found that a 2-wk talocrural joint mobilization intervention significantly improved self-reported function, DF ROM, and dynamic postural control. Despite these findings, no changes were identified in instrumented measures of ankle arthrometry or TTB postural control. Improvement in these measures signifies that the intervention employed in this study effectively improved patient-oriented and clinically-oriented measures of function; however, no improvements were detected in laboratory-oriented measures in this cohort of individuals with CAI.

Following the 2-wk joint mobilization intervention, subjects reported an increase in self-reported function as assessed with the FAAM and FAAM-S. The average increases in function 1 wk following the intervention were approximately 8% and 15% for the FAAM and FAAM-S, respectively. This indicates self-reported function improved beyond the minimally clinically important difference previously established¹²⁵ for these instruments and the MDC scores calculated in this study. This is supported by the moderate-to-large effect sizes associated with differences between measures prior to and following the intervention. Based on increases beyond the minimally clinically important difference, MDC, and moderate-to-large effect sizes, it can be concluded that the changes in self-reported function were beyond the instrument error and represent meaningful improvements in patient-reported function.

The joint mobilization intervention significantly improved DF ROM indicating the Maitland Grade III anterior-to-posterior talar glide joint mobilization had an impact

on the extensibility and flexibility of noncontractile tissues local to the talocrural joint. The increase in lunge distance on the weight-bearing lunge test was 1.4 cm following the intervention which equated to approximately 5° of change in range of motion⁷¹ and is 3.5x greater than the previously reported²⁷ increase in lunge distance following a single joint mobilization treatment. Therefore, it can be concluded that multiple bouts of joint mobilization have mechanical benefits which exceed the isolated effects of a single treatment.

It was hypothesized that the 2-wk intervention would significantly change talar/subtalar arthrometrics. The results of this study do not support this hypothesis because no changes were identified in any ankle arthrokinematic variables. Although no differences were noted in talar/subtalar arthrometric measurements, it can be determined that the intervention did not negatively impact arthrometrics. Changes in DF ROM without increases in posterior talar/subtalar displacement may be partially explained by recent studies¹⁴⁰⁻¹⁴¹ which identified there is a weak relationship between measures of posterior talar/subtalar displacement using the ankle arthrometer and weight-bearing measures of DF ROM. This indicates the relationship between non-weight-bearing measures of ankle arthrokinematics and weight-bearing DF ROM may need to be systematically evaluated to better understand the potential disconnect between these measures. Additionally, it cannot be determined if the joint mobilization intervention had an impact on the positioning of the talus. Anterior positional faults of the talus have been previously identified in those with CAI.²³⁻²⁴ However, no radiographic assessments were conducted in this study which limits the ability to determine if changes in talar positioning occurred. It cannot be concluded that joint mobilization had an impact on

talar/subtalar arthrometrics; however, future investigations may consider employing other methods to examine changes in talar positioning following joint mobilization.

Following the intervention, significant increases in reach distance were identified in the anterior, PM, and PL directions of the SEBT. Because improvements were identified in range of motion, the increased reach distances on the SEBT can most likely be attributed to the ability to incorporate additional range of motion into movement strategies on this assessment. This is a positive progression upon the previous study²⁷ which determined a single joint mobilization treatment was unable to change SEBT reach distances despite increased DF ROM and an increase in static postural control. As a result, the more robust increase in range of motion, the longer intervention period, and the longer time from the application of joint mobilization to re-assessment may allow the additional mechanical degrees of freedom to be integrated into functional strategies on the SEBT.

Based on previous studies^{36, 142} which speculated anterior reach deficits were specifically related to impairments in DF ROM in those with CAI, it was hypothesized the joint mobilization would have the greatest impact on the anterior reach direction. However, the results indicate that the joint mobilization intervention significantly improved the anterior, PM, and PL directions at nearly equal magnitudes based on effect size comparisons. Increases in weight-bearing DF ROM provides a logical explanation for increases in anterior reach as performance on these measures have demonstrated a significant positive relationship in previous studies.⁶⁹ However, significant improvements were also identified in the PM and PL directions which proposes that the joint mobilization intervention may have enhanced weight-bearing mobility in proximal lower

extremity joints. Because no other ranges of motion were investigated in this study, the origin of increases in the PM and PL reach cannot be determined. However, because increases in weight-bearing DF ROM were displayed, it can be speculated that weight-bearing knee and hip flexion may have also increased based on the known coupling between these motions.²⁶ Additionally, previous evidence⁶⁸ has determined that knee and hip flexion range of motion significantly influence PM and PL reach distances. This implies that the joint mobilization intervention may have resulted in concurrent increases in weight-bearing ankle dorsiflexion, knee flexion, and hip flexion which would provide a rational explanation for the observed increases in anterior and posterior reach distance.

Although improvements were identified in SEBT performance, no improvements were identified in TTB postural control measures. It was hypothesized that the joint mobilization intervention would result in significant improvements in TTB by stimulating sensory receptors in the noncontractile structures of the talocrural joint. Based on the results of this study, it may be that the SEBT and TTB are testing different aspects of sensorimotor system function which may provide differing but complimentary insights into the movement solution variability exhibited by the individual during postural control. The SEBT requires a combination of strength, range of motion, and balance throughout the lower extremity while TTB is more reliant on somatosensory information in order to make subtle changes in motor output. This implies the SEBT may provide a better assessment of the mechanical constraints limiting movement solution variability.

The differing aspects of sensorimotor system function captured by the SEBT and TTB is supported by studies^{27, 143} which identified an increase in TTB in those with CAI directly following a single joint mobilization treatment and in the presence of textured

insoles which targeted plantar cutaneous somatosensation. However, in the case of this study, no changes in TTB occurred in any of the post-intervention measurements which were at least 24 hours following the last treatment. Based on the results of this study and the previous study²⁷, it seems that the utility of joint mobilization to enhance sensory input may be isolated to a limited time window following treatment application that does not persist after 1 day.

Based on the findings of this study, the joint mobilization intervention satisfied the principles of enhancing functional capacity by increasing activity and participation in meaningful activities as indicated by changes in self-reported function.¹¹³ Additionally, the joint mobilization intervention may have enhanced movement system variability as indicated by increased reach distances on the SEBT; however, this is not supported by the lack of change in TTB measures of postural control.¹¹³ To elicit more global changes in sensorimotor function, the individual may need to experience systematic, purposeful, and active manipulation of task and environment constraints. In the case of this study, the intervention provided a purposeful but passive approach to manipulating organismic constraints experienced by those with CAI. Exploring intervention strategies which take a more active approach to manipulating organismic, task, and environmental constraints; as well as, improve aspects of impairment, activity, and participation may provide the best results for creating concurrent increases in functional capacity and movement solution variability in those with CAI.

Limitations and Future Research

It is acknowledged that joint mobilization would not be used in isolation in a clinical setting. Hence, a single cohort of people with CAI was investigated. The major

limitations of this design are the short follow-up period, the lack of blinding, and the lack of a control or sham group to compare against those receiving the joint mobilization intervention. Based on the results of this study, it appears that there are distinct benefits of utilizing joint mobilizations in those with CAI; however, it is recommended that joint mobilizations should be investigated in combination with other interventions known to enhance function in those with CAI using well-designed randomized controlled trials with longitudinal outcomes.

In the current study, significant improvements in self-reported function following the intervention were identified. Despite these improvements, the average FAAM and FAAM-S scores indicated that these individuals would still be classified with CAI based on the *a priori* level of function to be included in the study. Changes in laboratory measures of postural control were not identified, potentially as evidence that multiple joint mobilization treatments did not have a deleterious effect on this aspect of sensorimotor system function. Collectively, these findings support integrating joint mobilization with other rehabilitation strategies which attempt to increase self-reported function and sensorimotor function using an integrated rehabilitation approach.

Integrating joint mobilization with other rehabilitation strategies such as balance training may provide greater improvements in self-reported function and changes in static postural control.^{27,36} Joint mobilization passively targets local impairments in structure and function while balance training focuses on actively addressing global impairments in sensorimotor system function.^{27,36} Additionally, applying joint mobilization immediately prior to balance training may provide transient stimulation of sensory input from the ankle within a window which could enhance the effectiveness of balance exercises.²⁷

Therefore, complimenting balance training with joint mobilization may create a synergistic coupling of interventions to provide a more holistic rehabilitation strategy for those with CAI.

Conclusion

The 2-wk joint mobilization intervention which targeted the extensibility of the posterior ankle noncontractile structures resulted in significant improvements in self-reported function, DF ROM, and increased reach distance in the anterior, PM, and PL directions of the SEBT in those with CAI. No changes were detected in instrumented measures of ankle arthrokinematic motion or static postural control indicating the intervention did not negatively affect these aspects of function. By addressing local mechanical impairments in ankle function, the joint mobilization intervention successfully enhanced patient-oriented and clinician-oriented measures of function.

Table 4.1: Mean \pm SD and MDC for the FAAM and FAAM-S.

Dependent Variable	Baseline	Pre-intervention	Post-intervention	1-week Follow-up	MDC
FAAM (%)	77.99 \pm 13.11	78.27 \pm 12.62	87.30 \pm 11.07 ^{a, b}	86.80 \pm 11.06 ^{a, b}	3.96
FAAM-S (%)	56.25 \pm 14.72	58.59 \pm 11.08	73.69 \pm 17.65 ^{a, b}	74.21 \pm 18.94 ^{a, b}	7.90

^a Significant increase compared to baseline ($p \leq 0.05$).

^b Significant increase compared to pre-intervention ($p \leq 0.05$).

FAAM = Foot and Ankle Ability Measure

FAAM-S = Foot and Ankle Ability Measure Sport

MDC = minimal detectable change

Table 4.2: Mean \pm SD and MDC for DF ROM and ankle arthrometry.

Dependent Variable	Baseline	Pre-intervention	Post-intervention	1-week Follow-up	MDC
Maximum DF ROM (cm)	10.87 \pm 3.71	10.83 \pm 3.86	12.18 \pm 3.65 ^{a, b}	12.29 \pm 3.58 ^{a, b}	0.26
Posterior Displacement (mm)	6.81 \pm 1.68	6.82 \pm 1.30	6.76 \pm 2.01	7.10 \pm 1.74	1.05
Posterior Stiffness (N/mm)	20.47 \pm 3.66	20.64 \pm 4.12	23.02 \pm 5.11	21.16 \pm 4.43	1.96
Anterior Displacement (mm)	7.98 \pm 1.89	7.17 \pm 1.79	7.32 \pm 2.18	8.49 \pm 2.33	1.50
Anterior Stiffness (N/mm)	14.67 \pm 3.58	15.98 \pm 4.68	15.72 \pm 4.93	14.85 \pm 4.27	2.44
Inversion Rotation ($^{\circ}$)	24.09 \pm 8.60	20.97 \pm 7.20	22.32 \pm 8.48	23.09 \pm 7.70	4.33
Inversion Stiffness (N*mm/ $^{\circ}$)	171.56 \pm 57.89	185.04 \pm 51.42	179.50 \pm 49.50	172.47 \pm 48.50	37.01

^a Significant increase compared to baseline ($p \leq 0.05$).

^b Significant increase compared to pre-intervention ($p \leq 0.05$).

DF ROM = dorsiflexion range of motion

MDC = minimal detectable change

Table 4.3: Mean \pm SD and MDC for normalized reach distances on the SEBT.

SEBT Direction	Baseline	Pre-intervention	Post-intervention	1-week Follow-up	MDC
Anterior Reach (%)	75.06 \pm 5.19	76.18 \pm 5.76	78.30 \pm 5.63 ^{a,b}	78.71 \pm 4.97 ^{a,b}	1.56
Posteromedial Reach (%)	93.30 \pm 10.37	91.86 \pm 10.33	96.23 \pm 10.95 ^{a,b}	97.47 \pm 11.20 ^{a,b}	3.36
Posterolateral Reach (%)	85.92 \pm 11.97	87.15 \pm 12.60	91.92 \pm 11.15 ^{a,b}	93.09 \pm 12.96 ^{a,b}	4.28

^a Significant increase compared to baseline ($p \leq 0.05$).

^b Significant increase compared to pre-intervention ($p \leq 0.05$).

MDC = minimal detectable change

SEBT = Star Excursion Balance Test

Table 4.4: Mean \pm SD and MDC for eyes open TTB measures.

TTB Measure	Baseline	Pre-intervention	Post-intervention	1-week Follow-up	MDC
Mean TTB Minima AP (s)	4.95 \pm 1.29	4.77 \pm 1.67	5.06 \pm 1.17	5.12 \pm 1.16	0.72
Mean TTB Minima ML (s)	1.82 \pm 0.66	1.77 \pm 0.70	1.86 \pm 0.45	1.83 \pm 0.49	0.30
SD TTB Minima AP (s)	3.31 \pm 1.33	3.29 \pm 1.59	3.11 \pm 0.86	3.11 \pm 0.84	1.05
SD TTB Minima ML (s)	1.47 \pm 0.88	1.47 \pm 0.82	1.55 \pm 0.59	1.40 \pm 0.47	0.53

AP = anteroposterior

MDC = minimal detectable change

ML = mediolateral

SD = standard deviation

TTB = time-to-boundary

Table 4.5: Mean \pm SD and MDC for eyes closed TTB measures.

TTB Measure	Baseline	Pre-intervention	Post-intervention	1-week Follow-up	MDC
Mean TTB Minima AP (s)	2.17 \pm 0.51	2.19 \pm 0.57	2.27 \pm 0.58	2.18 \pm 0.60	0.40
Mean TTB Minima ML (s)	0.83 \pm 0.21	0.81 \pm 0.29	0.79 \pm 0.20	0.84 \pm 0.26	0.20
SD TTB Minima AP (s)	1.37 \pm 0.50	1.40 \pm 0.51	1.46 \pm 0.49	1.41 \pm 0.43	0.39
SD TTB Minima ML (s)	0.73 \pm 0.26	0.64 \pm 0.21	0.65 \pm 0.13	0.71 \pm 0.29	0.25

AP = anteroposterior

MDC = minimal detectable change

ML = mediolateral

SD = standard deviation

TTB = time-to-boundary

Figure 4.1: Study timeline.

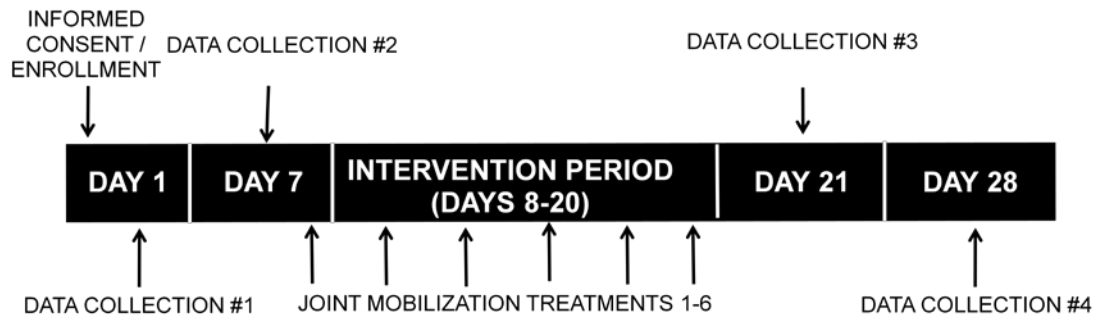


Figure 4.2: Weight-bearing lunge test



Figure 4.3: Ankle/subtalar arthrometric assessment



Figure 4.4: Position for static postural control assessment



Figure 4.5: Star Excursion Balance Test (anterior, posteromedial, posterolateral)



Chapter 5: Effect of Joint Mobilization on Gait Kinematics and Joint Coupling Variability
in Those with Chronic Ankle Instability

Introduction

It is estimated that 23,000 ankle sprains occur daily in the United States with an estimated 4.2 billion dollars spent annually on treatment for these injuries.⁴⁻⁵ In addition to the prevalence and healthcare burden of ankle sprains, up to 40% of individuals who sustain an ankle sprain will develop chronic ankle instability (CAI).¹⁴⁴ CAI is described as the subjective feeling of the ankle ‘giving way’ after an initial ankle sprain and repetitive bouts of instability resulting in numerous ankle sprains.⁸ Several contributing factors for CAI have been identified including alterations in walking and running gait mechanics.^{8, 55, 73} The cyclic transition between loaded (stance) and unloaded (swing) conditions during the gait cycle presents a logical context to examine mechanical and functional alterations which may perpetuate the phenomenon of CAI.

During gait, the mechanism of recurrent ankle sprains is thought to be a combination of a hypersupinated or inverted rearfoot, an externally rotated shank, and decreased ground clearance of the foot during the transition from unloaded to loaded conditions.⁸ Each of these mechanisms has been identified in laboratory investigations which analyzed the walking and running gait kinematics of those with CAI.^{55, 72-73} Alterations have also been demonstrated in ankle, knee, and hip kinematics in the phases of stance and swing related to force absorption and the transition to propulsion.^{31, 35} Additionally, those with CAI have exhibited greater variability in multiple lower extremity joint coupling relationships during terminal swing phase which is indicative of more variable foot position at initial contact.⁵⁵ The amalgamation of these impairments

suggests mechanical and sensorimotor system changes are likely responsible for the gait alterations displayed by those with CAI.

Although several gait alterations have been identified in conjunction with CAI, few studies have examined the effects of therapeutic interventions on gait parameters. Thus far, separate investigations have examined the effect of external bracing orthotics³⁵ and balance training⁷⁷ on rearfoot, shank, or ankle kinematics during walking and running gait. Balance training did improve summary measures of shank-rearfoot coupling coordination; however, neither intervention significantly altered gait kinematics.^{35, 77} This indicates additional interventions should be investigated to address gait alterations in those with CAI.

Interventions which manipulate specific mechanical impairments in ankle arthrokinematics have not been explored. A common arthrokinematic impairment associated with CAI is restrictions in posterior talar glide which results in decreased dorsiflexion.²⁸ Using joint mobilization to increase posterior talar glide may enable a more closed-pack position of the talocrural joint at initial contact enhancing the ability to absorb force and maintain a stable base of support during gait.³¹ Additionally, purposefully freeing distal lower extremity range of motion may also affect function of proximal joints; as well as, influence the coordination between joints and segments as assessed through joint coupling relationships. Therefore, addressing local mechanical impairments could influence global lower extremity function during gait.

Joint mobilization has demonstrated the ability to enhance step width and stance time associated with acute ankle sprains³³; however, the effect of joint mobilization on gait parameters in those with CAI has not been explored. Joint mobilization has increased

dorsiflexion range of motion, posterior talar glide, and instrumented measures of static postural control when applied to individuals with CAI.²⁷⁻²⁸ It is unknown if these mechanical and sensorimotor benefits of joint mobilization would contribute to changes in gait in individuals with CAI.²⁷ Therefore, the purpose of this study is to examine the effect of a 2-wk joint mobilization intervention on the kinematics and joint coupling variability patterns of the rearfoot, shank, ankle, knee, and hip throughout the walking and running gait cycle in those with CAI.

Methods

Design

This investigation employed a prospective cohort design. The independent variable was time (baseline, pre-intervention, post intervention, 1-wk follow-up). The dependent variables were lower extremity kinematics and joint coupling variability relationships. Subjects reported to the research laboratory for 4 separate testing sessions and 6 joint mobilization treatments across a 4-wk period to complete the study.

Subjects

Twelve subjects with self-reported CAI (6 M, 6 F; age = 27.4 ± 4.3 years; height = 175.4 ± 9.78 cm; mass = 78.4 ± 11.0 kg) volunteered to participate in the study. Subjects were recruited using advertisements posted throughout a large university over a 4 month period. To be included in the study subjects reported a history of at least one ankle sprain. Additionally, subjects had to report at least two episodes of “giving way” within the past 3 months. This was quantified by answering “yes” to question 1 and for a total of at least 4 questions on the Ankle Instability Instrument.¹²² An ankle sprain was defined as an incident in which the rearfoot was inverted or supinated and resulted in a combination of

swelling, pain, and time lost or modification of normal function for at least one day.⁸ An episode of giving way was described as an incident in which the rearfoot suddenly rolled, felt weak, or lost stability; however, the individual did not sustain an ankle sprain and was able to continue with normal function.⁸ Subjects also had to report functional loss as a result of their ankle sprain history by reporting disability scores of $\leq 90\%$ on the Foot and Ankle Ability Measure (FAAM) and a score of $\leq 80\%$ on the FAAM Sport Scale.¹²⁵ In the event subjects reported a bilateral history of ankle sprains, the limb with the greatest reported functional loss on the FAAM was included in the study. Subjects reported an average of 5.3 ± 5.5 total ankle sprains. The average number of episodes of giving way over the previous 3 months was 8.4 ± 7.4 . The average baseline FAAM score was $77.99 \pm 13.11\%$ and the average FAAM Sport score was $56.25 \pm 14.72\%$. Exclusion criteria consisted of the subject reporting an acute ankle sprain within the past 6 wks, a previous history of lower extremity surgeries or fracture, other lower extremity injuries within the past 6 months that resulted in time lost or modification of normal function for at least one day, and other health conditions known to affect balance. Prior to participation, all subjects provided written informed consent in compliance with the institutional review board.

Instrumentation and Data Capture

To assist in accurately placing the retroreflective markers used for three-dimensional motion analysis, all participants were barefoot, wore close-fitting shorts, and females wore tank tops and males wore no tops. A total of 50, 10 mm retroreflective spherical markers were placed on subjects using adhesive tape over specific landmarks on the lower extremities (Appendix A) using a modified marker set adapted from Pohl et

al.¹²⁸ Subjects performed barefoot walking and running, during which the three-dimensional kinematics of the markers were recorded at 100 Hz using 15 Eagle motion capture cameras and Cortex v1.0 software (Motion Analysis Corporation, Santa Rosa, CA, USA). The cameras were positioned in a circle around a dual belt treadmill customized with embedded forceplates (Model TM-09-P, Bertec Corp; Columbus, OH, USA) which provided standardized gait speeds, ground reaction forces, and instants of heel strike and toe off. Kinetic data were sampled at 500 Hz and were recorded using Cortex software. The motion analysis system was calibrated using the seed, wand, and floor method of the Cortex software prior to each data collection session.

Procedures

After being included into the study, subjects participated in the first data collection session (baseline). Following the baseline session, subjects were instructed to maintain normal physical activity and activities of daily living and report back to the laboratory in 1 wk for the second data collection session (pre-intervention). Immediately following the pre-intervention session, subjects received their first joint mobilization treatment and returned to the laboratory for 5 additional joint mobilization treatments over the next 2 wks. Subject underwent the third data collection session (post-intervention) within 1-2 days following the final joint mobilization treatment. After another wk, 1-wk follow-up data were collected. During each data collection session, 3-dimensional walking and running gait parameters were captured.

After being outfitted with retroreflective markers, a static trial was recorded in which subjects stood in the anatomic position with their feet positioned shoulder width apart. All subjects completed a warm-up and performed a 10-min walk at speeds which

were gradually increased from 0.5 to 1.32 m/s to allow subjects to adjust to the treadmill before data collection. A walking and running trial was recorded with the option of rest in between. For walking trials, once the target speed of 1.32 m/s was achieved and maintained for 1 min, a 30 s trial was recorded. For running trials, subjects were gradually progressed from a walking to a running speed of 2.64 m/s and a 30 s trial was recorded after at least 1 min of running.

Data Reduction

From the 30 seconds of data capture, approximately 20 strides of the involved limb were available for walking and 40 strides of the involved limb were available for running. From the available walking and running strides, mean ensemble curves were created for each variable of interest along with confidence intervals of 2 standard deviations. Strides which contained data points for any of the 6 kinematics variables that were outside the confidence interval were removed from analysis. Upon removal of all outliers, the first 5 nonconsecutive strides for walking and running in which all kinematics variables were available were entered into the analysis. Each stride was resampled to 101 frames to represent each percent of stride. This was done individually for each subject using a force plate threshold of 30 N to identify initial contact for each limb. Stride selection and the interpolation to 101 frames were completed through a custom program in Matlab 7.9.0 (Mathworks Inc, Natick, MA). One subject was unable to perform the running protocol and was omitted from running analyses. For each subject, a reference angle for each kinematic variable of interest was determined from the recorded static trial and was subtracted from the angles recorded during walking and running.^{55, 72} Data were smoothed using a 2nd-order Butterworth filter with a cut-off

frequency of 6 Hz which was determined by visually inspecting the raw data against the data at different cut-off frequencies.

Kinematic variables included 3-dimensional angles for 1) rearfoot inversion-eversion, 2) shank internal-external rotation, 3) ankle plantar flexion-dorsiflexion, 4) knee flexion-extension, 5) hip flexion-extension, 6) and hip abduction-adduction and were defined based on the anatomic locations of retro-reflective markers (Appendix B). Using vector-coding assessment techniques⁸³, the joint coupling variability of 1) shank internal-external rotation and rearfoot inversion-eversion, 2) knee flexion-extension and ankle plantar flexion-dorsiflexion, 3) knee flexion-extension and shank internal-external rotation, 4) hip abduction-adduction and rearfoot inversion-eversion, 5) hip flexion-extension and ankle plantar flexion-dorsiflexion, and 6) hip flexion-extension and knee flexion-extension angle-angle was determined. This technique quantifies the variability in vector angles and magnitudes between each consecutive point on an angle-angle plot across multiple strides.⁸³ The calculation is the same as Tepavac and Field-Fote's⁸³, which is based on circular statistics and corrects for trial size, but the coefficient has been reversed to present a range from 0 (no variability) to 1 (maximum variability) for each consecutive point-to-point vector.⁸⁵ Therefore, a vector coding coefficient was analyzed for each percent of stride. Additionally, the average of the vector coding coefficients for the entire stride (VCoverall) was calculated to provide a summary measure for each joint coupling relationship.

Joint Mobilization Intervention

The joint mobilization intervention consisted of 6 separate visits to the laboratory in which each subject received 2, 2-min sets of Maitland Grade II talocrural joint traction

and 4, 2-min sets of Maitland Grade III talocrural joint mobilization with 1 min of rest between sets. Traction was employed to distract the talus from the ankle mortise to promote posterior gliding of the talus for the joint mobilization treatments. The joint mobilization technique consisted of stabilizing the distal tibia and fibula and mobilizing the talus in an anterior-to-posterior direction. The joint mobilization was operationally defined as large-amplitude, 1-s rhythmic oscillations from the joint's mid-range to end range with translation taken to tissue resistance.^{56, 107} Compliance was 100%, meaning all subjects received all treatments within the designated treatment period. Each subject received an average of 1251 ± 40 oscillations over the 6 treatment periods. A grade III joint mobilization was selected in an attempt to increase the posterior capsular endpoint and provide stimulation of articular mechanoreceptors from oscillations which span the length of the available accessory motion. All joint mobilization treatments were conducted by the same Certified Athletic Trainer with 5 years of experience.

Statistical Analysis

To determine meaningful changes in lower extremity kinematics and joint coupling relationships, a curve analysis^{55, 72} using the mean \pm SE for each of the 101 data points were calculated across the entire stride (0% representing initial contact, 100% representing the point on the same limb prior to initial contact). Initial differences following the joint mobilization intervention were determined as at least 5 consecutive points where the SE for either the post-intervention or 1-wk follow-up measures did not overlap with either the baseline or pre-intervention measures. In the presence of non-overlapping points, the mean was calculated across the points for all measurement intervals of each subject. Time effects for differences in gait parameters as well as the

VOverall for each joint coupling relationship were examined using a 1-way ANOVA. Post-hoc comparisons were made in the presence of a time effect using Fisher's LSD. For all analyses the level of significance was set *a priori* at $p \leq 0.05$. No correction for multiple comparisons were performed on the alpha level to protect against making a type II error.¹²⁹ Instead, effect sizes (ES) were calculated based on the mean and pooled standard deviation using a bias-corrected *Hedge's g* with corresponding 95% confidence intervals (CI).¹³⁰ For all analyses, ES were interpreted as weak (0 – 0.39), moderate (0.40 – 0.69) and strong (≥ 0.70).¹³¹ All statistical analyses were conducted using Microsoft Excel 2007 (Redmond, WA, USA) and PASW version 18.0 (Chicago, IL, USA).

Results

No significant differences were detected in any walking or running kinematics variables over time. Additionally, no significant differences were detected in any walking or running joint coupling variability patterns or in the VOverall of any joint coupling relationships over time (Tables 5.1-5.2). Visual representations of all walking and running kinematics and joint coupling variability patterns are displayed in Appendix D.

Discussion

We hypothesized that purposefully freeing distal lower extremity range of motion using talocrural joint mobilization would have an effect on lower extremity kinematics and the joint coupling variability during walking and running. However, the results of this study determined that the 2-wk joint mobilization intervention did not significantly alter any walking or running kinematics or joint coupling variability patterns in this cohort of individuals with CAI. This conclusion is based on the overlapping SE intervals associated with the mean ensemble curves across each measurement interval for each kinematic

variable and joint coupling relationship in both walking and running. The lack of change in walking and running gait parameters indicates that the joint mobilization did not have a positive or a negative influence on this aspect of function which implies the intervention did not exacerbate the previously identified gait deviations in those with CAI.

Although this study did not identify any gait changes following the intervention, the concurrent study which used the same subjects identified significant improvements in self-reported function assessed by the FAAM and the FAAM-S, weight-bearing dorsiflexion range of motion assessed through the weight-bearing lunge test, and sensorimotor function as indicated by increased reach distances in the SEBT following the joint mobilization intervention. However, these functional alterations did not translate into changes in gait. The lack of change in gait following the intervention is an indication that the improvements induced by joint mobilization did not have a large enough effect to change gait behavior or the joint mobilization intervention did not address the underlying sources of gait deviation in those with CAI.

Those with CAI have demonstrated dorsiflexion deficits in the fully loaded periods of the stance phase.³¹ Drewes et al.³¹ hypothesized that joint mobilization techniques targeting restrictions in posterior non-contractile tissues of the talocrural joint may address this specific gait deviation. In light of that report, we employed a Maitland Grade III joint mobilization intervention with the aim of increasing posterior talar glide and dorsiflexion range of motion in this study.^{27, 102} However, no changes were displayed in ankle sagittal plane kinematics during walking or running gait following the joint mobilization intervention. The lack of change in dorsiflexion during gait was surprising based on the increase in the weight-bearing dorsiflexion identified in the concurrent study,

and the strong correlation previously identified between peak dorsiflexion during gait and performance on the weight-bearing lunge test.⁹⁸ The strong correlation identified between peak dorsiflexion during gait and the weight-bearing lunge test was in healthy adults⁹⁸ and this study may provide preliminary evidence that the same correlation is not present in those with CAI. It is possible that the relationship between weight-bearing measures of dorsiflexion and maximal dorsiflexion during gait have a non-linear relationship and the 5° increase in dorsiflexion range of motion exhibited in the concurrent study was not enough to significantly impact gait function.

In addition to no changes in ankle kinematics, no changes were identified in kinematics of the hip, knee, shank, or rearfoot. The cohort of individuals with CAI included in this study demonstrated consistent patterns during walking and running for all kinematic variables with relatively small SEs between the baseline and pre-intervention measures. Consistency at baseline and the narrow SE confidence intervals suggest that the lack of gait changes exhibited in this study is likely because no alterations occurred in gait behavior and not because the instrumentation, data reduction, and data analysis techniques were unable to detect changes if they were present.

No differences were identified in any of the vector coding curve analyses or summary measures used in this study. The regions of the gait cycle that were associated with greater vector coding coefficients were consistent across days, regardless of the intervention. Consistency in vector coding coefficients implies the sensorimotor organization of the lower extremity during gait remained constant across all measurement intervals and was not positively or negatively influenced by the intervention. Based on the results from Chapter 3 and Drewes et al.⁵⁵, those with CAI have demonstrated

increased coordination variability in multiple coupling relationships particularly around the transition from an unloaded condition to a loaded condition. It was evident the joint mobilization intervention did not have an effect on this aspect of joint coupling variability in this study.

The lack of change in joint kinematics and joint coupling variability indicates the joint mobilization did not change movement solution variability during gait. This conclusion is based on examining multiple local representations of joint coupling variability which when examined collectively suggest that there were no global changes in sensorimotor system organization during walking and running. This provides evidence that the gait deviations experienced by those with CAI may be preferred patterns in behavior which exhibit little flexibility and are resistant to change. The joint mobilization intervention used in this study attempted to passively alter gait behavior by manipulating the structure of the ankle and local afferent activity. It may be that active interventions which require a greater level of engagement by the patient and purposefully manipulate organismic, task, and environmental constraints are required to generate change in these preferred patterns of gait behavior. Therefore, coupling passive interventions such as joint mobilization with active interventions may be needed to change this aspect of function.

It is unknown how joint mobilization might benefit those with CAI when combined with other strategies designed to enhance joint coupling variability during the unloaded-loaded transition during gait. Following balance training, those with CAI demonstrated no changes in rearfoot or shank gait kinematics; however, summary measures of rearfoot-shank coupling variability indicated an overall decrease in joint coupling variability following balance training.⁷⁷ In that study, the decreased summary

measure of joint coupling variability was interpreted as an overall more stable relationship between the rearfoot and shank.⁷⁷ Therefore, a synergizing effect may be present when combining rehabilitation techniques such as balance training and joint mobilization which may have an impact on joint coupling variability and sensorimotor function during gait for those with CAI.

Limitations and Future Directions

In this study, we did not specifically include individuals with CAI who demonstrated a minimal dorsiflexion asymmetry. Instead, we included individuals who had CAI with any combination of mechanical or functional instabilities. Therefore, the results from this study cannot be directly generalized to individuals with a specific dorsiflexion deficit. This may be a subset of those with CAI for whom joint mobilization might be optimal which should be systematically investigated in the future. Based on the results of the concurrent and previous studies²⁷, joint mobilization has the capacity to improve multiple aspects of function. It may be that changes in gait are not as important as changes in other measures. However, we currently don't have a complete understanding of this phenomenon as this study is the first to investigate these trends in this way.

Another limitation is that the findings from this study can only be applied to barefoot treadmill walking and jogging at a constant speed. It is important to note that while no differences were found in this study, the results should not be generalized to the 3-dimensional kinematics of all types of functional activities for those with CAI. Based on significant changes in self-reported function in the concurrent study, there may be functional benefits that might be captured with other types of activities following joint

mobilization. The subjects of this study reported the lowest levels of function related to jump landing and cutting activities on the FAAM-S with fairly uniform improvements in all sports related activities following the intervention. Examining jump landings and cutting activities may bring about the demands that typically manifest decreases in function. Future studies should explore the effect of joint mobilization on other function activities that may be of interest in those with CAI.

The gait deviations in proximal and distal lower extremity kinematics and joint coupling variability previously identified in those with CAI are thought to originate from a combination of mechanical and sensorimotor alterations.⁵⁵ The large array of impairments diffuses the ability to draw unambiguous conclusions regarding the exact underpinnings of the gait deviations common to all individuals with CAI. The lack of clarity in the origin of gait alterations is compounded by the repetitive nature of gait which likely creates a less flexible behavior to manipulate in individuals who present with this chronic condition. This is evident by the lack of changes in gait demonstrated in those with CAI following a balance training intervention⁷⁷, the application of external bracing orthotics³⁵, or the joint mobilization intervention in this study. While all of these studies utilized different approaches to modify gait, none of the studies had an immense positive or negative effect on the gait parameters exhibited by those with CAI. From this perspective, future research is required which can further identify the underlying sources of gait deviation and the appropriate clinical interventions to restore gait function.

While it was apparent the intervention used in this study had no effect on gait, it did have a positive effect on other aspects of function. The findings from the concurrent study indicate that the volume and dosage of joint mobilization was appropriate for

eliciting improvements in dorsiflexion range of motion, Star Excursion Balance Test reach distances, and self-reported function; however, the optimal volume and dosage associated with joint mobilization is unknown. In future studies, a more robust intervention associated with a longer treatment period and a greater amount of oscillations may be required to elicit changes in gait. However, it is more likely that joint mobilization will need to be combined with other interventions which improve global aspects of sensorimotor function or the neuromuscular properties of the hip, core, and ankle stabilizers to successfully address the gait deviations exhibited by those with CAI. This integrated approach to using joint mobilization is more characteristic of clinical practice and may elucidate additional considerations for the place of joint mobilization in the rehabilitation for those with CAI.

Conclusion

The 2-wk joint mobilization intervention which targeted the extensibility of the posterior ankle noncontractile structures resulted in no significant changes in hip, knee, ankle, shank, or rearfoot kinematics or joint coupling variability patterns during walking or running gait in those with CAI. No changes in walking or running gait parameters indicate the intervention did not negatively affect this aspect of function. By addressing local mechanical impairments in ankle function, the joint mobilization intervention did not successfully enhance laboratory-oriented measures of gait in those with CAI.

Table 5.1: Mean \pm SD for the average vector coding coefficients of the walking stride.

Joint-Coupling Relationship	Baseline	Pre-intervention	Post-intervention	1-wk Follow-up	p-value
Hip (Sagittal Plane)-Ankle	0.20 \pm 0.03	0.19 \pm 0.03	0.19 \pm 0.02	0.20 \pm 0.03	0.68
Hip (Sagittal Plane)-Knee	0.27 \pm 0.04	0.26 \pm 0.04	0.25 \pm 0.03	0.28 \pm 0.07	0.39
Hip (Frontal Plane)-Rearfoot	0.43 \pm 0.06	0.41 \pm 0.04	0.45 \pm 0.05	0.43 \pm 0.05	0.06
Knee-Ankle	0.19 \pm 0.04	0.19 \pm 0.04	0.20 \pm 0.03	0.21 \pm 0.04	0.46
Knee-Shank	0.26 \pm 0.03	0.26 \pm 0.03	0.26 \pm 0.04	0.27 \pm 0.04	0.59
Shank-Rearfoot	0.46 \pm 0.05	0.44 \pm 0.05	0.47 \pm 0.06	0.45 \pm 0.05	0.42

Table 5.2: Mean \pm SD for the average vector coding coefficient of the running stride.

Joint Coupling Relationship	Baseline	Pre-intervention	Post-intervention	1-week Follow-up	p-value
Hip (Sagittal Plane)-Ankle	0.18 \pm 0.03	0.18 \pm 0.03	0.17 \pm 0.03	0.17 \pm 0.03	0.28
Hip (Sagittal Plane)-Knee	0.24 \pm 0.03	0.23 \pm 0.03	0.22 \pm 0.03	0.21 \pm 0.03	0.08
Hip (Frontal Plane)-Rearfoot	0.40 \pm 0.09	0.39 \pm 0.06	0.39 \pm 0.05	0.41 \pm 0.06	0.85
Knee-Ankle	0.15 \pm 0.02	0.15 \pm 0.03	0.15 \pm 0.03	0.15 \pm 0.02	0.92
Knee-Shank	0.21 \pm 0.03	0.21 \pm 0.02	0.21 \pm 0.04	0.21 \pm 0.03	0.97
Shank-Rearfoot	0.40 \pm 0.07	0.38 \pm 0.08	0.41 \pm 0.09	0.40 \pm 0.06	0.64

Chapter 6: Summary

The purposes of this dissertation were to examine lower extremity gait kinematics and joint coupling variability in those with CAI compared to those without CAI; as well as, examine the effect of a 2-wk talocrural joint mobilization intervention on self-reported function measured by the Foot and Ankle Ability Measure (FAAM) and Foot and Ankle Ability Measure Sport (FAAM-S), measures of ankle arthrokinematics with an instrumented arthrometer, DF ROM measured on the weight-bearing lunge test (WBLT), static and dynamic postural control assessed by TTB measures and the SEBT, and walking and running gait parameters captured with 3-dimensional motion analysis. To summarize the findings, the hypotheses from Chapter 1 are revisited.

Hypothesis for Specific Aim 1: Those with CAI will demonstrate kinematic differences in rearfoot, shank, and ankle motion; as well as, different shank-rearfoot coupling variability patterns during walking and running gait when compared to the group without CAI.

Finding: It was confirmed that those with CAI exhibited greater rearfoot inversion during stance phase and greater shank external rotation during terminal swing. While the CAI group demonstrated trends which suggested they had less dorsiflexion in stance and terminal swing, these differences fell outside the level of significance. It was not confirmed in this study that those with CAI demonstrated differences in the shank-rearfoot coupling relationship compared to health subjects. Other findings from this investigation were that those with CAI exhibited less hip and knee flexion in the time leading up to initial contact and that those with CAI demonstrated greater coupling variability in terminal stance in several coupling relationships which indicates that their

behavior when approaching initial contact may be less stable than a healthy subject.

Hypotheses for Specific Aim 2:

Hypothesis 1: Following the 2-week talocrural joint mobilization intervention subjects will demonstrate significant improvements in patient-oriented measures of function as indicated by FAAM and FAAM-S scores.

Finding: This hypothesis was confirmed as the cohort of individuals with CAI in this study demonstrated a significant increase in their post-intervention and 1-wk follow-up FAAM and FAAM-S scores compared to baseline and pre-intervention scores.

Hypothesis 2: Following the 2-week talocrural joint mobilization intervention subjects will demonstrate significant improvements in clinically-oriented measures of function as indicated by increased DF ROM, increased posterior talar glide, and increased reach distances on the SEBT.

Finding: This hypothesis was confirmed in 2 of 3 clinician-oriented measures of function as the cohort of individuals with CAI in this study demonstrated significant improvements in DF ROM and the anterior, PM, and PL reach directions of the SEBT in the post-intervention and 1-wk follow-up measures compared to baseline and pre-intervention measures. This hypothesis was not confirmed in any measures of instrumented ankle arthrometry as no changes were detected before or after the joint mobilization intervention.

Hypothesis 3: Following the 2-week talocrural joint mobilization intervention subjects will demonstrate significant improvements in laboratory-oriented measures of function as indicated by significant improvements in TTB measurements.

Finding: This hypothesis was not confirmed as the individuals in this study demonstrated

no significant changes in any measures of TTB postural control magnitude or variability before or after the joint mobilization intervention.

Hypothesis for Specific Aim 3: Joint mobilizations will result in alterations of various gait parameters such as DF ROM, rearfoot inversion, and joint coupling relationships of the lower extremity.

Finding: No changes were observed in any kinematic or joint coupling variability gait parameters at the ankle, knee, or hip before or after the joint mobilization intervention.

Synthesis and Application of Results

The first study of this dissertation enhanced the previous knowledge associated with the gait deviations associated with CAI by examining both distal and proximal lower extremity joints during walking and running and also providing a comprehensive exploration of joint coupling variability patterns through multiple joint coupling comparisons. The results of this study determined that those with CAI experience proximal and distal kinematic alterations which have implications for force absorption, limb placement, and maintaining a base of support. It was also determined that those with CAI experience subtle differences in joint coupling variability particularly around the transition from unloaded to loaded conditions in walking and running which has implications for the precision and stability of motor behavior during limb placement at initial contact. This study provides evidence of concurrent changes in functional capacity and movement solution variability which provides a foundation for examining changes in self-reported function, lower extremity kinematics, and global changes in sensorimotor system function during gait following the application of an intervention.

To systematically evaluate the effects of multiple joint mobilization treatments in

those with CAI, this study used patient-, clinician-, and laboratory-oriented measures (PCL Model) to capture function at the level of the person in their environment, as well as, local and global impairments in range of motion and sensorimotor system function. In these studies, the PCL Model provided a rich basis to explore the interaction of different types of evidence on the overall effectiveness of the intervention. Without applying each component of the PCL Model, clinicians and researchers are left to speculate on the patient's perception of the intervention, clinical indicators that may be associated with positive or negative results, or ways to refine the types of laboratory methods used to examine future interventions. The results of this study indicate that multiple bouts of joint mobilization had specific benefits related to patient-oriented and clinician-oriented outcomes associated with CAI; however, the joint mobilization intervention did not significantly change laboratory-oriented outcomes associated with CAI. Overall, this study provides evidence that manipulating local ankle function through multiple joint mobilization treatments is beneficial for those with CAI.

The most important finding of this study was the increase in self-reported function following the joint mobilization intervention. This study included individuals with CAI who may have had any combination of different mechanical or functional instabilities. However, one common trend across the included cohort was decreased levels of functional capacity from both an activities of daily living and sports perspective. Increases in self-reported function may have been related to specific mechanical and/ or functional improvements identified following the intervention; however, it is likely that the intervention changed self-reported function based on the individual needs of each subject and possibly for reasons that were not examined in this study. Regardless of the

exact mechanism, this study provides patient-oriented evidence that multiple joint mobilization treatments can provide at least short-term improvements in health related quality of life for those with CAI.

Following the joint mobilization intervention, weight-bearing DF ROM was significantly increased compared to the pre-intervention measures. This finding supports one of the most common usages of joint mobilization which is to increase osteokinematic range of motion by manipulating the agonist arthrokinematic range of motion. The precise mechanism by which DF ROM increased in this study can only be hypothesized because no changes were identified in instrumented measures of posterior talar glide. Based on the available evidence¹⁴⁰⁻¹⁴¹ it appears the relationship between measures of weight-bearing dorsiflexion and non-weight-bearing posterior talar glide is weak. Future studies which evaluate weight-bearing posterior talar glide may be able to provide a more comprehensive understanding of this relationship.

This study identified significantly greater SEBT reach distances; however, no changes were demonstrated in the magnitude or variability of TTB measures following the joint mobilization intervention. These findings indicate the intervention created improvements in the ability to incorporate additional mechanical degrees of freedom into motor strategies on the SEBT and that multiple joint mobilization did most likely not create any enduring or long lasting changes in somatosensory function that would influence TTB. Potentially, multiple joint mobilization treatments may decrease the overall constraint experienced by the sensorimotor system from a mechanical perspective; however, it appears the utility of this modality to influence sensory input requires additional investigation. Examining the windows in which joint mobilization does

stimulate sensory input may further enhance the optimal parameters for the application of joint mobilization when combined with other rehabilitation techniques in the clinical setting.

No changes were identified in any of the 3-dimensional analyses of gait parameters in this study. While the joint mobilization intervention did not improve gait kinematics or joint coupling variability, the intervention did not exacerbate any of the previously identified gait deviations in those with CAI. These findings suggest that to alter gait a longer or more intensive joint mobilization intervention may be required, joint mobilization may need to be integrated with other active rehabilitation strategies, or the underlying impairments which alter gait need additional consideration. Although no changes in gait kinematics were identified, the effect of joint mobilization on jump landing and cutting maneuver kinematics should be systemically investigated in the future as these activities were identified with the greatest amount of self-reported disability in the individuals in this study.

The studies presented in this dissertation provided interesting insights into the relationship between functional capacity and movement solution variability. In Chapter 3 there was evidence of decreased functional capacity and alterations in movement solution variability measured through joint coupling variability in walking and running gait. However, Chapters 4 and 5 demonstrated evidence of increased functional capacity and no changes in movement solution variability beyond those associated with increased reach distances on the SEBT. This indicates the measures of gait and postural control used in these studies may have examined different aspects of movement solution variability. Additionally, the disparity in these measures support the idea that functional

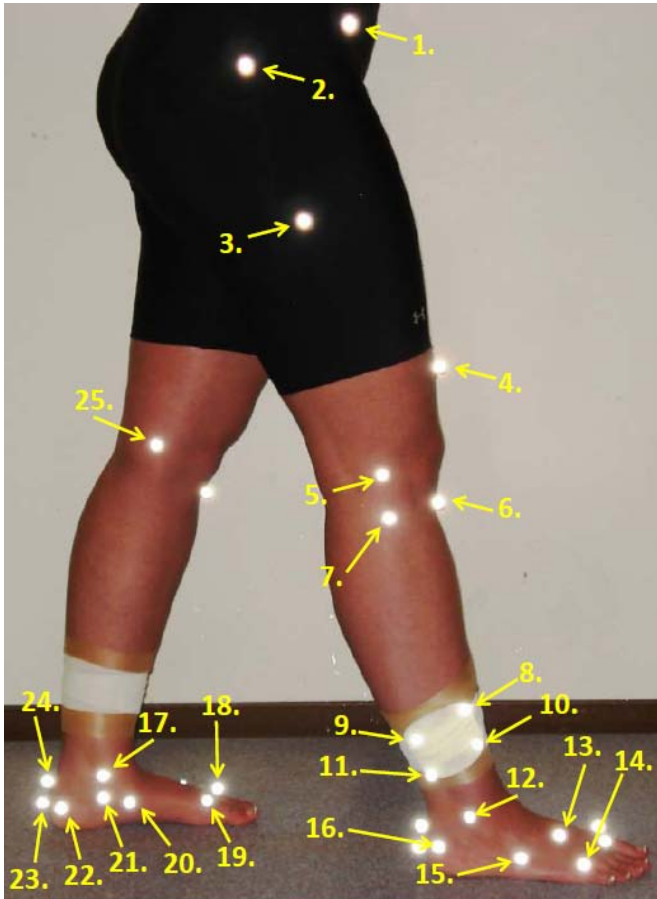
capacity and aspects of movement solution variability may have a nonlinear relationship. This nonlinear relationship means that increases in functional capacity may not be associated with immediate or equal changes in movement solution variability. Although no changes in movement solution variability were identified 1-wk following the intervention in static postural control or joint coupling variability during gait, it may take a longer to re-integrate freed degrees of freedom as a result of the intervention into the available movement solutions for a given task. Therefore, re-examining these subjects in the future may have afforded a different understanding of sensorimotor system organization in response to certain therapeutic interventions. Although the methods of examining movement solution variability in these studies have successfully discriminated between those with and without CAI, the intervention may have affected aspects of sensorimotor system function that were not examined. Providing a more comprehensive analysis of the tasks or activities associated with CAI-related disability may provide insight into the most appropriate ways to examine movement solution variability in the future.

In conclusion, multiple treatments of Maitland Grade III anterior-to-posterior talar glide joint mobilization significantly increased self-reported function, DF ROM, and dynamic postural control. No changes were detected in static postural control, instrumented ankle arthrometry, or gait parameters following the intervention. Based on these results, I recommend using joint mobilization in the rehabilitation of those with CAI because this modality produced specific therapeutic benefits which in the least resulted in no deleterious changes in the aspects of function evaluated in this study. Because this study is the first to examine this intervention in those with CAI, the overall

recommendation for incorporating this intervention strategy into clinical practice would be greatly strengthened by external validation of the results in future investigations.

Finally, the results of this study advocate for future investigation of the effects of joint mobilization on longitudinal outcomes including self-reported function, incidences of instability, and recurrent sprains as this treatment is systematically integrated with other rehabilitation techniques for those with CAI.

Appendix A



*Posterior Superior Iliac Spine
marker not shown

1. Anterior Superior Iliac Spine

2. Greater Trochanter

3. Thigh

4. Thigh Offset

5. Lateral Femoral Condyle

6. Tibial Tuberosity

7. Fibular Head

8. Anterior-Superior Shank

9. Posterior Superior Shank

10. Anterior Inferior Shank

11. Posterior Inferior Shank

12. Lateral Malleolus

13. Foot Offset

14. Head of 5th Metatarsal

15. Base of 5th Metatarsal

16. Lateral Calcaneus

17. Medial Malleolus

18. Head of 2nd Metatarsal

19. Head of 1st Metatarsal

20. Navicular Tuberosity

21. Sustentaculum Tali

22. Medial Calcaneus

23. Inferior Calcaneus

24. Superior Calcaneus

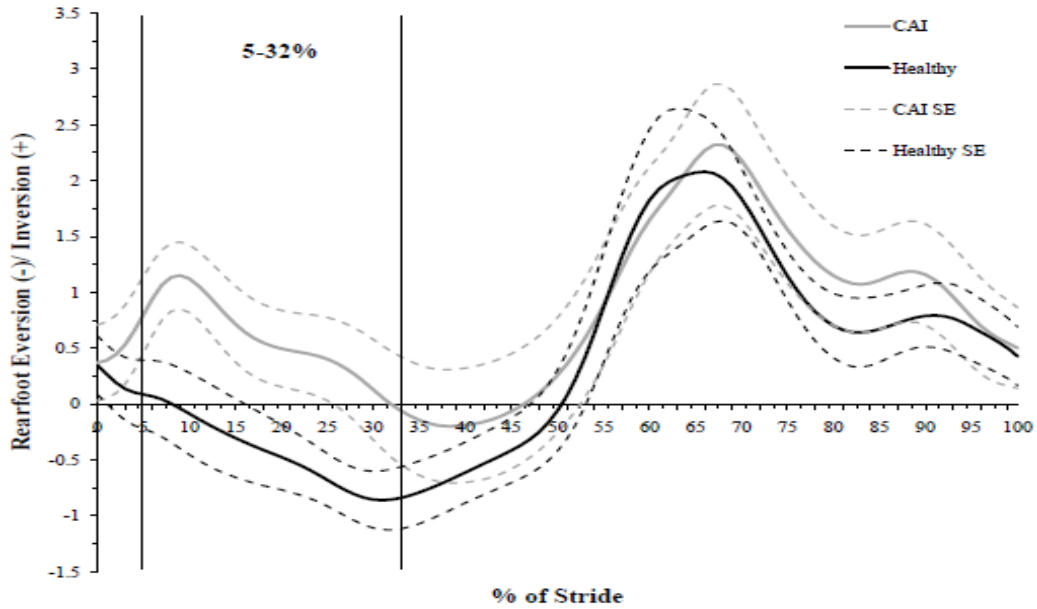
25. Medial Femoral Condyle

Appendix B

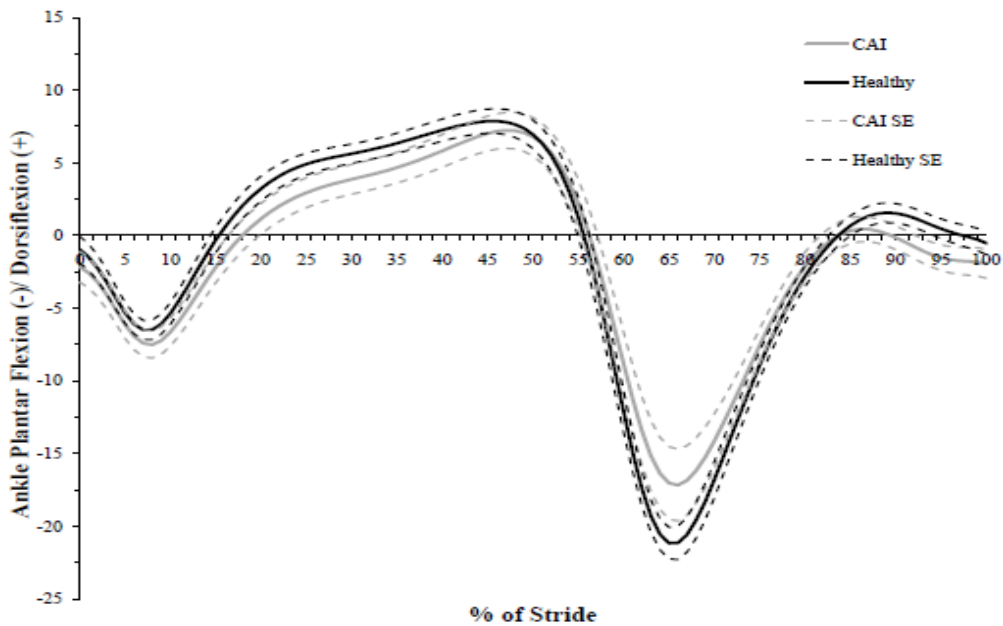
Kinematic Variable	Marker 1	Marker 2	Marker 3	Marker 4
Rearfoot Inversion-Eversion	Medial Calcaneous	Lateral Calcaneous	Lateral Malleolus	Medial Malleolus
Ankle Dorsiflexion-Plantar Flexion	Lateral Femoral Condyle	Lateral Malleolus	Head of 2 nd Metatarsal	----
Shank Internal-External Rotation	Lateral Femoral Condyle	Medial Femoral Condyle	Anterior Inferior Shank	Posterior Inferior Shank
Knee Flexion-Extension	Greater Trochanter	Lateral Femoral Condyle	Lateral Malleolus	----
Hip Flexion-Extension	Anterior Superior Iliac Spine	Greater Trochanter	Lateral Femoral Condyle	----
Hip Abduction-Adduction	Anterior Superior Iliac Spine	Greater Trochanter	Lateral Femoral Condyle	----

Appendix C

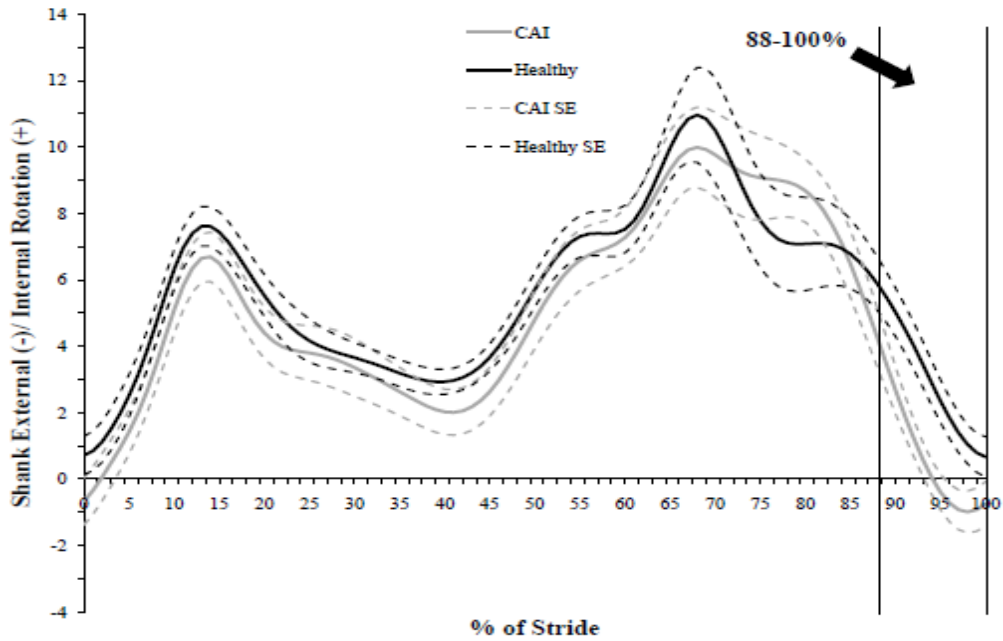
Rearfoot inversion-eversion walking kinematics. Positive values represent inversion and negative values represent eversion. Those with CAI were more inverted from 5-34%.



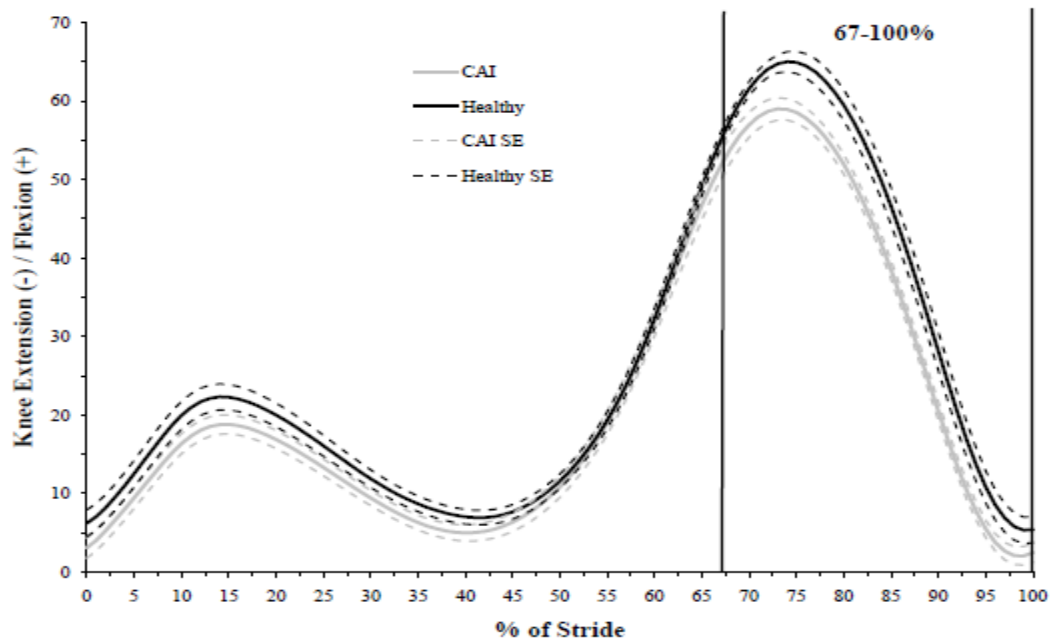
Ankle plantar flexion–dorsiflexion walking kinematics. Positive values represent dorsiflexion and negative values represent plantar flexion.



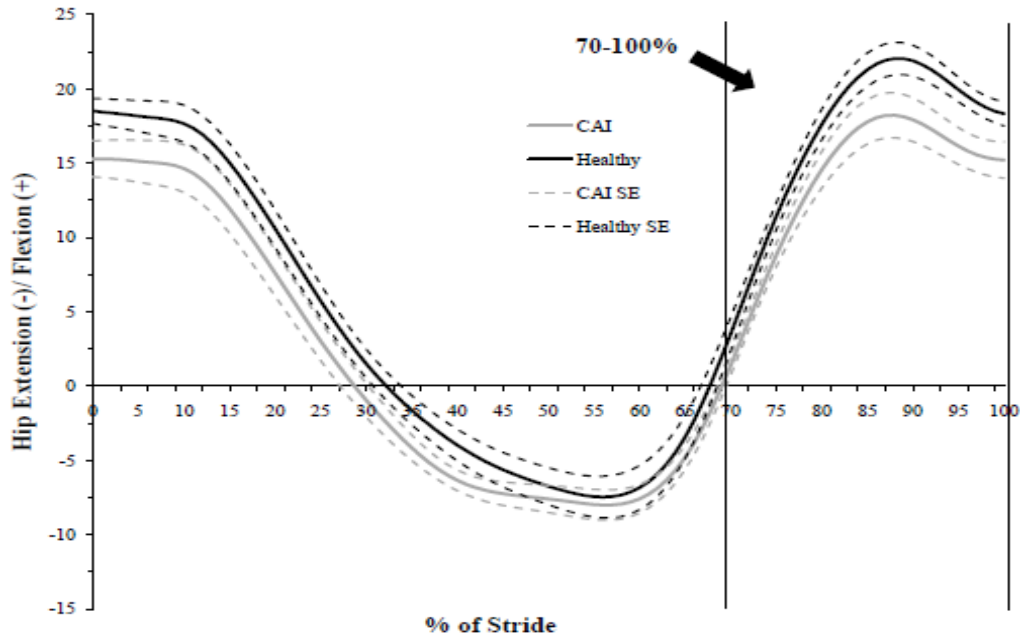
Shank rotation walking kinematics. Positive values represent internal rotation and negative values represent external rotation. Those with CAI were more externally rotated during terminal swing.



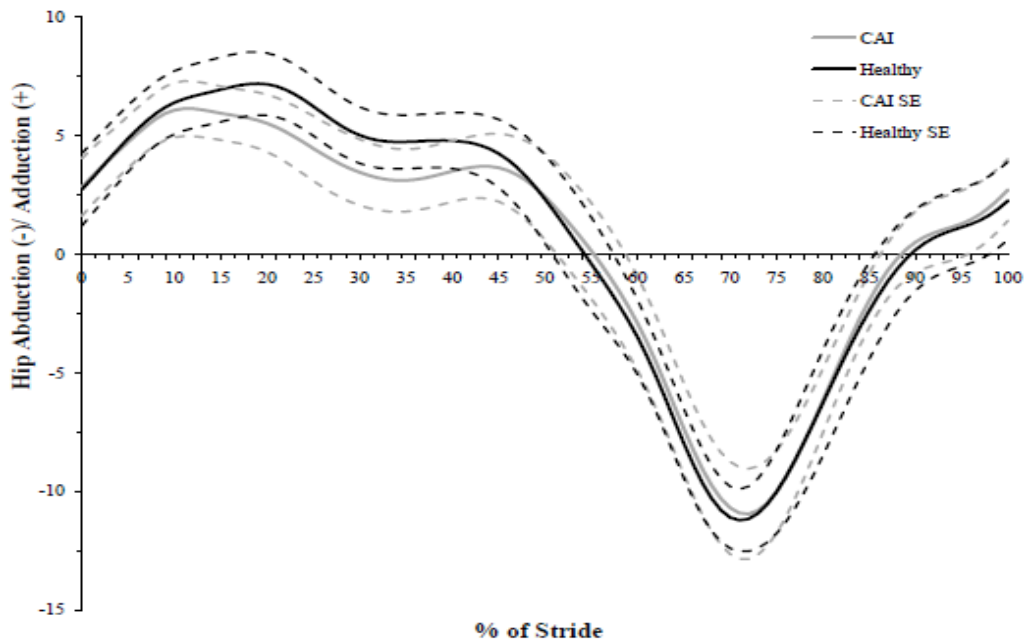
Knee flexion–extension walking kinematics. Positive values represent flexion and negative values represent extension. Those with CAI were more extended in swing.



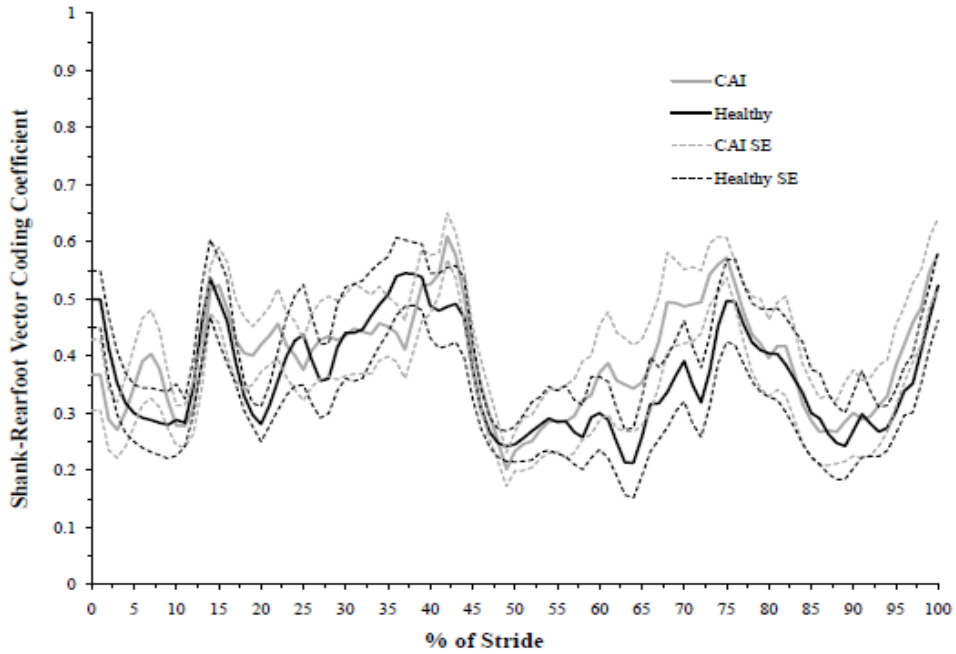
Hip flexion–extension walking kinematics. Positive values represent flexion and negative values represent extension. Those with CAI were more extended in swing phase.



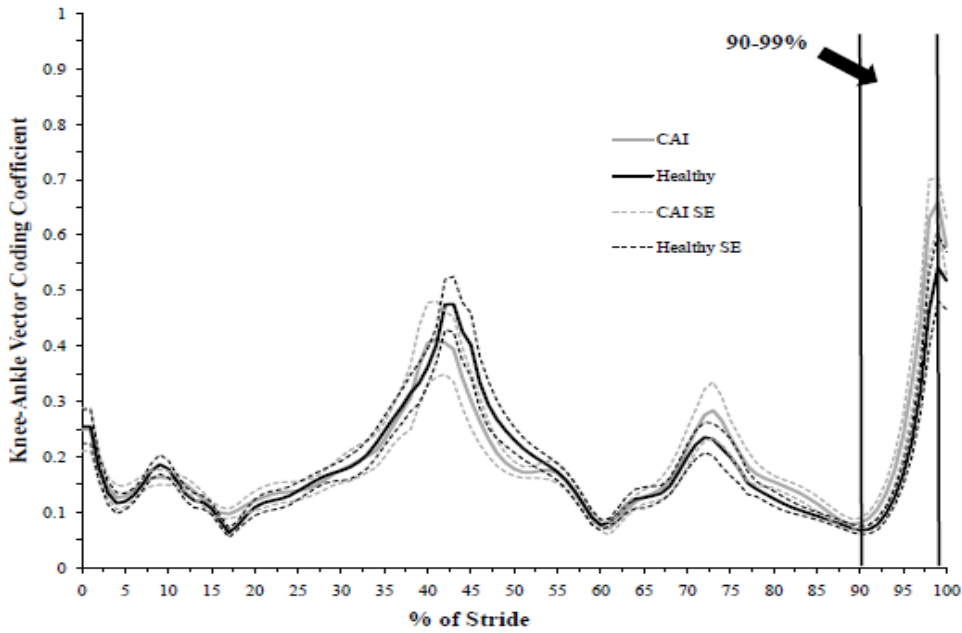
Hip abduction–adduction walking kinematics. Positive values represent adduction and negative represents abduction.



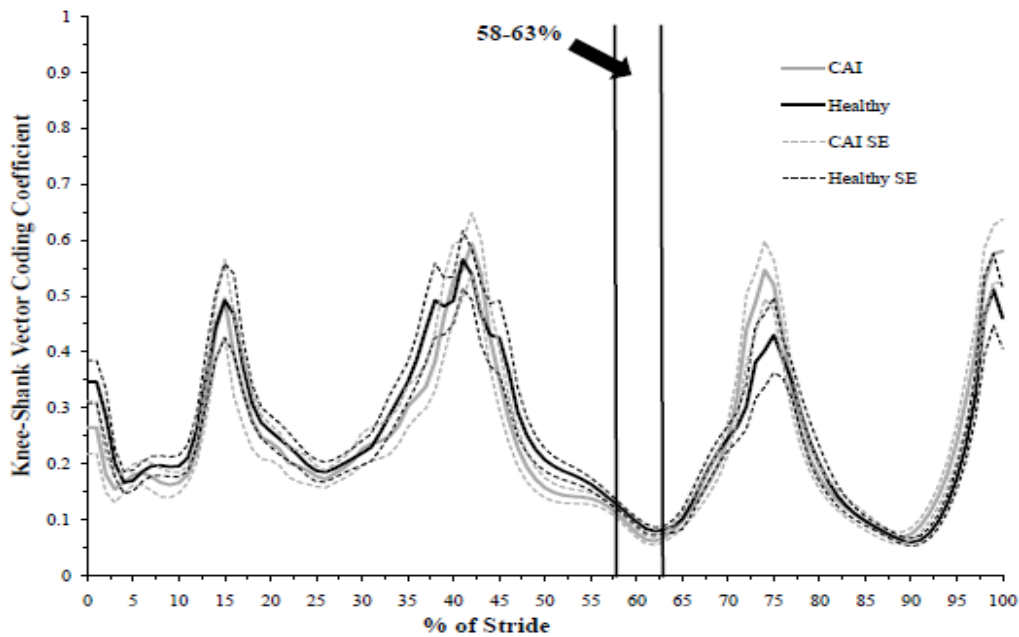
Shank-rearfoot coupling variability during walking. Coefficients closer to 0 represent low variability and coefficients closer to 1 represent high variability.



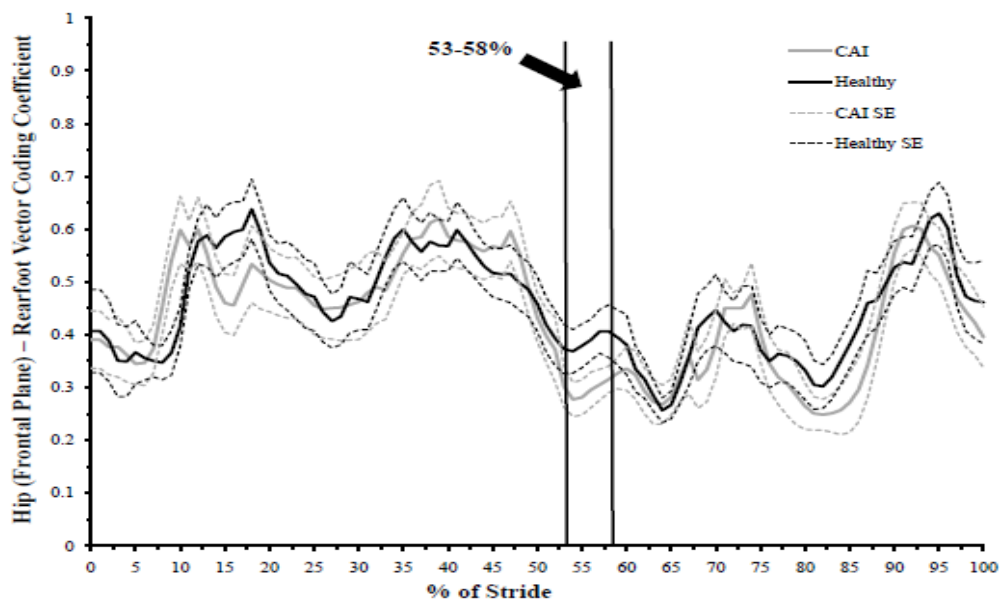
Knee-ankle coupling variability during walking. Coefficients closer to 0 represent low variability and coefficients closer to 1 represent high variability. Those with CAI had great joint coupling variability during swing phase.



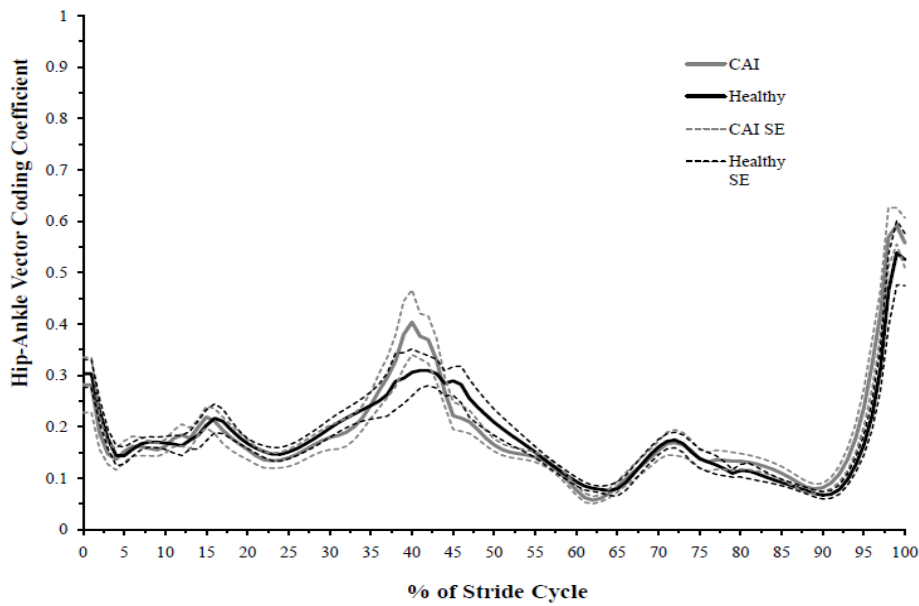
Knee-shank coupling variability during walking. Coefficients closer to 0 represent low variability and coefficients closer to 1 represent high variability. Those with CAI had less joint coupling variability during stance phase.



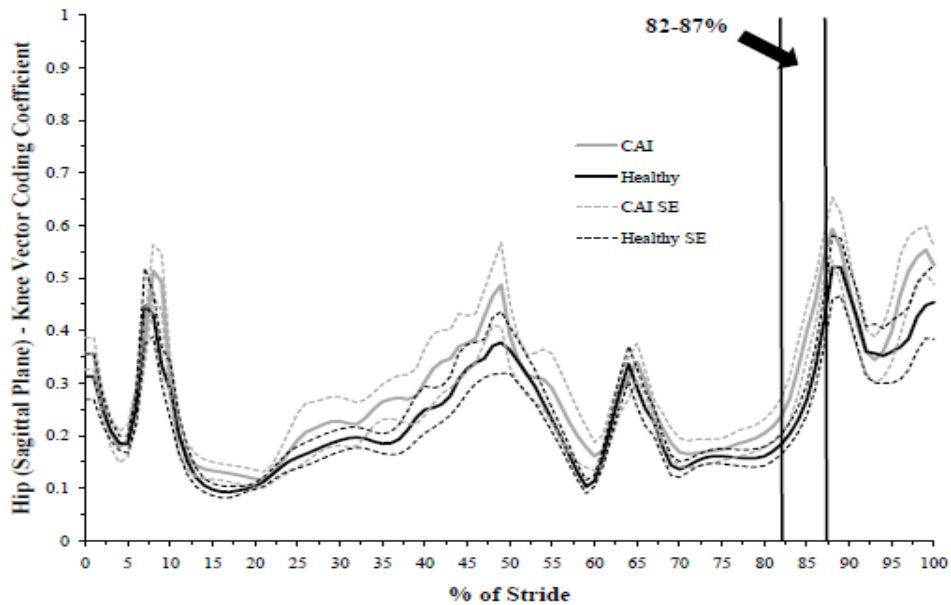
Hip abduction/adduction-rearfoot coupling variability during walking. Coefficients closer to 0 represent low variability and coefficients closer to 1 represent high variability. Those with CAI had less joint coupling variability during stance phase.



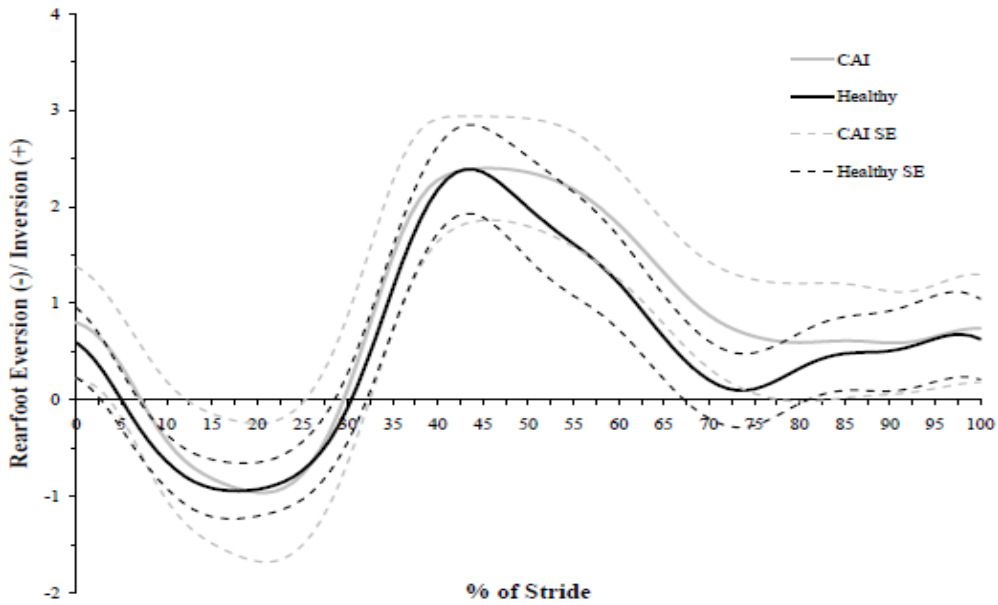
Hip flexion/extension-ankle coupling variability during walking. Coefficients closer to 0 represent low variability and coefficients closer to 1 represent high variability.



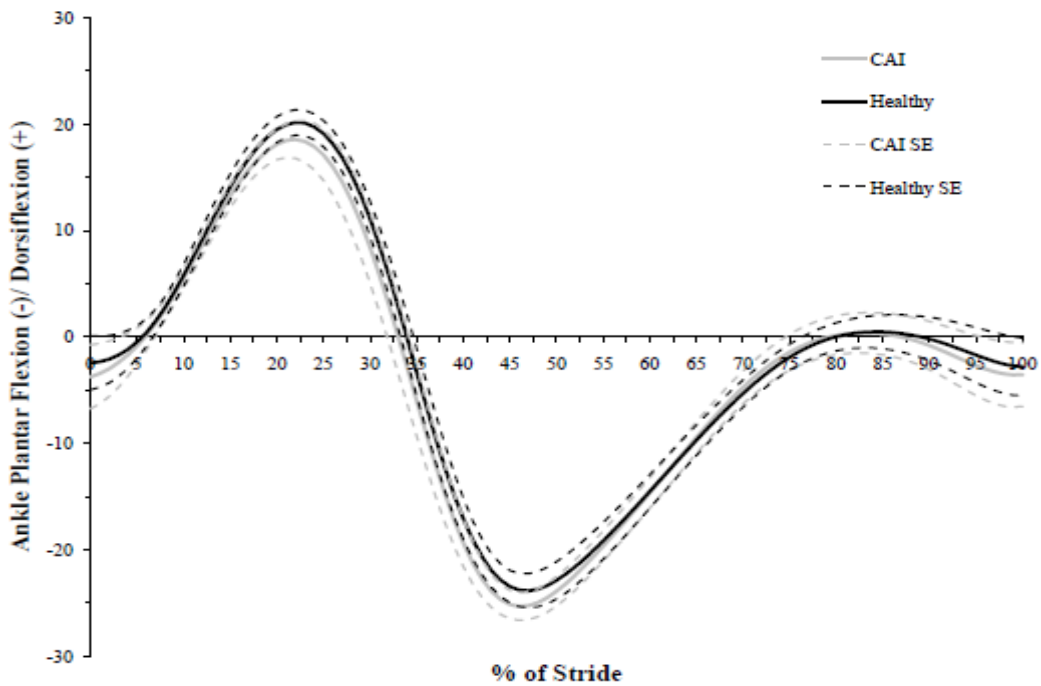
Hip flexion/extension-knee coupling variability during walking. Coefficients closer to 0 represent low variability and coefficients closer to 1 represent high variability. Those with CAI had greater joint coupling variability during swing phase.



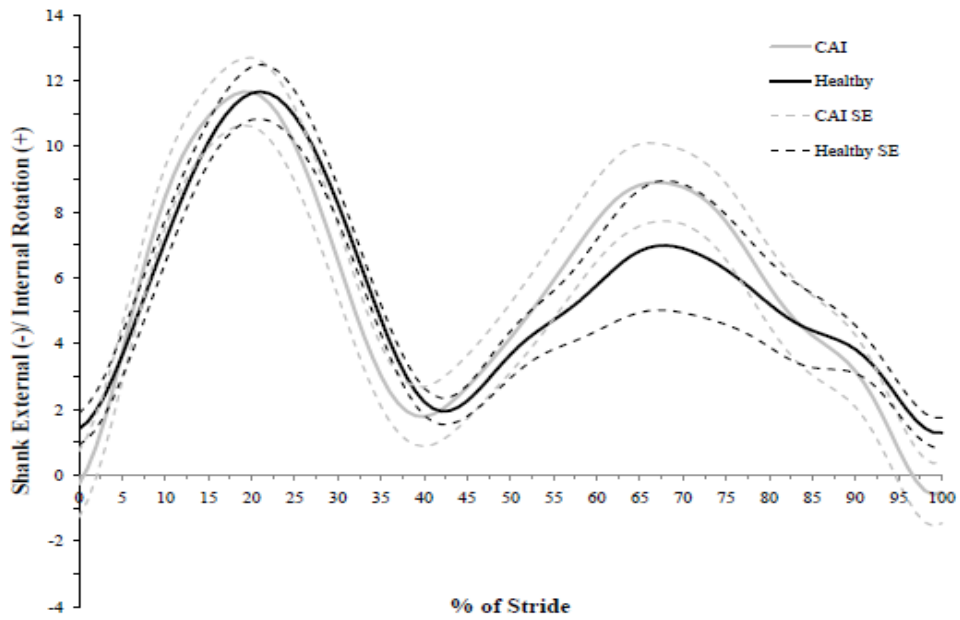
Rearfoot inversion-eversion running kinematics. Positive values represent inversion and negative values represent eversion.



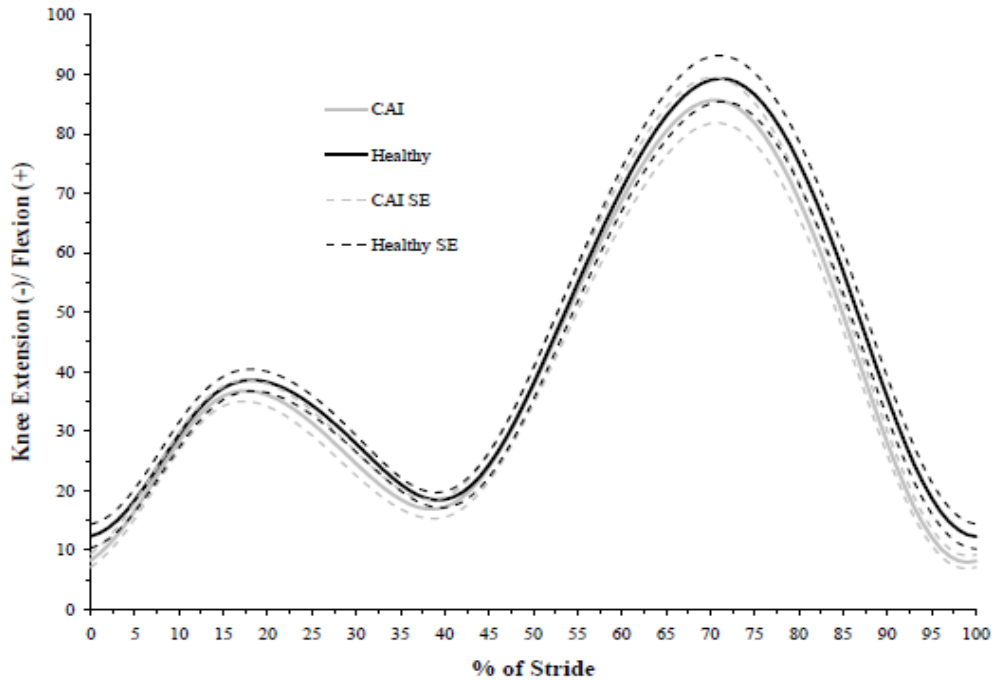
Ankle plantar flexion-dorsiflexion running kinematics. Positive values represent dorsiflexion and negative values represent plantar flexion.



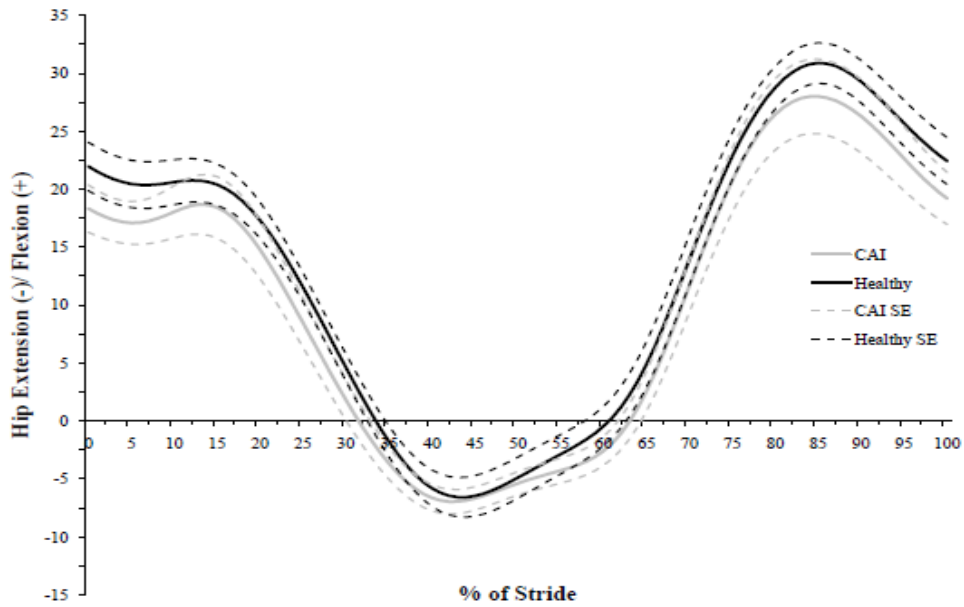
Shank internal–external rotation running kinematics. Positive values represent internal rotation and negative values represent external rotation.



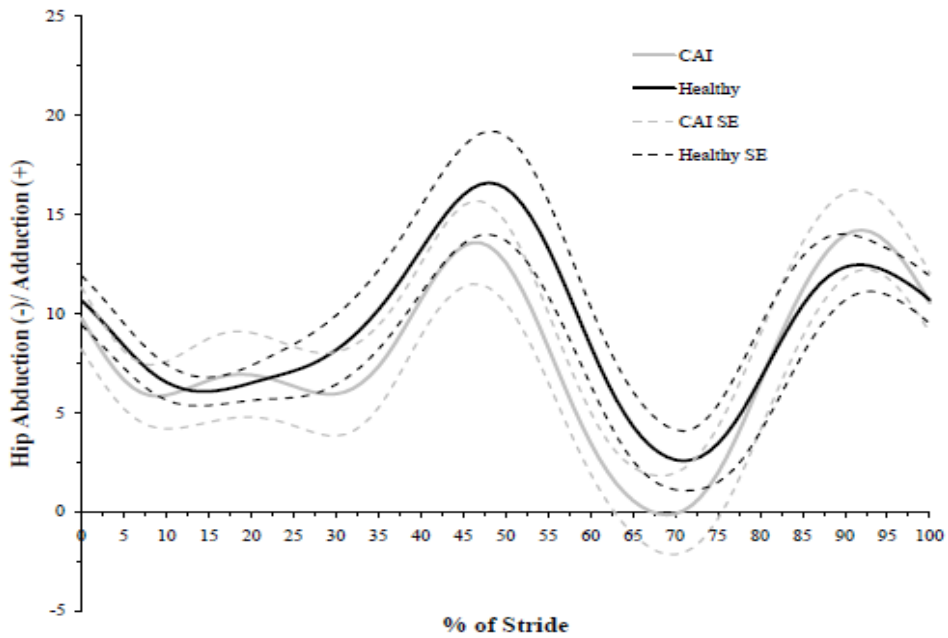
Knee flexion–extension running kinematics. Positive values represent flexion and negative values represent extension.



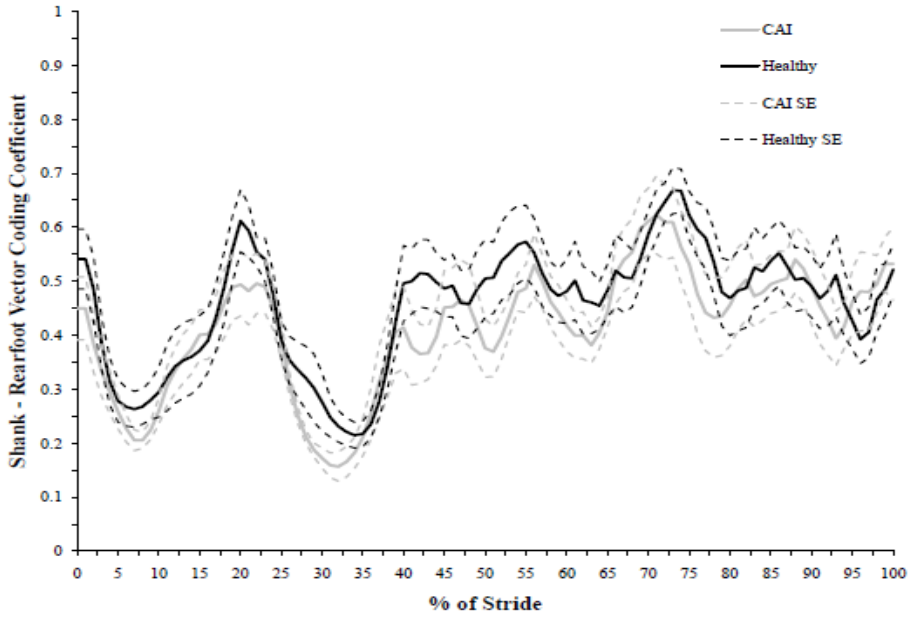
Hip flexion–extension running kinematics. Positive values represent flexion and negative values represent extension.



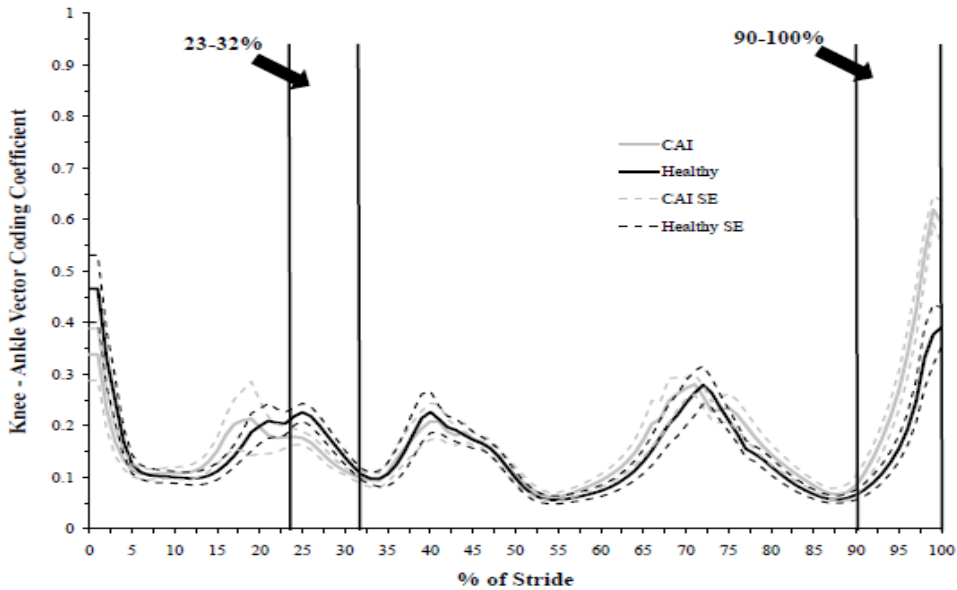
Hip abduction–adduction running kinematics. Positive values represent adduction and negative values represent abduction.



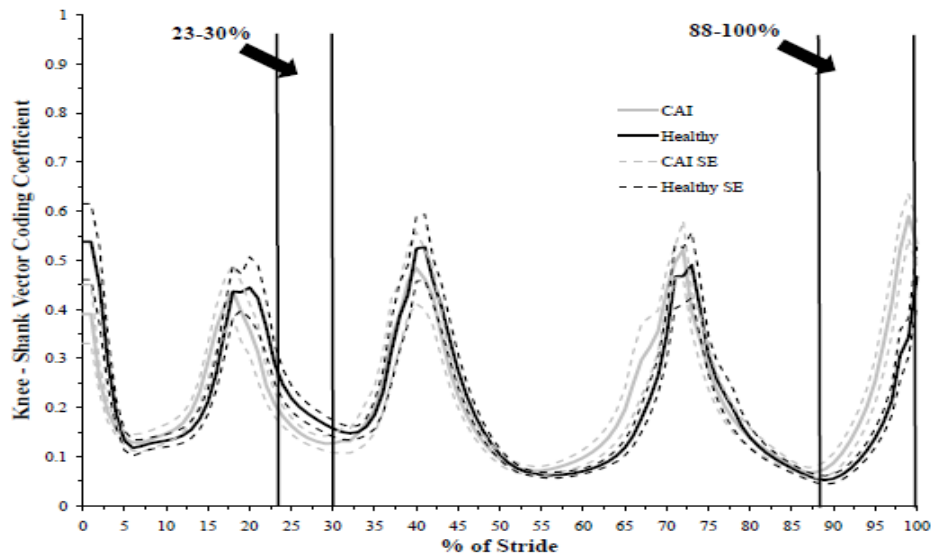
Shank-rearfoot coupling variability during running. Coefficients closer to 0 represent low variability and coefficients closer to 1 represent high variability.



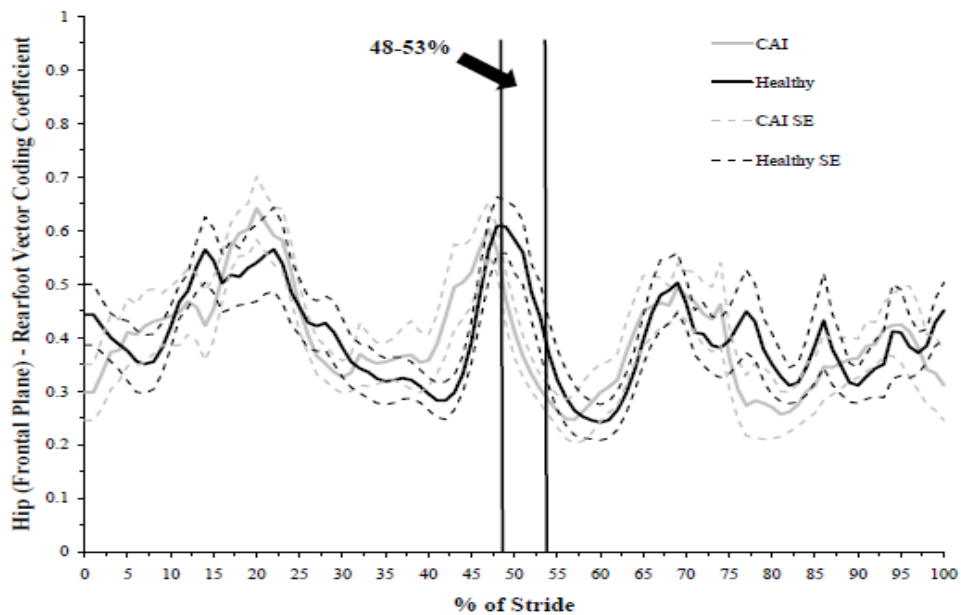
Knee-ankle coupling variability during running. Coefficients closer to 0 represent low variability and coefficients closer to 1 represent high variability. Those with CAI had less joint coupling variability during stance phase and greater variability during swing phase.



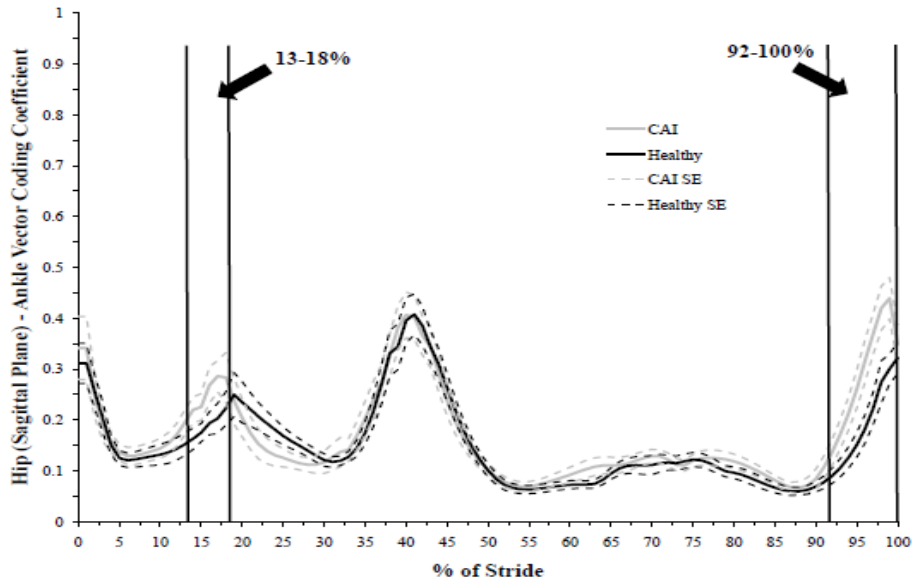
Knee-shank coupling variability during running. Coefficients closer to 0 represent low variability and coefficients closer to 1 represent high variability. Those with CAI had less joint coupling variability during stance phase and greater variability during swing phase.



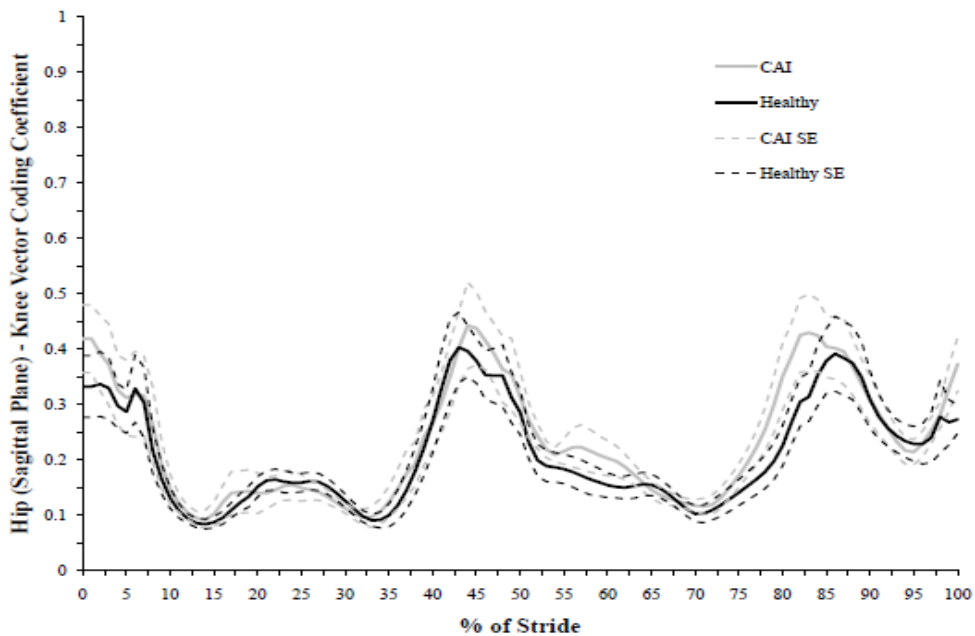
Hip abduction/adduction-rearfoot coupling variability during running. Coefficients closer to 0 represent low variability and coefficients closer to 1 represent high variability. Those with CAI had lower joint coupling variability during swing phase.



Hip flexion/extension-ankle coupling variability during running. Coefficients closer to 0 represent low variability and coefficients closer to 1 represent high variability. Those with CAI had greater joint coupling variability during stance and swing phases.

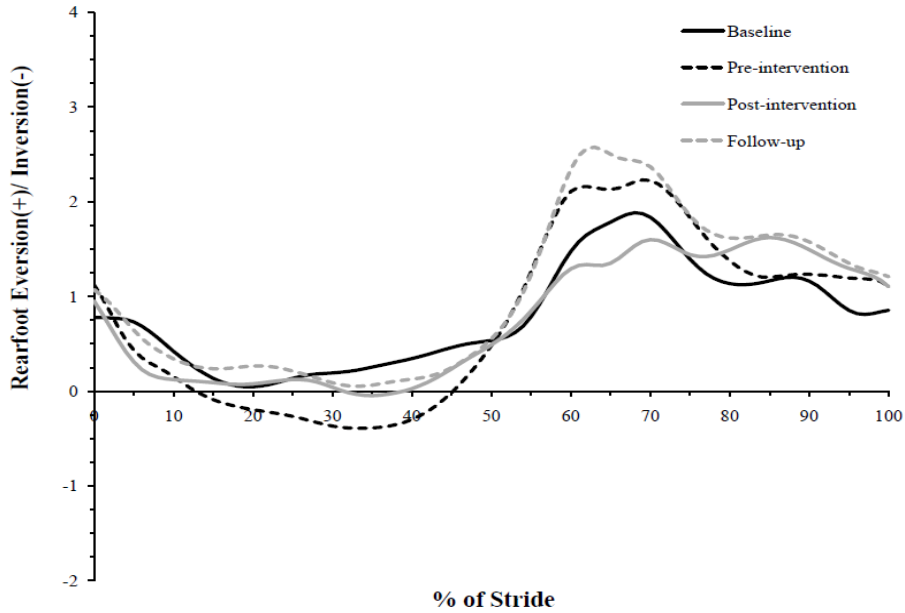


Hip flexion/extension-knee coupling variability during running. Coefficients closer to 0 represent low variability and coefficients closer to 1 represent high variability.

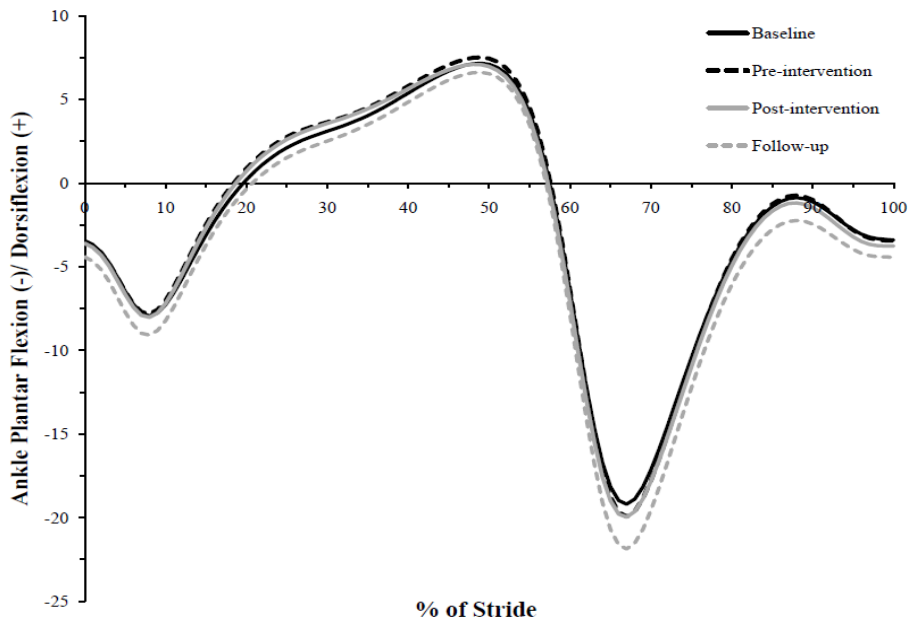


Appendix D

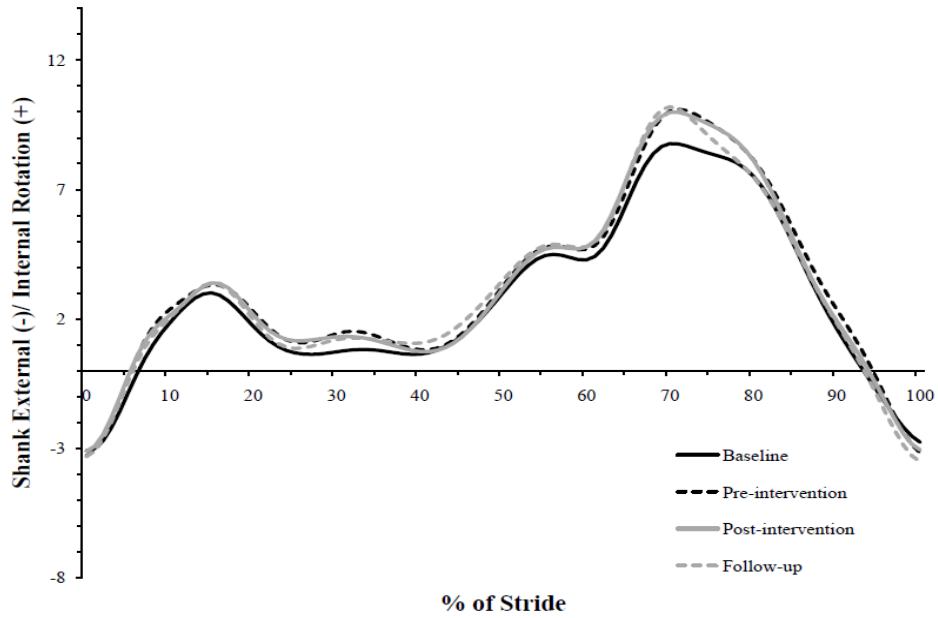
Rearfoot inversion/eversion walking kinematics. Positive values represent inversion and negative values represent eversion.



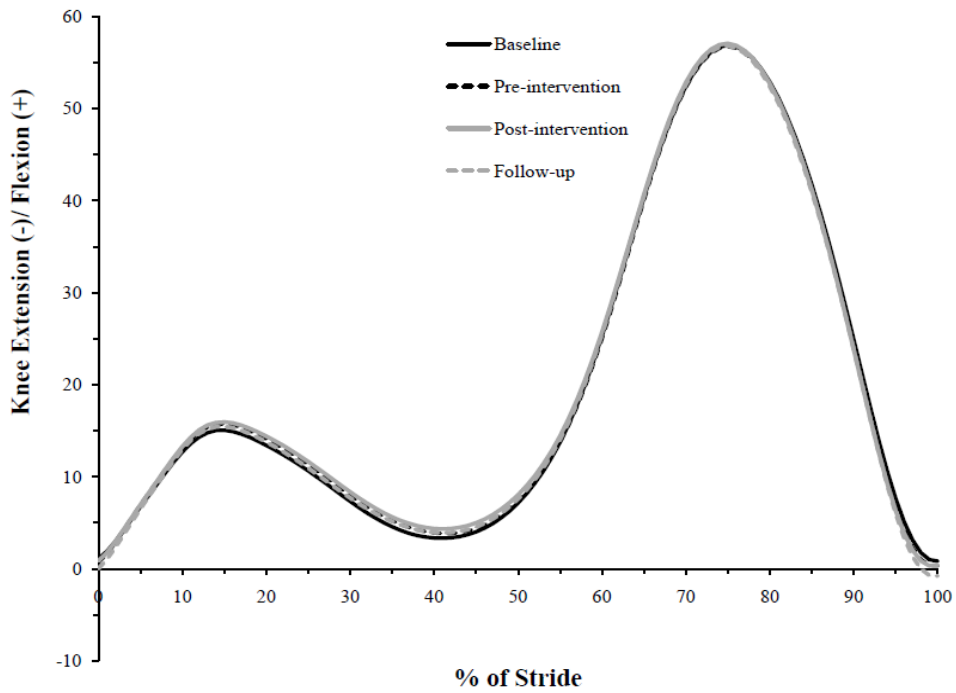
Ankle plantar flexion/dorsiflexion walking kinematics. Positive values represent dorsiflexion and negative values represent plantar flexion.



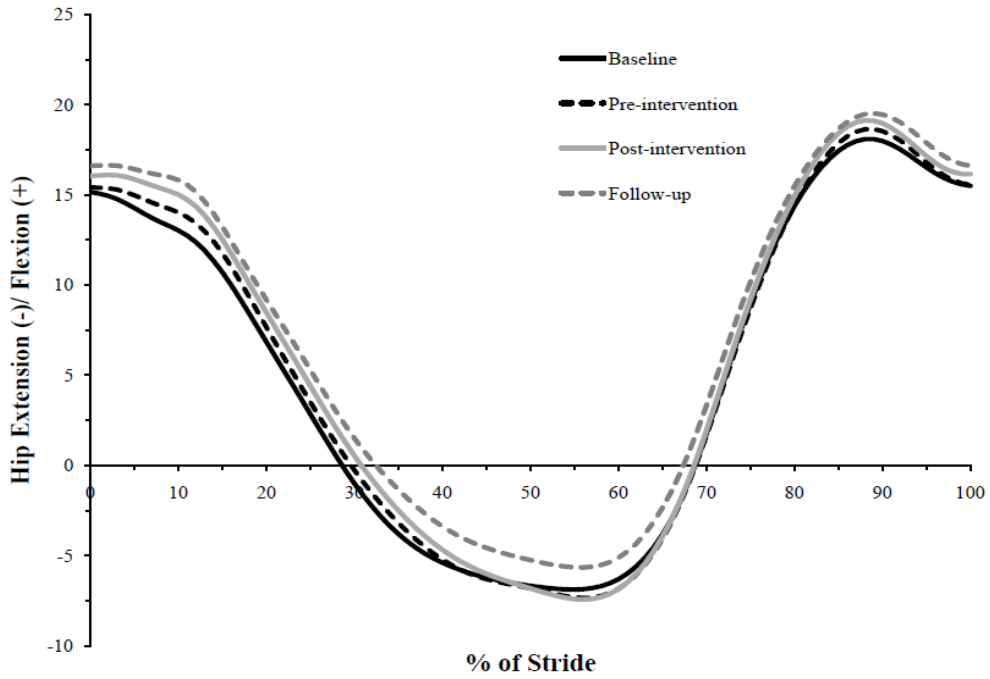
Shank internal/external rotation walking kinematics. Positive values represent internal rotation and negative values represent external rotation.



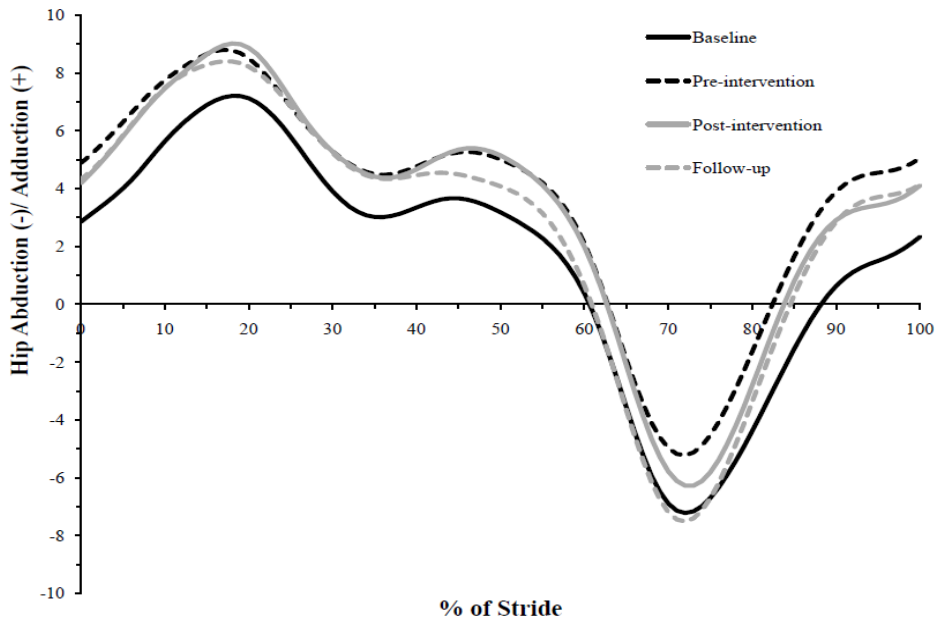
Knee flexion/extension walking kinematics. Positive values represent flexion and negative values represent extension.



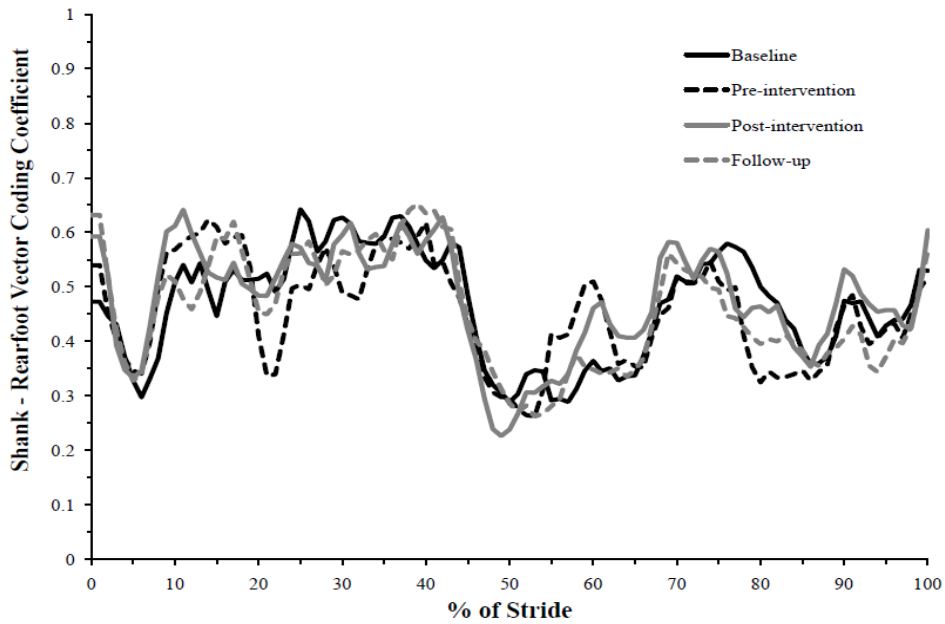
Hip flexion/extension walking kinematics. Positive values represent flexion and negative values represent extension.



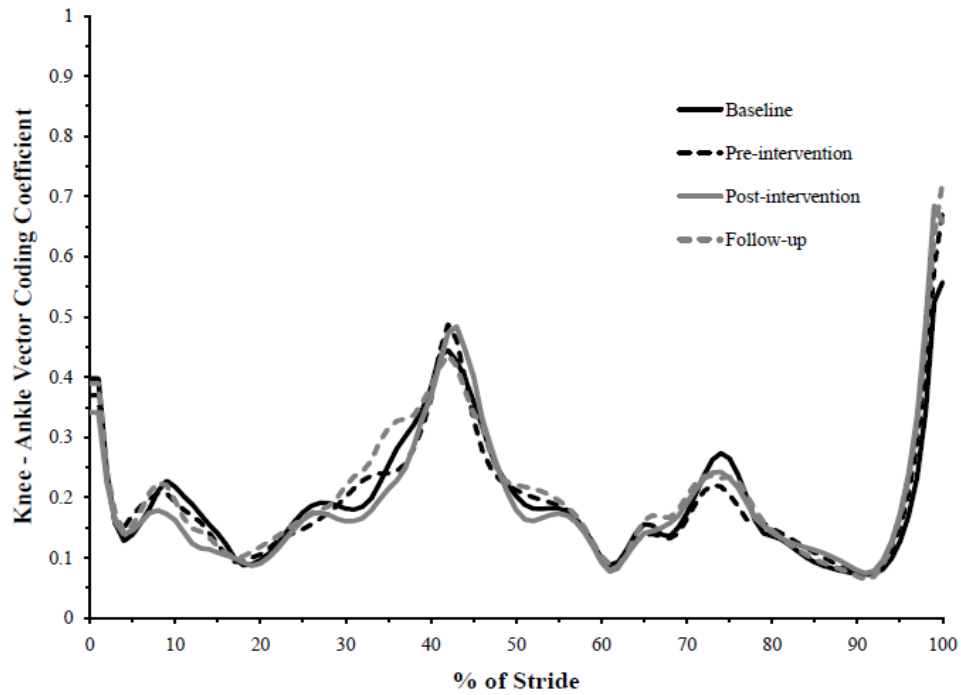
Hip abduction/adduction walking kinematics. Positive values represent adduction and negative represents abduction.



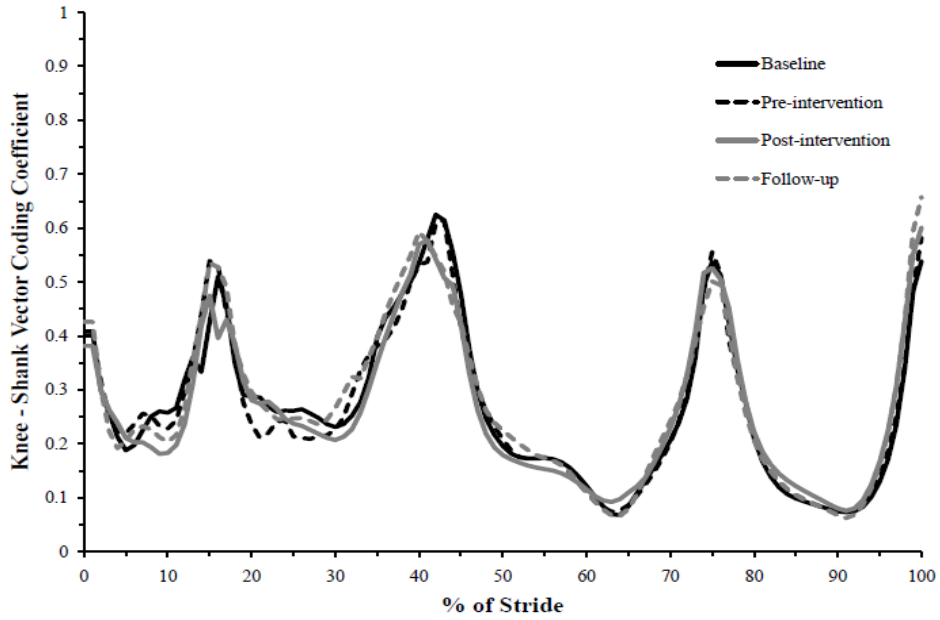
Shank-rearfoot coupling variability during walking. Coefficients closer to 0 represent low variability and coefficients closer to 1 represent high variability.



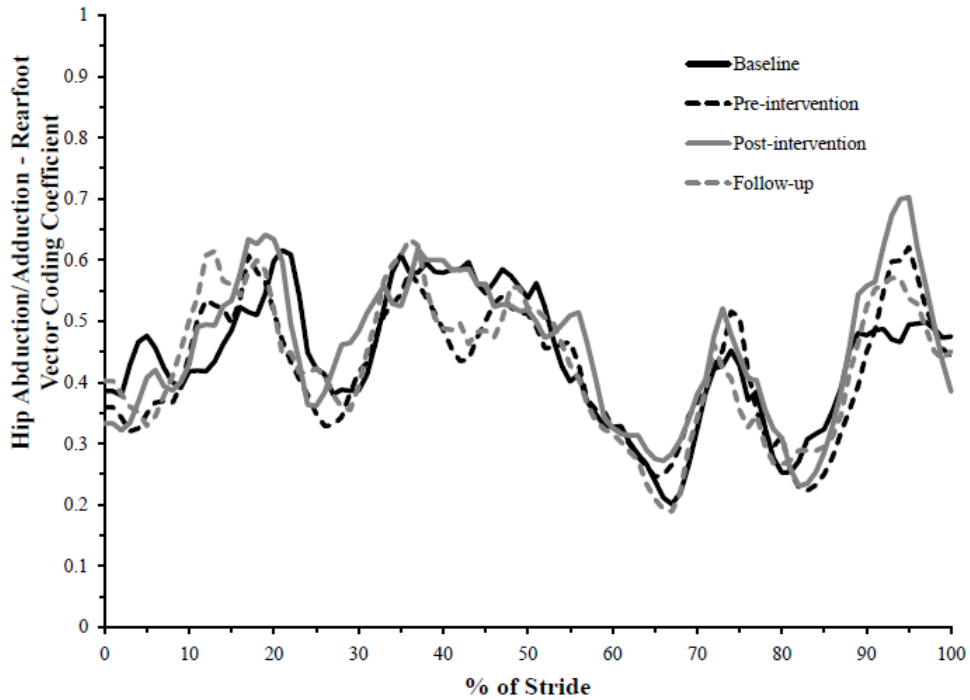
Knee-ankle coupling variability during walking. Coefficients closer to 0 represent low variability and coefficients closer to 1 represent high variability.



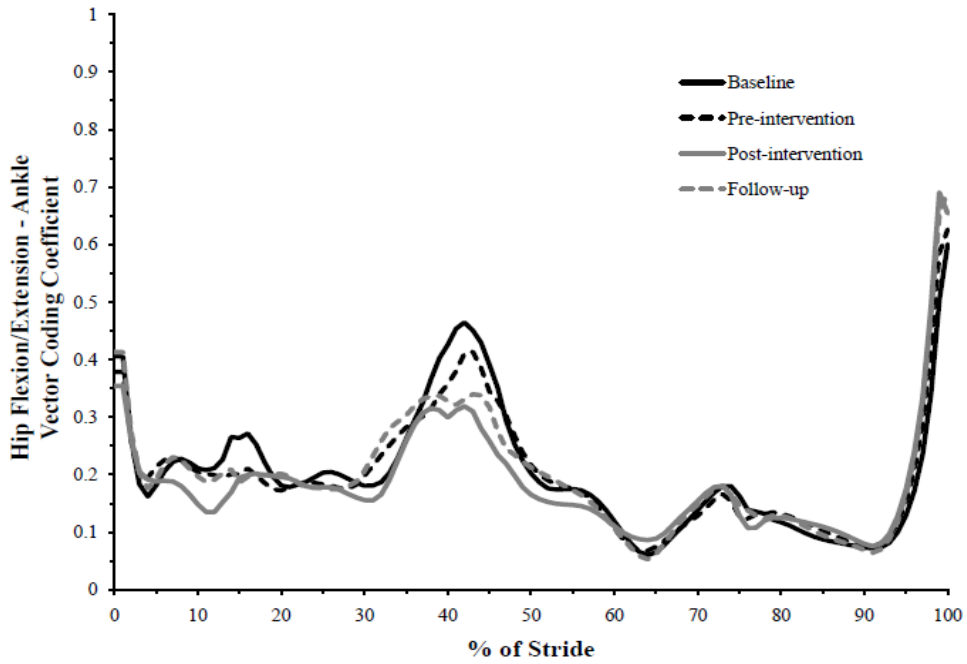
Knee-shank coupling variability during walking. Coefficients closer to 0 represent low variability and coefficients closer to 1 represent high variability.



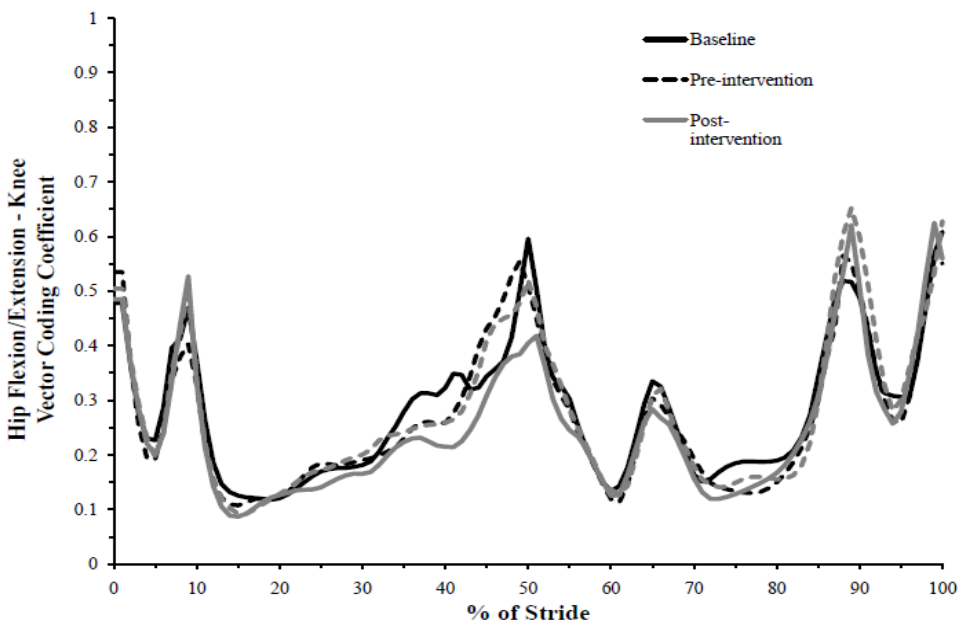
Hip abduction/adduction-rearfoot coupling variability during walking. Coefficients closer to 0 represent low variability and coefficients closer to 1 represent high variability.



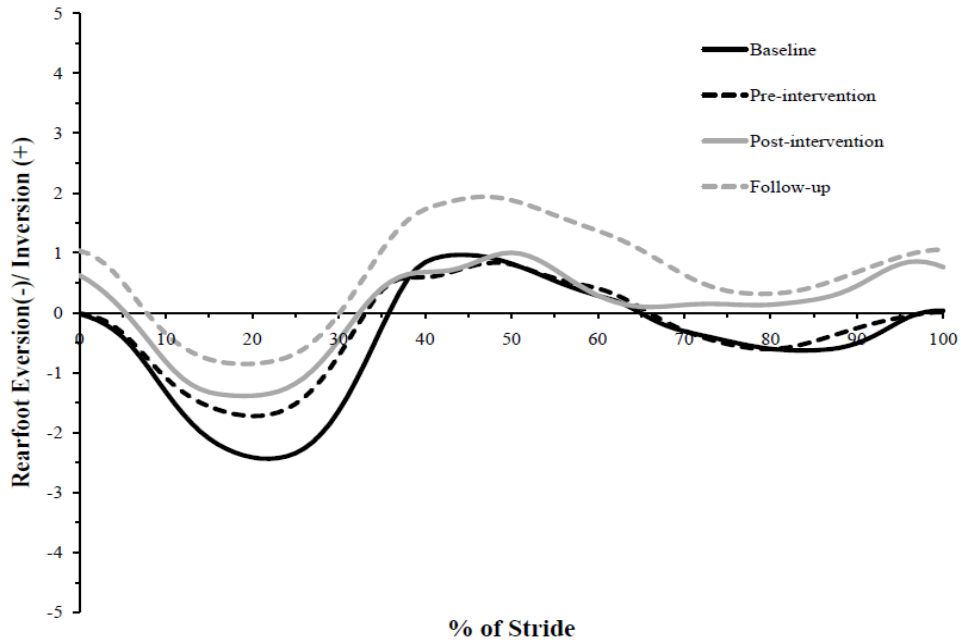
Hip flexion/extension-ankle coupling variability during walking. Coefficients closer to 0 represent low variability and coefficients closer to 1 represent high variability.



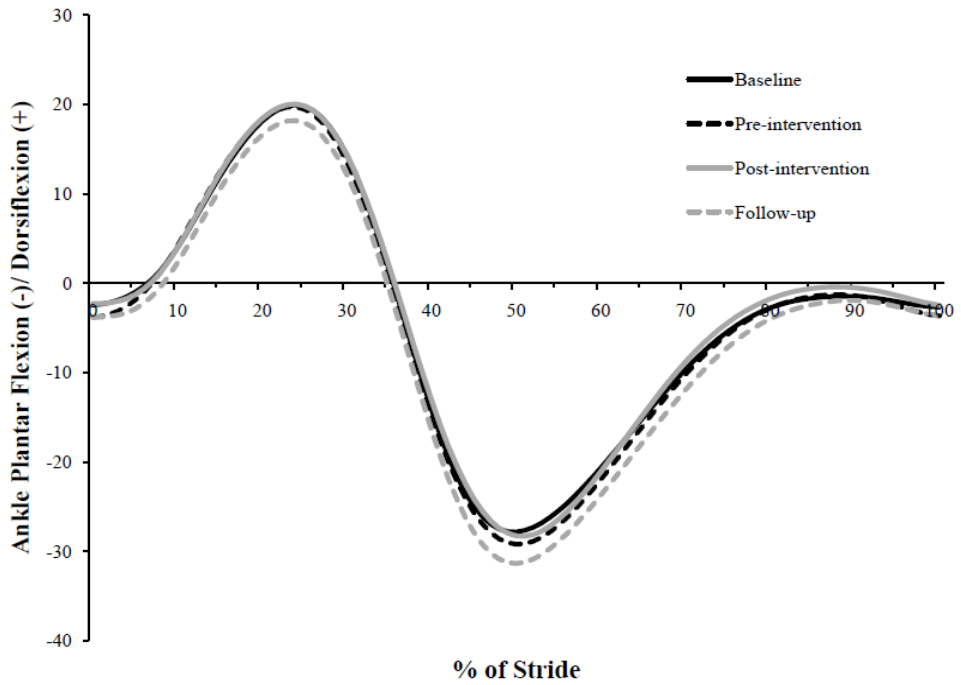
Hip flexion/extension-knee coupling variability during walking. Coefficients closer to 0 represent low variability and coefficients closer to 1 represent high variability.



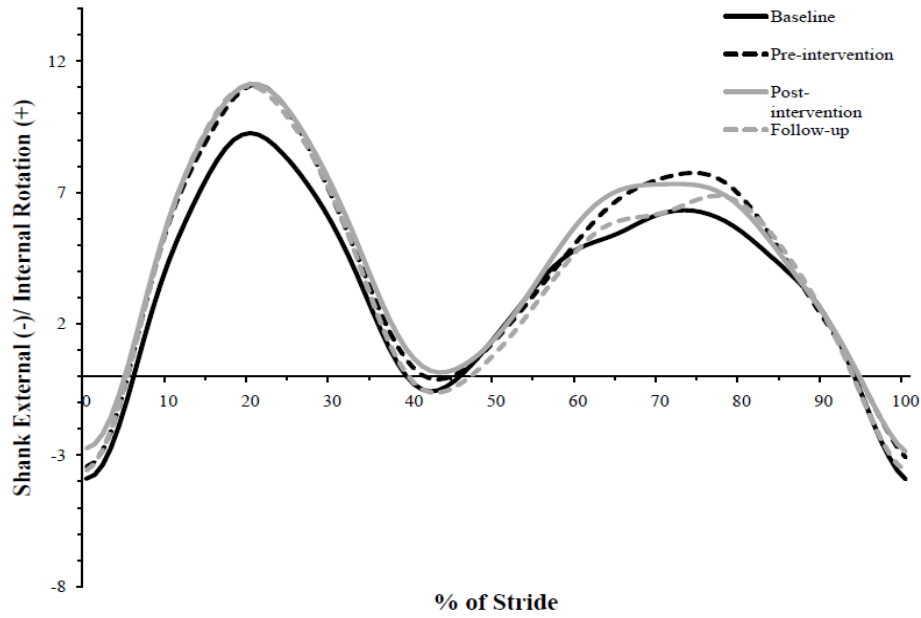
Rearfoot inversion-eversion running kinematics. Positive values represent inversion and negative values represent eversion.



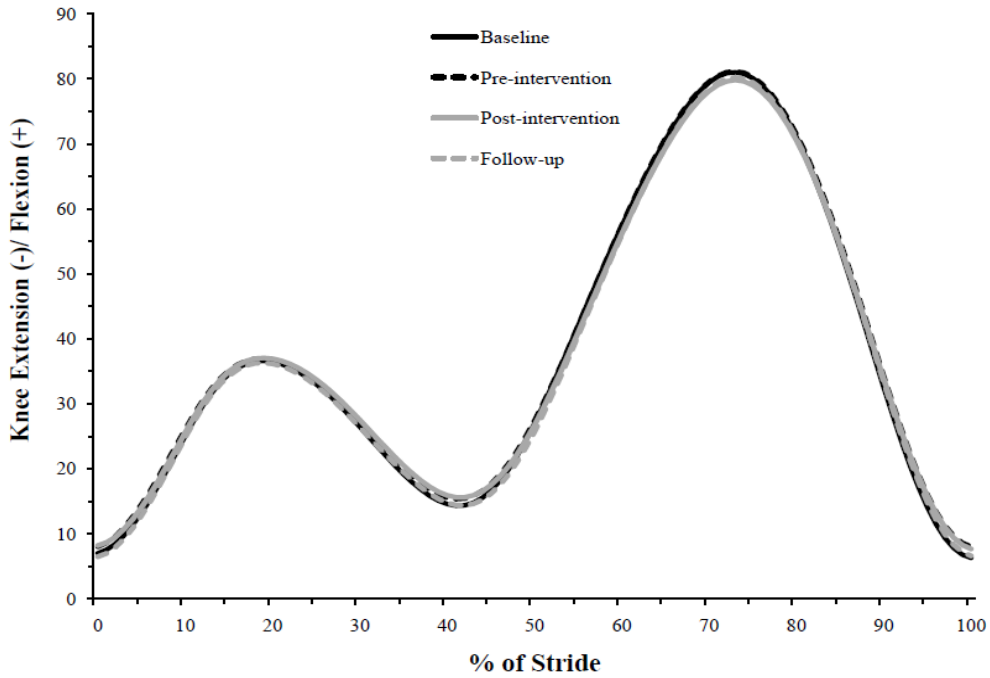
Ankle plantar flexion/dorsiflexion running kinematics. Positive values represent dorsiflexion and negative values represent plantar flexion.



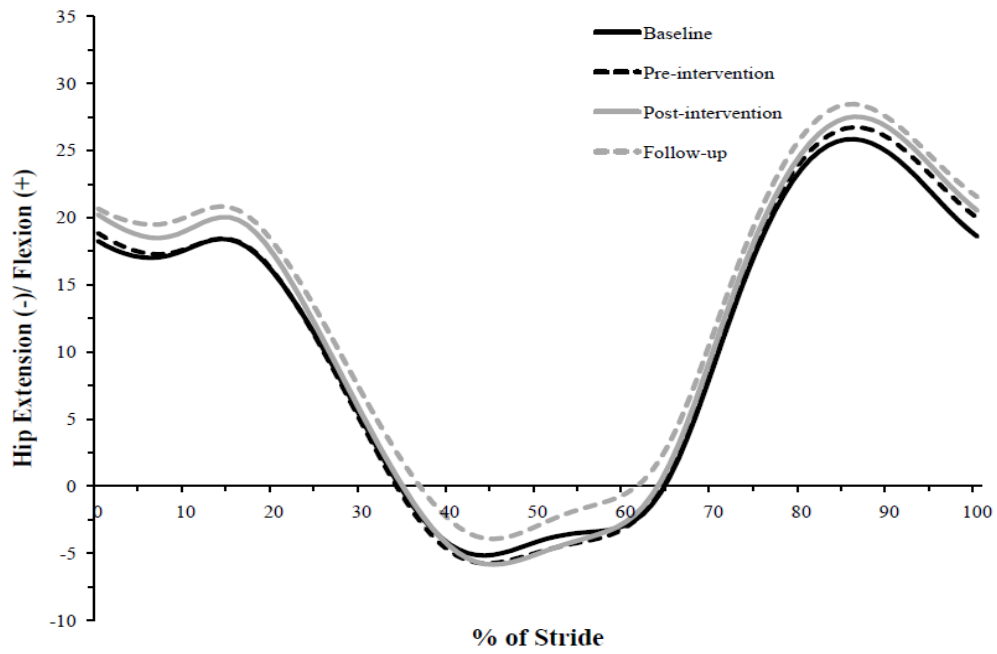
Shank internal/external rotation running kinematics. Positive values represent internal rotation and negative values represent external rotation.



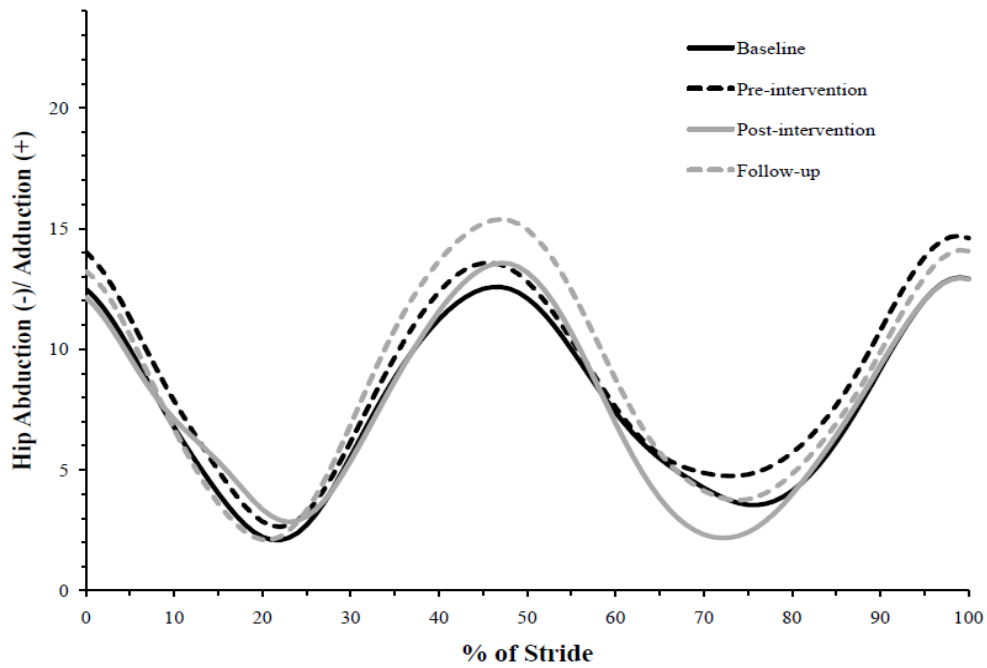
Knee flexion/extension running kinematics. Positive values represent flexion and negative values represent extension.



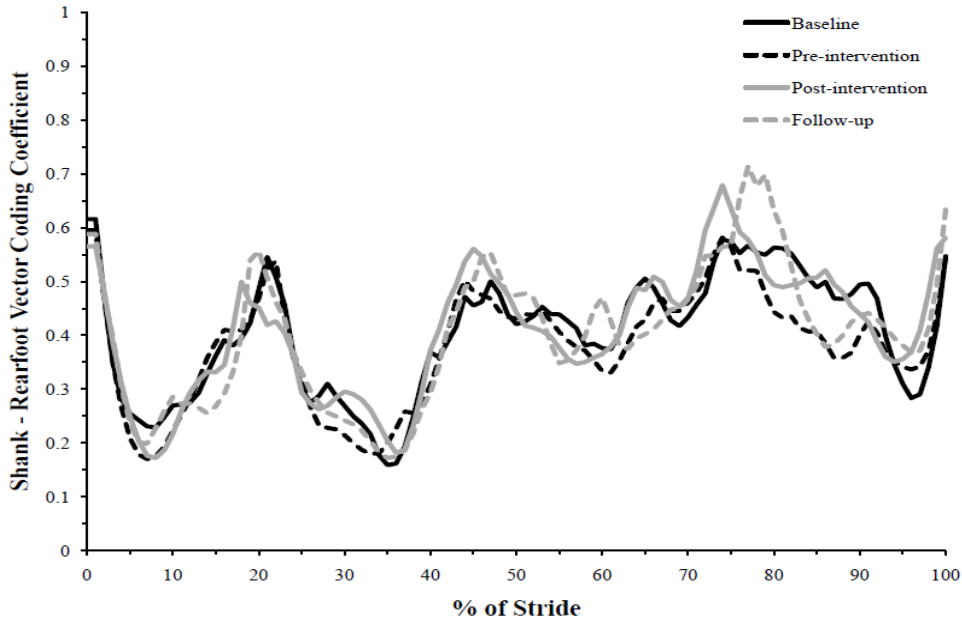
Hip flexion/extension running kinematics. Positive values represent flexion and negative values represent extension.



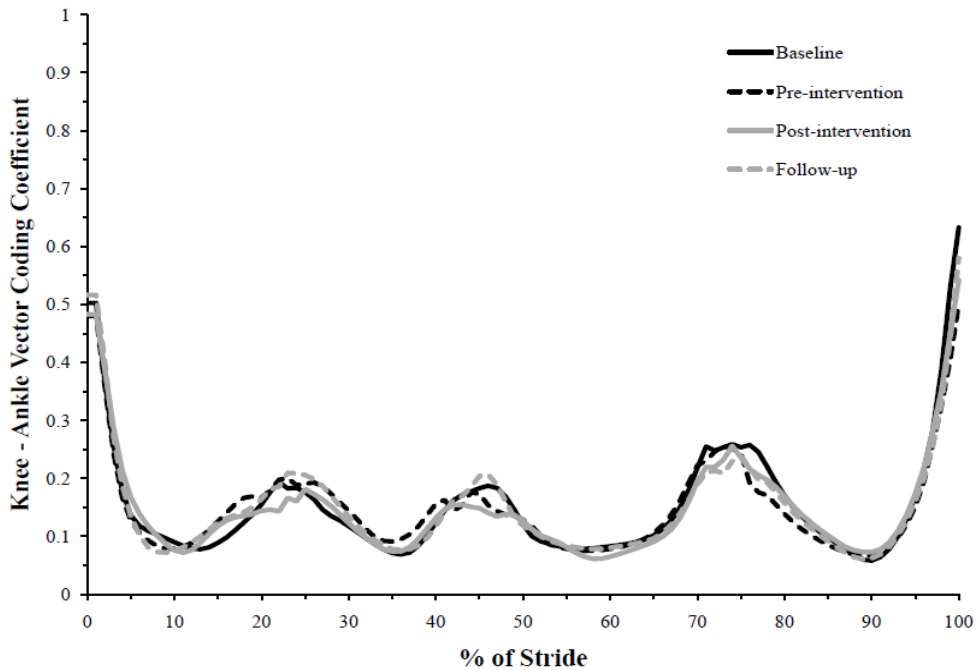
Hip abduction/adduction running kinematics. Positive values represent adduction and negative values represent abduction.



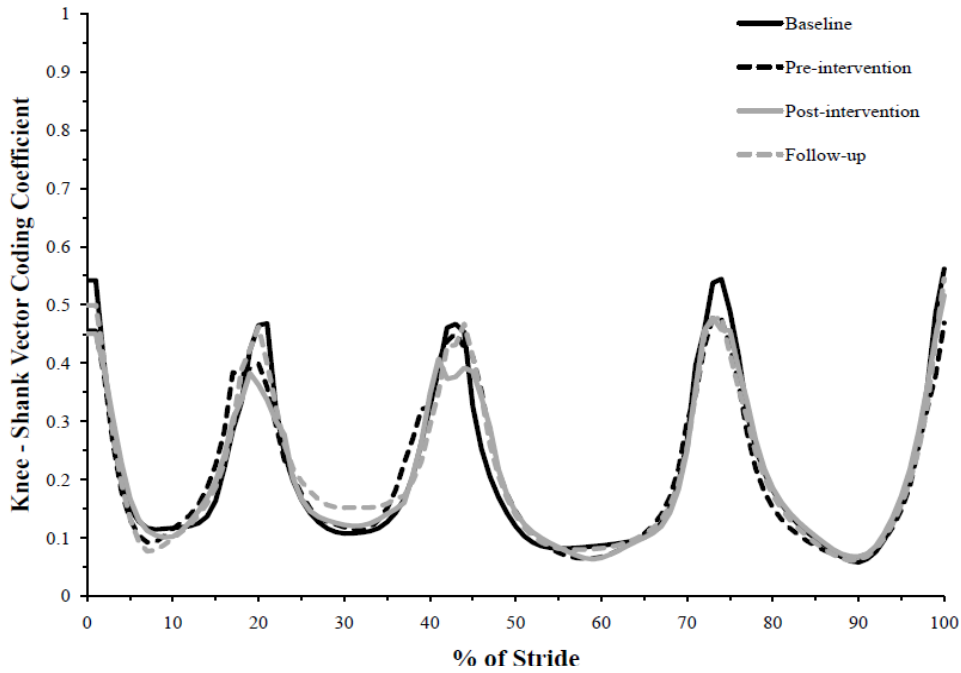
Shank-rearfoot coupling variability during running. Coefficients closer to 0 represent low variability and coefficients closer to 1 represent high variability.



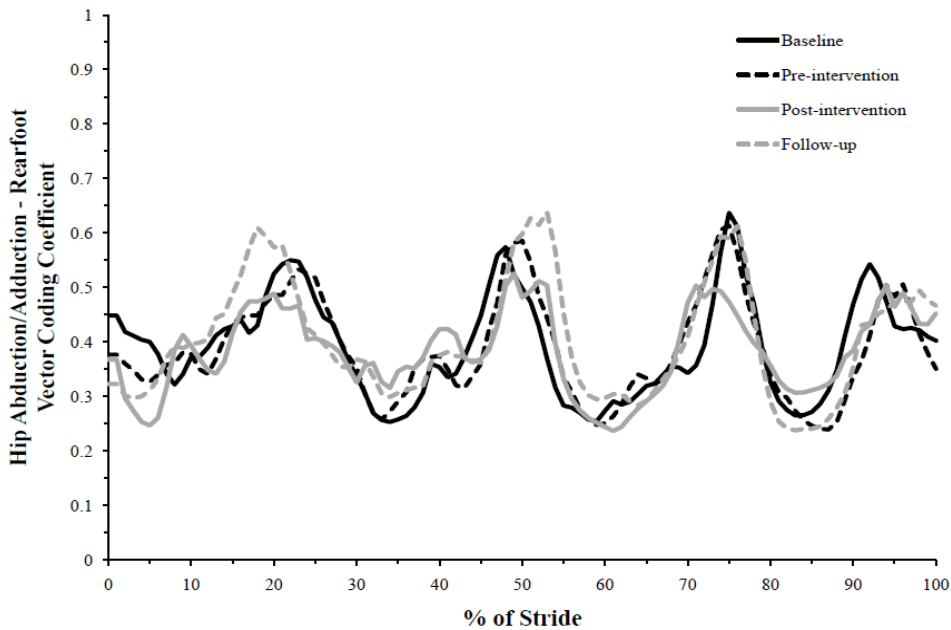
Knee-ankle coupling variability during running. Coefficients closer to 0 represent low variability and coefficients closer to 1 represent high variability.



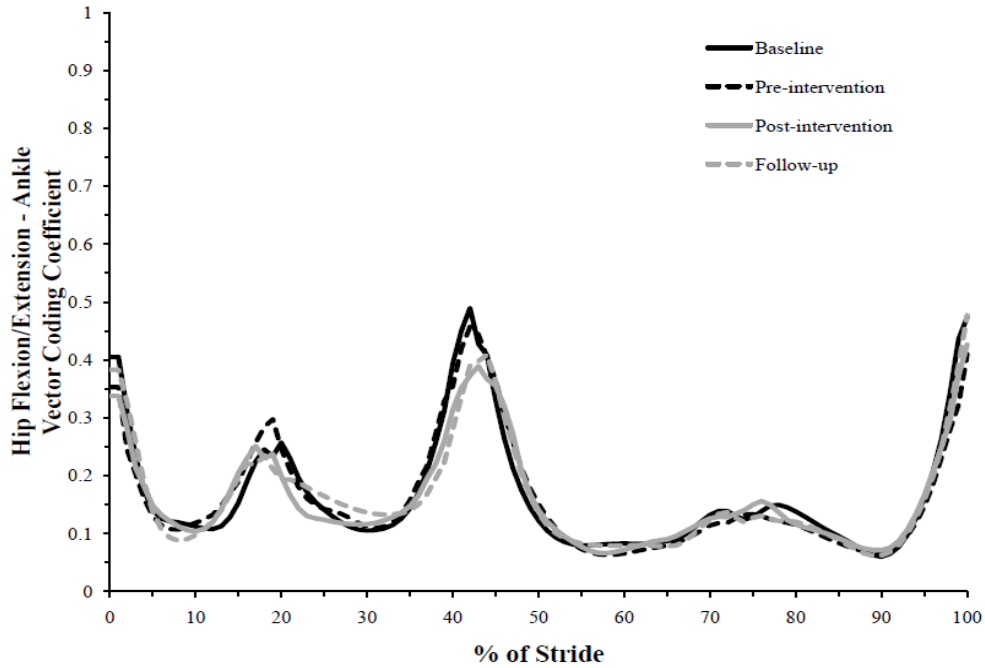
Knee-shank coupling variability during running. Coefficients closer to 0 represent low variability and coefficients closer to 1 represent high variability.



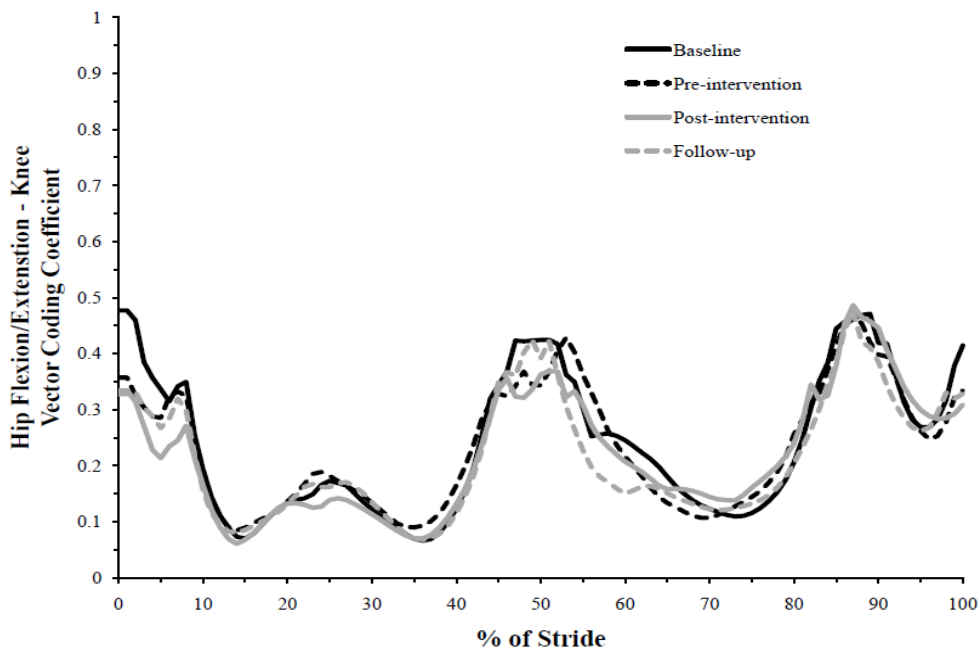
Hip abduction/adduction-rearfoot coupling variability during running. Coefficients closer to 0 represent low variability and coefficients closer to 1 represent high variability.



Hip flexion/extension-ankle coupling variability during running. Coefficients closer to 0 represent low variability and coefficients closer to 1 represent high variability.



Hip flexion/extension-knee coupling variability during running. Coefficients closer to 0 represent low variability and coefficients closer to 1 represent high variability.



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142. Hoch MC, Silkman CL. Clinical research review: Balance training improves postural control and function in those with chronic ankle instability. *Athl Ther Today.* 2010;15(1):9-11.
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Vita

Matthew C. Hoch ATC

General Information

Birth place and date: West Hazleton, PA, 08/01/1984

Certificate or Specialty Board Licensure:

National Athletic Trainers Association Board of Certification #060602331

I. Education

- 2008 – Present The University of Kentucky, College of Health Sciences,
Doctor of Philosophy, Rehabilitation Sciences
Expected Completion: May 2011
Dissertation: The Effect of Joint Mobilization on Functional
Outcomes Associated with Chronic Ankle Instability
- 2006 – 2008 Ohio University, College of Health and Human Services,
Master of Science, Recreation and Sports Sciences,
concentration in Athletic Training
- 2002 – 2006 East Stroudsburg University, College of Health Sciences,
Bachelor of Science, Athletic Training

II. Professional Experiences

- August 2008 – Present Research Assistant
Advisor: Patrick O. McKeon PhD, ATC
Division of Athletic Training
Department of Rehabilitation Sciences
University of Kentucky, Lexington, KY
- June 2006 – June 2008 Graduate Assistant Athletic Trainer
Ohio University
Athens, OH

III. Teaching Activity

University of Kentucky

- Spring 2011 AT695: Orthopaedic Evaluation and Rehabilitation of the Lower
Extremity – Teaching Assistant
- Spring 2011 AT671: Scientific Inquiry in Athletic Training II – Teaching
Assistant

- 2009-2011 AT740: Musculoskeletal Anatomical Dissection – Teaching Assistant
- 2010-2011 AT670: Scientific Inquiry in Athletic Training I – Teaching Assistant

IV. Honors

- 2011 Robinson Award for Research Creativity, University of Kentucky
- 2010 Academic Excellence Scholarship, University of Kentucky
- 2009 Wright Endowment Recipient, University of Kentucky
- 2009 Doctoral Student Scholarship, National Athletic Trainers Association

V. Speaking Engagements/Presentations

Invited

- June 2011 National Athletic Trainers Association Annual Meeting and Symposium
New Orleans, LA
Manual therapy techniques for the treatment of chronic ankle instability and acute ankle sprains.
- June 2010 National Athletic Trainers Association Annual Meeting and Symposium
Philadelphia, PA
Applying motor control theory to patient-centered care: Insights into chronic ankle instability.
- May 2009 University of Kentucky Sports Medicine Symposium
Lexington, KY
Getting a Leg Up on Lower Extremity Rehabilitation

Peer Reviewed

- June 2011 National Athletic Trainers Association Annual Meeting and Symposium
New Orleans, LA
Poster - *Elevations in coordination variability correspond with phase transitions in walking gait in healthy adults.* Hoch MC, Mullineaux DR, Kyoungyu J, McKeon PO
- June 2011 National Athletic Trainers Association Annual Meeting and Symposium
New Orleans, LA
Oral - *Age-related postural control alterations among pre-adolescents, adolescents, and adults.* Lounsberry NL, Hoch MC, McKeon PO
- June 2011 National Athletic Trainers Association Annual Meeting and Symposium
New Orleans, LA
Poster - *The relationship between ankle range of motion and dynamic postural control in healthy individuals and those reporting chronic ankle instability.* McKeon PO, Staton GS, Hoch MC, McKeon JM, Mattacola CG.

- June 2011 American College of Sports Medicine Annual Meeting
Denver, CO
Oral - *Plantar cutaneous vibrotactile detection threshold changes are present in those with chronic ankle instability.* Hoch MC, McKeon PO, Andreatta RD.
- June 2011 American College of Sports Medicine Annual Meeting
Denver, CO
Poster - *Dorsiflexion range of motion and dynamic balance asymmetry in adolescents.* McKeon PO, Hoch MC, Silkman CL, Hoch JM, McKeon JM
- June 2010 American College of Sports Medicine Annual Meeting
Baltimore, MD
Poster - *Reliability and responsiveness of the Star Excursion Balance Test in those with chronic ankle instability.* Hoch MC, Staton GS, McKeon PO
- June 2010 National Athletic Trainers Association Annual Meeting and Symposium
Philadelphia, PA
Oral - *Joint mobilization improves spatiotemporal postural control and ankle range of motion in those with chronic ankle instability.* Hoch MC, Staton GS, McKeon PO
- June 2010 National Athletic Trainers Association Annual Meeting and Symposium
Philadelphia, PA
Oral - *Dorsiflexion range of motion significantly influences dynamic balance.* McKeon PO, Hoch MC, Staton GS
- June 2009 National Athletic Trainers Association Annual Meeting and Symposium
San Antonio, TX
Oral - *Adolescents demonstrate lower spatiotemporal postural control compared to healthy adults.* Hoch MC, McKeon PO, McKeon JM, Silkman C

VI. Research Creative Productivity

Publications: Peer Reviewed Journals

Hoch MC, McKeon PO. *Normative range of weight-bearing lunge test performance asymmetry in healthy adults.* Manual Therapy. In Press.

Hoch MC, McKeon PO. *Peroneal reaction time is not a risk factor for ankle sprain in healthy adults.* Journal of Sport Rehabilitation. In Press.

Hoch MC, McKeon PO. *Joint mobilization improves spatiotemporal postural control and range of motion in those with chronic ankle instability.* Journal of Orthopaedic Research. 2011; 29(3):326-32.

Hoch MC, Staton GS, McKeon PO. *Dorsiflexion range of motion significantly influences dynamic balance.* Journal of Medicine and Science in Sport. 2011; 14(1), 90-92.

Hoch MC, McKeon PO. *The effectiveness of mobilization with movement at improving dorsiflexion following ankle sprain*. Journal of Sport Rehabilitation. 2010; 19(2), 226-232.

Silkman CL, Hoch MC, McKeon JM. *Perturbation training prior to ACL reconstruction*. Athletic Therapy Today. 2010; 15(3), 11-15.

Hoch MC, McKeon PO. *Integrating contemporary models of motor control and health in chronic ankle instability*. Athletic Training and Sports Health Care. 2010; 2(2), 82-88.

Doeringer JR, Hoch MC, Krause BA. *Ice application effects on peroneus longus and tibialis anterior motoneuron excitability in subjects with functional ankle instability*. International Journal of Neuroscience. 2010; 120(1), 17-22.

Hoch MC, Silkman CL. *Balance training improves postural control and function in those with chronic ankle instability*. Athletic Therapy Today. 2010; 15(1), 9-11.

Krause BA, Hoch MC, Doeringer JR, Sheets C. *Hydration status does not have a significant effect on soleus motoneuron excitability*. International Journal of Neuroscience. 2009; 119(10),1693-1704.

Doeringer JR, Hoch MC, Krause BA. *The effect of focal ankle cooling on spinal reflex activity in subjects with chronic ankle instability*. Athletic Training and Sports Health Care. 2009; 1(2), 59-64.

Hoch MC, Krause BA. *Intersession reliability of H:M ratio is greater than the H-reflex at a percentage of M-max*. International Journal of Neuroscience. 2009; 119(3), 345-352.