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Kyle B. Kosik, Student

Dr. Phillip A. Gribble, Major Professor

Dr. Esther Dupont-Versteegden, Director of Graduate Studies

CHRONIC ANKLE INSTABILITY AND AGING

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
Kyle B. Kosik

Lexington, Kentucky

Co-Directors: Dr. Phillip A. Gribble, Associate Professor of Athletic Training and
Dr. Nathan F. Johnson, Assistant Professor of Physical Therapy

Lexington, Kentucky

2017

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ABSTRACT OF DISSERTATION

CHRONIC ANKLE INSTABILITY AND AGING

Lateral ankle sprains are the most common musculoskeletal injury among the general population and U.S. military personnel. Despite the common perception of being a minor injury, at least 1 out of 3 individuals with a previous ankle sprain will develop chronic ankle instability (CAI). This clinical phenomenon creates a significant barrier for patients to return to their prior level of physical function. Specifically, CAI is associated with reductions in physical activity level, leading to decreases in lower health-related quality of life and increase risk of developing of post-traumatic ankle osteoarthritis. Current evidence has largely focused on characterizing the mechanical and sensorimotor insufficiencies associated with CAI in adolescent and young-adult populations, with little attention on middle- and older-aged adults. This restricts our understanding of how these insufficiencies associated with CAI that develop in early adulthood progress over time and contribute to other chronic diseases such as post-traumatic osteoarthritis. Therefore, the overall objective of this study was to compare self-reported and physical function between three age groups: 1) young, 2) middle-aged, and 3) older-aged adults with and without CAI. We hypothesized participants with CAI would have age-related changes in self-reported and physical function compared to non-injured individuals across the lifespan.

The objective of this dissertation was to compare regional and global health-related quality of life (HRQoL), static and dynamic balance, spinal reflex excitability of the soleus muscle, open- and closed-kinetic chain dorsiflexion range of motion and spatiotemporal gait parameters between those with and without CAI across the lifespan. Her callIt was hypothesized that all self-reported and physical characteristics would be decrease with age, but significantly more in those with CAI compare to non-injured individuals.

Results from the first study demonstrated participants with CAI had worse regional HRQoL compared to healthy-controls as evidenced by the lower Foot and Ankle Disability Index scores. Likewise, participants with CAI reported having worse overall physical function and pain interference during activity compared to healthy-controls. There was no significant interaction for Injury (CAI and healthy-control) and Age group (young, middle, and old) for any dependent variable. In the second, it was determined that static and dynamic balance, spinal reflex excitability, ankle (dorsiflexion and

plantarflexion) and hip extension torque were all lower in the older-aged participants compared to the younger-aged adults. In addition, it was determined that participants with CAI had decreased dorsiflexion range of motion, ankle (dorsiflexion and plantar flexion) and hip extension peak isometric torque compared to the healthy-control group. However, no significant interaction was found for Injury (CAI & healthy-control) and Age (young, middle, old) for any dependent variable. In the third study, there were no differences in spatiotemporal gait parameters between groups (CAI vs. healthy-controls) or age categories.

It can be concluded from this dissertation that regardless of the age, individuals with CAI have worse region-specific HRQoL, lower overall physical function, greater pain interference, limited dorsiflexion range of motion, and decreased ankle and hip peak isometric torque compared to healthy-controls. Several age-related observations were found including decreased static and dynamic balance, ankle and hip strength, and spinal reflex excitability. Though no relationship was found between CAI and age, several interactions were found to be trending towards significance. Therefore, future work is needed to better understand the consequences of CAI on middle- and older-aged adults.

KEY WORDS: ankle instability, patient-reported outcomes, mechanical instability, functional instability, gait

Kyle B. Kosik
Student's Signature

June 6th, 2017
Date

CHRONIC ANKLE INSTABILITY AND AGING

By

KYLE B. KOSIK

Phillip A. Gribble, Ph.D., ATC, FNATA

Co-Director of Dissertation

Nathan F. Johnson, Ph.D., PT, DPT

Co-Director of Dissertation

Esther Dupont-Versteegden, Ph.D.

Director of Graduate Studies

June 6, 2017

Date

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Chapter 1: Introduction

Background

Lateral ankle sprains (LAS) account for a substantial portion of the acute injuries occurring among physical active populations including military personnel,¹ high school² and collegiate athletes,³ as well as the general population.⁴ As a result, lateral ankle sprains have become a common reason for emergency room visits causing a serious economic burden to treat these injuries.⁵ The aggregate health care cost associated with the treatment of lateral ankle sprains has been estimated to be over \$2 billion in the United States alone.⁴ While the proper healing time needed following damage to the lateral ligament complex has been suggested to be between 6 and 12 weeks,⁶ a recent report found over 75% of athletes sustaining a lateral ankle sprain returned to full activity within 7 days.⁷ A hastened return to activity likely does not provide adequate healing time and may contribute to the reported large recurrent injury rates,⁸ as well as the residual symptoms such as pain and ankle joint instability reported by up to 70% individuals with a history of an ankle sprain.⁹ Chronic ankle instability (CAI) is the comprehensive term used to describe the chronic symptoms and recurrent joint injuries previously described.

Increased concern over the development of CAI has been sparked by reports of individuals with CAI reporting lower levels of health-related quality of life,^{10,11} functional limitations,¹² and diminished physical activity levels.¹³ Furthermore, emerging evidence has illustrated that CAI increases the rate of developing posttraumatic ankle osteoarthritis, which requires costly diagnostic techniques and treatment strategies.^{14,15}

These reports provide clear evidence that CAI is a significant public health concern that requires further investigation into the factors that are associated with the development of CAI.

Over the past half-century, researchers have attempted to identify the underlying mechanism of CAI. In doing so, researchers^{16,17} have tried to link mechanical alterations of the ankle joint to the development of CAI; whereas others¹⁸ have attempted to link sensorimotor insufficiencies to the cause of CAI. In spite of this effort, no significant conclusion has been made into identifying the exact underlying mechanism that contributes to the recurrent joint injury and episodes of “giving-way” at the ankle. Rather than a singular factor related to the mechanism of CAI, it is likely that a combination of mechanical and sensorimotor insufficiencies result in CAI.

To date, the majority of the research focused on examining the consequences of CAI has been on younger-aged adults. This restricts our understanding of how the development of these mechanical and sensorimotor insufficiencies impacts the function and mobility of middle- and older-aged adults with CAI. The presence of CAI in middle- and older-aged adults might exacerbate these mechanical and sensorimotor insufficiencies because aging alone has been shown to cause deterioration in physical function.

The Problem

It is well documented that aging brings progressive reductions in physical function that negatively affect the health and independence of individuals. More specifically, age-related changes in balance,^{19,20} lower extremity strength,²¹ integrity of the spinal reflex system,²²⁻²⁵ dorsiflexion range of motion²⁶ and walking mechanics²⁷ all

have a significant impact on self-reported function²⁸⁻³² and risk of serious injury in older adults.^{25,33-35} Unfortunately, similar sensorimotor and mechanical impairments are associated with early decreases in health and function of younger-aged adults with CAI.³⁶⁻³⁹ With these impairments developing in early adulthood, the added neuromuscular consequences of CAI likely compounds the effects of aging, suggesting that individuals with a history of an ankle injury might be at risk for greater deficiencies in self-reported health and physical function as the age. However, despite the growing body of evidence demonstrating individuals with CAI develop several sensorimotor and mechanical alterations early in life,³⁷ little attention has been placed on middle- and older-aged adults with CAI.⁴⁰ Therefore, it is important to determine if middle- and older-aged adults with CAI experience exacerbated sensorimotor and mechanical insufficiencies compared to uninjured individuals.

Experimental Aims and Hypothesis

Our long-term goal is to promote healthy and regular physical activity across the lifespan by reducing the negative consequences of musculoskeletal injury. An important step in achieving this long-term goal is to understand the underlying mechanism by which aging and the additive effects of CAI compromise self-reported and physical function. The overall objective of this study was to examine the combined effects of CAI and age-related changes in neuromuscular function on health and disability across three age groups: 1) young, 2) middle-aged, and 3) elderly adults. Our central hypothesis was that the presence of CAI would amplify age-related changes in self-reported and physical-function. The research will advance our understanding of CAI by describing self-reported limitations and physical mal-adaptations that exist in patients of all ages

with CAI. A better understanding of this information will be valuable in designing novel and unique programs that are capable of restoring and maintaining function in CAI patients of all ages. To test our central hypothesis, the following specific aims were examined:

Specific Aim 1: Determine whether region specific and global self-reported measures of health-related quality of life (HRQoL) differ between young-adults, middle-aged adults and older-aged adults with and without CAI.

Hypothesis 1: Participants with CAI will self-report having worse region-specific and global HRQoL compared healthy-controls.

Hypothesis 2: Region-specific and global HRQoL will be worse in the middle-aged adults compared to the younger-aged adults; the older-aged adults will have worse scores compared to both groups.

Hypothesis 3: Younger-, middle-, and older-aged adults with CAI will self-report having worse region-specific and global HRQoL compared to their age-matched healthy counterpart.

We will evaluate region specific HRQoL using the Foot and Ankle Disability (FADI) Activities of Daily Living (ADL) and Sports subscale. To evaluate global HRQoL we will utilize the PROMIS-43 adult profile questionnaire.

Specific Aim 2: Determine if differences exist in mechanical and sensorimotor outcomes between young-adults, middle-aged adults and older-aged adults with and without CAI.

Hypothesis 4: Participants with CAI will have decreased sensorimotor and mechanical outcome measures compared to healthy-controls.

Hypothesis 5: Sensorimotor and mechanical outcome measures will be decreased in middle-aged adults compared to the younger-aged adults; the older-aged adults will have decreased sensorimotor and mechanical outcome measures compared to both groups.

Hypothesis 6: Younger-, middle-, and older-aged adults with CAI will have decreased mechanical and sensorimotor outcome measures compared to their age-matched healthy counterpart.

The sensorimotor dependent variables include eyes-open single limb balance, dynamic balance assessed by the Star Excursion Balance Test (SEBT), spinal excitability of the soleus muscle and torque measures of the ankle (dorsiflexion, plantarflexion) knee (extension), and hip (extension and abduction). The mechanical dependent variables include open-kinetic Dorsiflexion Range of Motion (DF-ROM) and the Weight-Bearing Lunge Test (WBLT).

Specific Aim 3: Determine if differences exist in spatiotemporal walking gait parameters between young-adults, middle-aged adults and older-aged adults with and without CAI.

Hypothesis 7: Participants with CAI will have decreased spatiotemporal gait variables compared to healthy-controls.

Hypothesis 8: Middle-aged participants will have decreased spatiotemporal gait variables compared to younger-aged adults; the older-aged adults will have decreased spatiotemporal gait mechanics compared to both groups.

Hypothesis 9: Younger-, middle- and older-aged adults with CAI will have decreased spatiotemporal gait variables compared to their age-matched healthy counterpart.

We will evaluate group means for the following spatiotemporal gait parameters: gait velocity, cadence, bilateral measures of step time, cycle time, stride, step length and swing, stance single-support and double-support percent of gait cycle.

Significance

The current body of literature has identified numerous sensorimotor and mechanical insufficiencies associated with CAI in young-adults. As a result, researchers have been successful at designing rehabilitation programs to target the sensorimotor^{41,42} and mechanical^{16,43} insufficiencies, along with patient-oriented outcomes.⁴⁴ Despite the long-term health consequences associated with an ankle sprain, the majority (~93%) of patients never receive physical therapy.⁴⁵ Consequently, it is likely that individual's sustaining an ankle sprain early in life will continue to experience residual symptoms and loss of function throughout their life. Yet, the majority of the research examining the consequences of an ankle sprain is within young-adults, with little attention on middle-aged and older-aged adults with ankle sprain history. This restricts our knowledge of how to treat these different age populations and whether current treatment techniques are translatable to older adults.

Therefore, this research is significant because it: (1) will guide future investigations into examining the underlying mechanisms associated with CAI in older adults; (2) provide a framework for future rehabilitation interventions designed for individuals across the lifespan; and (3) direct future research in understanding the

relationship between CAI and other chronic injuries. This research is an important step forward in promoting a healthy aging process.

Operational Definitions

Chronic Ankle Instability: a self-reported ankle pathology characterized by recurrent ankle sprains, repeated episodes of ‘giving-way and/or perceived ankle instability.

Dorsiflexion: Sagittal plane motion in which the angle of the leg and dorsum of the foot decrease.

Dynamic Postural Control: An individual’s ability to maintain their center of mass within their base of support while transitioning to a more difficult position.

Global Health Related Quality of Life: A multidimensional approach of understanding an individuals overall-well being by assessing an individual’s social, physical and psychological health.

Hip Abduction: Frontal plane motion in which the leg moves away from the body.

Hip Extension: Sagittal plane motion in which the upper leg moves behind the trunk.

Hoffman Reflex: An electrically induced reflex equivalent to the spinal stretch reflex.

Knee Extension: Sagittal plane motion in which the angle between the upper and lower leg approaches zero.

Maximal Hoffman Reflex: Estimate of the proportion of motoneurons an individual is capable of activating maximally.

Maximal Muscle Response: Electrically induced activation of the entire motoneuron pool.

Plantarflexion: Sagittal plane motion in which the angle of the leg and dorsum of the foot increase.

Region-Specific Health Related Quality of Life: A multidimensional approach of understanding how a specific condition or body-region by assessing an individual's social, physical and psychological health.

Sensorimotor Function: The process of sensory information being transmitted to the central nervous system, the integration and processing of this sensory information and the motor output produced.

Spatiotemporal: Descriptors of gait related to space and time.

Static Postural Control: An individual's ability to maintain their center of mass within their base of support while minimizing any segment or body movement.

Star Excursion Balance Test: A series of single-limb squats requiring an individual to reach maximally in different directions while maintaining their balance.

Time-to-Boundary: A spatiotemporal analysis of the anteroposterior and mediolateral center of pressure (COP) trajectories that estimates the time it would take for the (COP) trajectories to reach the boundary of the base of support if it was to maintain its path and velocity.

Torque: The amount of rotational force produced around a center of axis.

Assumptions

It will be assumed:

- 1) Participants enrolled into the CAI group have the condition of interest.
- 2) Participants enrolled into the middle-aged and older-aged category with CAI sustained their first ankle sprain before the age of 35 years old.
- 3) Participants gave their best effort during data collection.
- 4) Participants answered questions on all patient-reported questionnaires truthfully.

Delimitations

- 1) Participants with symptomatic ankle osteoarthritis were not enrolled.
 - a. Participants with symptomatic ankle osteoarthritis were not enrolled because osteoarthritis alone is known to impact several of these outcomes.
- 2) All participants were free from any: 1) diagnosed balance, vestibular or respiratory disorder; 2) history of low back pain in the previous 6 months; 3) history of seizures; 5) history of concussion in the past 6 months; 6) history of neurological injuries or diseases
 - a. Participants will be free of any peripheral neuropathies because of their potential influence on the outcome variables included.
- 3) All participants will be free from lower extremity surgery.
- 4) All participants will not be allowed to use any assistive-walking device.
- 5) All participants will have no history of lower extremity surgery.
- 6) All assessments will be performed barefoot.

Chapter 2: Review of the Literature

Introduction

Lateral ankle sprain is the most common lower extremity injury among young physically activity individuals. Epidemiological studies indicate up to 40% of injuries among U.S. high school athletes are classified as an ankle sprain.^{2,8} These trends continue into collegiate athletics, with reports from the National Collegiate Athletic Association injury surveillance program indicating between 7%⁷ and 15%³ of all injuries reported are classified as an ankle sprain. Moreover, previous research has found the incidence rate for ankle sprains among U.S. military personnel to range from 34.95¹ to 45.14⁴⁶ per 1000 person-years; 5 times greater than the general population. Considering the increase in sport participation, it is reasonable to speculate the rate of ankle sprains will continue to increase.

The high incidence rate is not limited to athletes and military personnel. Data collected from emergency departments clearly demonstrates ankle sprains are common among the general population. During the span of a single year, researchers found ankles sprains were the most common reason for individuals attending the emergency department in the U.S.⁵ Specifically, the authors estimated the incidence rate to be 2.06 per 1000 person-years.⁵ This was confirmed by a later study that reported the incidence rate for an ankle sprain over four-years to be 2.15 per 1000 person-years.⁴⁷ Therefore, damage to the lateral ligament complex is a serious concern among the general population.

While incidence rate is the highest for individuals between 15 and 24 years of age,⁴⁷ older populations are at risk of sustaining an ankle sprain. The foot and ankle is the second most common injured body site among physically active older adults (>50 years).^{48,49} Notably, the incidence for ankle sprain in the U.K. for adults 50 years and older reporting to emergency departments range from 1.4 to 3.7 per 1000 person-years.⁵⁰ These epidemiological reports for an ankle sprain demonstrate the significant impact these injuries have on individuals of all ages and physical activity levels.

The high incidence rate of an ankle sprain not only causes concern, but the prognosis of an ankle sprain can be poor. At least 1 out of 3 individuals with a previous ankle sprain will experience residual symptoms.^{9,51-54} Primary complaints include persistent pain and swelling, fear of ‘giving-way’, loss of function and recurrent ankle sprains.^{9,51-55} Chronic ankle instability (CAI) is the term used to describe these lingering symptoms.^{36,56} Tanen et al⁵⁷ surveyed 512 high school and Division 1 collegiate student athletes and found approximately 25% of athletes reported having CAI when measured using the Cumberland Ankle Instability Tool (CAIT). While CAI is most often identified in younger-aged populations, investigators examining the prevalence of chronic musculoskeletal ankle pathologies among the general population (age 18 to 65 years) provide evidence that lingering symptoms after an ankle sprain impact individuals of all ages. Hiller et al⁵⁸ found that 23.7% of participants surveyed had a chronic ankle disorder, with 50% of individuals reporting symptoms lasting longer than 10 years. Furthermore, of those who reported having a chronic ankle disorder, 65% of individuals reported having to limit or modify their physical activity level because of their ankle.⁵⁸

Even more troubling than the high prevalence rate of individuals developing CAI⁵⁷ after an ankle sprain are the general health-related consequences that are associated with CAI. Researchers examining the health-related quality of life (HRQoL) have found individuals with CAI report having worse region-specific and global (HRQoL) compared to uninjured individuals. Houston et al¹⁰ undertook a systematic review with meta-analysis and found strong evidence suggesting participants with CAI report worse region-specific HRQoL compared to healthy-controls. Furthermore, investigators¹² have found that the presence of CAI results a deterioration of global HRQoL. These findings indicate that CAI does not only impact how they perceive their ankle function, rather, it has an influence on individuals overall well-being.

Reports examining the health consequences associated with developing CAI at an early age suggest that it can create a significant barrier for individuals to remain physically active.^{13,58} Hubbard-Turner and Turner¹³ found college-aged students with CAI took fewer steps during a 7-day period compared to age-matched healthy-controls, suggests those with CAI participate in less physical activity. A reduction in physical activity following an acute ankle sprain is not limited to younger-aged adults; rather, emerging evidence suggests physical activity is decreased throughout the lifespan. Hiller et al⁵⁸ found the majority of participants (aged 18-65 years) with chronic musculoskeletal ankle disorders limited or modified their activity. Moreover, researchers^{13,59} using animal models have demonstrated mice with an acute ankle sprain ran significantly fewer minutes each day throughout their lifespan compared the control group. This decrease in physical activity following can potentially lead to the development of other chronic disease. Indeed, Turner et al⁵⁹ found the mice with an ankle sprain history and reduced

physical activity levels had decreased performance of the left ventricle, suggesting that an ankle sprain might initiate a negative cycle of events across the lifespan.

Furthermore, a majority of individuals never seek formal rehabilitation after a traumatic ankle joint injury^{45,60} and return to physical activity before adequate healing can occur.^{6,7} Inadequate treatment and a hastened return to physical activity level likely contribute to the development of post-traumatic osteoarthritis seen in patients with CAI. It has been suggested that between 66-78% of patients with CAI develop ankle PTOA.¹⁵ The progression of PTOA is concerning because it can develop as soon as 10 years after CAI onset.⁶¹ This means that ankle PTOA could present as early as the 3rd decade of life.⁶¹ Ankle arthrodesis (fusion) remains the standard of care for treating ankle PTOA because few non-surgical treatment options exist.⁶² However, ankle arthrodesis is not ideal as it causes biomechanical changes up the kinetic chain.⁶³ Therefore, the potential CAI has on triggering the onset of other chronic diseases associated with decreased physical activity levels and stress-related joint diseases like osteoarthritis, makes CAI a significant public health concern. By examining the factors related to the development of CAI, more effective interventions can be designed to reduce the potential for other chronic diseases from occurring and help individuals maintain a healthy and active lifestyle.

Despite a growing body of evidence, the exact etiology behind the development of CAI remains unknown. Hertel et al³⁷ first proposed a theoretical model suggested that the development of CAI was likely caused by a combination of mechanical and sensorimotor insufficiencies. This caused researchers to start examining several different sensorimotor alterations such as static and dynamic balance, spinal reflex excitability,

impaired proprioception, lower extremity strength and muscle activation patterns in participants with CAI. Sefton et al¹⁸ used 25 different sensorimotor outcome variables to discriminate between participants with and without CAI. This study¹⁸ revealed 7 separate variables related to static balance and spinal reflex excitability accurately classified approximately 85% of participants with CAI. Because Sefton et al¹⁸ did not include any measures of mechanical instability, Hubbard et al³⁸ included a wide spectrum of mechanical and sensorimotor outcomes to identify which variables are most predictive of CAI group membership. Interestingly, the authors³⁸ found that decreased anterior and posteromedial reach of the SEBT, plantarflexion peak torque, and increased inversion laxity were best at discriminating between individuals with and without CAI.

Both of these studies^{18,38} highlight the multifactorial nature of CAI. In response, Hiller et al⁶⁴ proposed that CAI is not a homogenous population. Rather, several sub-groups likely make up the development of CAI. Therefore, Hiller et al⁶⁴ proposed an updated model of CAI by sub-classifying participants into three categories: those with 1) mechanical instability; 2) perceived instability; and 3) recurrent joint injury. They suggested that each of these, including those with recurrent sprain, can exist independently or in combination.⁶⁴ Using this model, Terada et al⁶⁵ examined differences in selected sensorimotor, mechanical, and psychological measures, revealing 8 outcome measures from neural excitability postural control, static postural and HRQoL and that correctly classified only 58% of group membership for participants with perceived instability and recurrent joint injuries.

Therefore, CAI is a multifactorial and heterogeneous population that requires an in-depth understanding of the multiple negative health consequences associated with it

and the factors that contribute to its etiology. The purpose of this literature review is to: 1) discuss the current evidence regarding the self-reported limitations associated with CAI, 2) discuss the current evidence regarding sensorimotor insufficiencies including static & dynamic balance, spinal reflex excitability and strength, 3) discuss the current evidence regarding mechanical insufficiencies including open- & closed-kinetic chain range of motion associated with CAI, 4) discuss the alterations in gait biomechanics associated with CAI.

Health-Related Quality of Life

The evaluation of health-related quality of life (HRQoL) has been increasingly recognized in healthcare as an important component of evidence-based medicine because it provides valuable information on how the patient perceived their health condition.⁶⁶ HRQoL is a multidimensional concept that is targeted at understanding multiple domains of health including the physical, psychological, and social domains, all of which are affected by individual experiences, expectations, beliefs, and perceptions.⁶⁷ HRQoL is typically evaluated through the use of patient-oriented outcome instruments, which are questionnaires or surveys that ask patients about their health status.⁶⁷ These patient-oriented outcome instruments are differentiated as either global (generic) or region-specific. Global outcome tools are multidimensional to allow for the assessment of multiple health domains and to provide a general understanding of individual's health status.⁶⁷ The advantage of global outcome instruments is their utility for assessing HRQoL within or across several different patient populations. Whereas region-specific instruments are used in the evaluation of a the specific health domain that can be affected by a certain injury, disease, body region or injury site.⁶⁷ These outcome instruments are

designed by using questions that are highly relevant to a condition or injury. The high specificity associated with region-specific questionnaires makes them more apt to observe a change resulting from a treatment or therapeutic intervention.⁶⁷ Furthermore, this high specificity has enabled region-specific instruments to be used as discriminative or evaluative.⁶⁸ Discriminative instruments are used to identify individuals with a particular injury or disease (i.e. CAI). In contrast, evaluative instruments are designed to measure an individual's change in health status because of a specific injury or disease. Therefore, because the aim of this dissertation is to understand the long-term impact CAI has on changing an individual's health status, this literature review will only focus on previous literature using the patient-reported outcomes to evaluate a change in health status associated with CAI. Furthermore, because HRQoL is evaluated using both global and region-specific outcome tools, this literature review will discuss the previous studies evaluating both concepts separately.

Region Specific

Before discussing the evidence demonstrating CAI is associated with worse region-specific HRQoL compared to healthy-controls, it is necessary to acknowledge the multiple patient-reported questionnaires used to assess region-specific HRQoL in patients with CAI.¹⁰ Eechaute and colleagues⁶⁹ undertook a systematic review to identify the evaluative instruments for individuals with CAI and review the evidence to support their use. Four instruments were found within the literature: the Ankle Joint Functional Assessment Tool (AJFAT), the Foot and Ankle Outcome Score (FAOS), the Foot and Ankle Disability Index (FADI), and the Foot and Ankle Ability Measure (FAAM).⁶⁹ Eechaute et al⁶⁹ concluded that the FAAM and FADI are the most appropriate patient-

assessed tools to quantify self-reported functional limitations related to CAI because of the overall strong strong clinimetric properties reported within the literature. Hale and Hertel⁷⁰ first demonstrated the FADI has good to strong content and construct validity, reliability and responsiveness in patients with CAI. After that, the FADI underwent rigorous psychometric analysis and it was determined that four items related to pain and one item related to sleep could be eliminated from the original FADI. Subsequently, the FAAM was designed and has been shown to have acceptable and useful test-retest reliability, content and construct validity, and responsiveness in patients with foot and ankle disorders.^{71,72} Furthermore, the advantage of the FAAM and FADI over the AJFAT and FAOS is that both questionnaires include a sports subscale. This subscale is useful in better understating the functional impairments patients with CAI experience related to exercise.

Region-specific questions are often used to identify functional limitations in patients with CAI.^{70,72-90} Because of the overwhelming amount of evidence for decreased region-specific HRQoL in patients with CAI, Houston et al¹⁰ conducted a comprehensive review of the literature to critically appraise the current evidence assessing self-reported limitations between those with and without CAI. Based on the meta-analysis performed, the authors¹⁰ found strong evidence to suggest that individuals with CAI report having greater self-reported functional limitations related to activities of daily living and sports because of their foot and ankle compared to healthy-controls and Copers. This was determined through the use of several questionnaires such as the FAAM, FADI, AJFAT, and the Cumberland Ankle Instability Tool (CAIT). Therefore, it was concluded that individual with CAI have greater difficulty completing activities of daily living and tasks

related to exercise because of their ankle compared to uninjured controls and Copers. However, Houston et al¹⁰ found conflicting evidence when they compared the self-reported questionnaires between a group of healthy-controls and a group of individuals identified as being a Coper. The lack of consistency between these studies indicates that individuals with CAI develop unique impairments following an ankle sprain that result in decreased self-reported function.¹⁰

Whereas majority of the evidence suggesting CAI is associated with decreased region-specific HRQoL, research demonstrating improved scores on patient-reported outcomes tools in patients with CAI provides further support.^{16,42,43,91-104} Kosik et al⁴⁴ systematically reviewed the literature identifying common therapeutic interventions used to improve region-specific HRQoL in patients with CAI. The authors⁴⁴ found a variety of therapeutic interventions have been used to target region-specific HRQoL in patients with CAI including balancing training,^{91,92,96,99,101,105} multi-modal,^{95-97,100,102,103} joint mobilization,^{16,42,43,98} resistive training,^{99,105} calf-stretching,⁴² soft-tissue mobilization,⁴² and orthotics.⁹³ The authors found consistent evidence suggesting that balance training is the most effective intervention for improving self-reported limitations related to activities of daily living and exercise.

Taken together, these two systematic reviews^{10,44} provide strong evidence that ankle region-specific HRQoL is compromised by the development of CAI. Therefore, measures related to ankle region-specific HRQoL are needed to provide a better understanding of the long-term implications of CAI.

Global

The short form-36 (SF-36) is the most common patient-oriented outcome measured used to assess global HRQoL. The SF-36 is constructed of 8 domain scales: physical function, role-physical, bodily pain, general health, vitality, social functioning, role emotional, and mental health. These scales are combined to create the physical component scale and mental component scale. Using the SF-36, Anandacoomarasamy et al⁹ first conducted a retrospective case control study to evaluate the global HRQoL in a group of patients referred to a large metropolitan hospital in Australia for an acute lateral ankle sprain. The authors contacted the patients at an average of 29 months after reporting to the hospital.⁹ The results demonstrated the patients who had sprained their ankle reported lower scores on the SF-36 compared to the age-matched healthy-control group.⁹ These findings provide evidence that an ankle sprain can significantly influence an individual's global HRQoL. However, the limitation of this study was that the authors did not confirm if the patients developed CAI. Subsequently, Arnold et al¹¹ enrolled a group of participants with and without CAI and compared scores on the SF-36. The participants with CAI reported lower scores on the SF-36 physical component summary scale, physical function domain scale and the bodily pain domain scale.¹¹ These results provide evidence that CAI impacts the overall physical health of individuals. However, CAI does not appear to impact the mental health of individuals. While this study demonstrated evidence for the negative impact CAI has on global HRQoL, all of the participants included scored higher than the normative scores reported for the general population.¹¹ The disparity between the results from Arnold et al¹¹ and SF-36 normative scores reported for the general population¹⁰⁶ was likely because the authors enrolled

younger-aged physical active adults. Therefore, Houston et al¹² evaluated the global HRQoL in a cohort of control group using the Disablement in the Physically Active Scale (DPA). The DPA was designed specifically to evaluate the global HRQoL for physically active individuals, and, therefore might be a better tool for assessing global HRQoL in younger-aged adults with CAI.¹⁰⁷ Not surprisingly, Houston et al¹² demonstrated lower scores on the DPA in the group of subjects with CAI compared to the healthy-control group. These results further confirm the previous studies reporting lower global HRQoL in participants with CAI.^{9,11} Taken together there is strong evidence demonstrating CAI is associated with lower global HRQoL compared to uninjured individuals.¹⁰ Therefore, global HRQoL should continue to be examined in those with CAI to provide a better understanding of the negative consequences associated with CAI

Sensorimotor Alteration of CAI

Postural Control

Balance is an individual's ability to maintain their center of mass within their base of support to avoid falling. Balance, or postural control, is measured under static and dynamic conditions. Measures of static postural control require the individual to establish a stable base of support and minimize any segment or body movement. Conversely, dynamic balance is measured by evaluating an individual's ability to maintain their balance while transitioning from a dynamic to a static position. Dynamic postural control is believed to more accurately reflect the demands of physical activity than the assessment of static postural control.

Several valid and reliable non-instrumented and instrumented methods are used for evaluating static and dynamic postural control deficits in those with CAI. Non-

instrumented measures have the advantage of requiring little equipment or experience to perform and can be done at the clinic.¹⁰⁸ While non-instrumented measures of balance might be more useful in the clinic, they might not be sensitive enough to detect subtle differences in postural control between those with and without CAI. Therefore, this section will provide a review of the current literature for both instrumented and non-instrumented assessments of static and non-instrumented measures for dynamic balance.

Static Postural Control

Non-Instrumented Methods

The balance error scoring system (BESS) is a standard clinical test often used to quantify postural control while balancing for 20-seconds on two different surfaces (firm and foam) and in three different stances (double, tandem, and single). Balance is quantified based on the number of errors during each test, with greater errors corresponding with worse static balance. Using a modified Rhomberg test, a component of the BESS, Freeman et al¹⁰⁹ were the first to report patients with a history of repetitive ankle sprains had worse static balance compared to un-injured controls. Docherty et al¹¹⁰ later confirmed these findings when they used the full version of the BESS. Specifically, the researchers¹¹⁰ found that participants with CAI had a greater total number of errors on the BESS compared to healthy controls.

The foot-lift test is another error-based clinical assessment of static balance. Similar to the BESS, participants are required to balance on a single-limb for 30-seconds and the number of times any part of the foot loses contact with the ground is counted as an error.¹¹¹ Relative to healthy-controls, individuals with CAI have a greater number of foot-lifts during a 30-second trial.¹¹²

Collectively, these findings indicate error based assessments of static balance are capable of distinguishing between those with and without ankle instability. While these results are valuable, more research is needed to determine whether error based measures of static balance are sensitive to identify improvements in balance following rehabilitation.

Instrumented Methods

Instrumented measures of single-limb balance have become standard for identifying balance deficits associated with ankle instability. As a result, several dependent variables have been derived to quantify differences in the center-of-pressure (COP) between groups; however, two common dependent variables include the overall length of the path of COP and the COP velocity. Based on individual reports comparing instrumented measures of balance, the literature seems to suggest that those with CAI have worse static balance relative to uninjured controls. However conflicting results exist and make it difficult to reach a definitive conclusion.¹¹³⁻¹¹⁶ In the attempt to better understand the relationship between ankle instability and single-limb balance, a series of systematic reviews¹¹⁷⁻¹²⁰ and subsequent meta-analyses¹¹⁸⁻¹²¹ have been conducted to synthesize the evidence to better understand this relationship. Therefore, the current literature review will highlight these systematic reviewers and meta-analysis.

McKeon and Hertel¹¹⁷ performed a comprehensive literature review to summarize the evidence related to ankle instability and postural control deficits in those with CAI. The authors retrieved eight articles comparing single-limb balance between those with and without CAI. The analysis revealed a broad range of point estimates (-0.29 to 1.31), with positive effect sizes indicating worse postural control in the CAI group. Although

several of the point estimates suggest worse postural control in the CAI group, several of the confidence intervals crossed zero. Therefore, based on these findings the authors were unable to conclude whether balance deficits are associated with CAI.

Despite the lack of consensus reported by McKeon and Hertel,¹¹⁷ a series of meta-analyses were later conducted to determine if postural control deficits are present in those with CAI.¹¹⁹⁻¹²¹ Compared to a systematic review, a meta-analysis compiles all of the evidence and provides a quantitative estimate of the overall effect size. Wikstrom et al¹¹⁹, using fifteen articles comparing single-limb balance between those with and without CAI, reported a moderate cumulative effect size (ES = 0.570, CI: 0.426 to 0.714, $p < 0.0001$) suggesting postural control deficits are associated with CAI. Arnold et al¹²¹ found similar results; however, they noted time-based measures of single-limb balance were more likely to differentiate between those with and without an injured ankle. Collectively, these findings provide evidence CAI is associated with single-limb balance deficits, particularly when time-based measures of single-limb balance are utilized.

The above research provides strong evidence that postural control on the involved limb is impaired in those with CAI. However, centrally mediated changes have been previously reported that might impact postural control on the uninvolved limb in those with CAI. Therefore, Wikstrom et al¹¹⁸ performed a systematic review and meta-analysis to determine if bilateral postural control impairments are associated with CAI. Results from the meta-analysis indicated that CAI is associated postural control impairments on the involved limb (ES = 0.388, CI: 0.153 to 0.623, $p < 0.001$) but not the un-involved limb (ES= 0.070, CI: -0.16 to 0.301, $p = 0.552$) compared to uninjured controls. The authors attributed the lack of bilateral postural controls deficits in those with CAI to the

myriad of postural control methods, the wide range of inclusion criteria used to identify individuals with CAI and a lack of statistical power.¹¹⁸ While the authors failed to identify a difference in bilateral postural control, several reports have demonstrated bilateral neuromuscular control deficits at both the ankle and proximal joint structures. Therefore, clinicians should consider global rehabilitation programs for both the involved and uninvolved limbs for those with CAI.

Dynamic Postural Control

Non-instrumented Methods

The Star Excursion Balance Test (SEBT) was first described as a rehabilitative tool for lower extremity injuries but has gained popularity for its clinical utility to identify dynamic postural control impairments among people with ankle instability.¹²² The SEBT is a series of 8 reach distances that evaluates an individual's ability to maintain a stable base of support during a single-limb stance while using the non-stance limb to maximally reach in 1 of 8 designated directions. Smaller reach distances are indicative of worse dynamic postural control.

Early reports assessing test-retest reliability found overall poor intertester and intratester reliability. Intratester reliability estimates (intraclass correlation coefficients [ICC]) for the anteromedial, anterolateral, posteromedial and posterolateral ranged from 0.67 to 0.87.¹²³ However, when examining scores of the SEBT, Robinson and Gribble¹²⁴ found a practice effect associated with the performance of the SEBT, with participants reaching farther as they performed more trials. Subsequently, they found that the scores on the SEBT stabilized after the fourth practice trial, making the recommendation that at least 4 practice trials be given before recording reach distances. Once controlling for the

number of practice trials, the test-retest reliability (ICC) ranged from 0.84 to 0.92.¹²⁵ Further investigation into the properties of the SEBT revealed that there was considerable redundancy when performing all 8-reach directions of the SEBT.¹²⁶ To avoid capturing redundant information, authors¹²⁶ have recommended that only 3-reach directions (anterior, posteromedial, and posterolateral) should be conducted. Another important consideration for the SEBT is normalization. Gribble and Hertel¹²⁷ found maximum reach distances on the SEBT are strongly correlated with limb-length. Therefore, the authors¹²⁷ recommend normalizing the distance reached to subjects' limb-length to make a valid comparison between groups.

Olmsted et al¹²⁸ were the first to identify dynamic balance deficits among those with CAI using the SEBT. The total score for all 8 directions was lower in the ankle instability group (78.6cm) compared to the control group (82.8cm) and when compared to the non-injured side (81.2cm).¹²⁸ The decreased reach distance observed within the CAI group resulted in the authors concluding the SEBT is capable of detecting differences in dynamic balance between those with and without CAI. However, as mentioned above, limb length is significantly correlated with reach distance and should be considered when comparing between groups. Therefore, Gribble et al¹²⁹ advanced this work by showing that the normalized reach distances for the CAI group in the anterior ($p=0.03$), medial ($p=0.02$), and posterior ($p=0.02$) directions were significantly less compared to the control group. Several authors^{16,18,122,126,130,131} have later confirmed decreased test performance among patients with CAI compared to healthy individuals. Collectively, the decreased reach distance observed on the SEBT indicates individuals

with CAI have to remain closer to the center of their base of support when performing a maximal reach to prevent from falling over.¹²²

Spinal-Reflexive Excitability

Investigators have pointed towards arthrogenic muscle inhibition (AMI) as one possible explanation for the neuromuscular dysfunction observed in the surrounding ankle musculature of those with CAI.¹⁸ AMI is an ongoing reflex inhibition of the uninjured musculature surrounding an injured or distended joint.¹³² This reflexive inhibition is hypothesized to be a protective mechanism to decrease excessive forces from acting on an injured joint.¹³³ However, persistent inhibition of the surrounding ankle musculature can be detrimental to an individual's recovery after a traumatic ankle joint injury.¹³³

Depressed motor neuron pool excitability (MNPE) is the hallmark characteristic of AMI.¹³³ The Hoffman reflex (H-reflex) is a technique commonly used to estimate the MNPE of a targeted muscle. H-reflex represents the proportion of the motor units excitable by a stimulus of the afferent pathway of a peripheral nerve.¹³² Whereas the afferent and efferent pathways contribute to the H-reflex, electrical stimulation of a peripheral nerve can also evoke a purely efferent response commonly referred to as the maximal muscle response (M-response).¹³² The M-response is representative of the maximal excitability of the motor-neuron pool.¹³² Therefore, the H-reflex is often normalized to the M-response to obtain the H:M ratio.¹³² The H:M ratio represents the proportion of the motor neuron pool capable of being activated relative to the maximal motor neuron pool excitability.¹³² A smaller H:M ratio would suggest fewer motor neurons are available to be recruited and, therefore, indicate the presence of AMI.

Authors have examined changes in motor neuron pool excitability using artificial ankle-effusion models,¹³⁴ however, only one group¹³⁵ has compared the effect of an acute ankle sprain on the motor neuron pool excitability. Klykken et al¹³⁵ examined the H:M ratio of the soleus, tibialis anterior, and fibularis longus of the injured limb 24 to 72 hours after an ankle sprain with that of the uninjured contralateral limb and the leg of healthy controls. Interestingly, the only significant difference was the soleus H:M ratio of the injured leg was higher than in the uninjured limb.¹³⁵ The increased motor neuron pool excitability observed was attributed to those with an acutely sprained ankle attempt at placing the injured ankle in a more open-packed position to prevent stress being put on the injured tissues.¹³⁵ The researchers were quick to point out that placing the ankle in a more open-packed position might predispose an individual to a chronic injury because the ankle is in a less stable position and subsequently more likely to invert.¹³⁵

No serial investigation of the motor neuron pool excitability of the soleus after an acute ankle sprain exists. However, it is reasonable to speculate that if the soleus muscle is not targeted after an acute ankle sprain during rehabilitation, persistent alterations in the motor neuron pool excitability of the soleus may contribute to the development of CAI. The importance of targeting alterations in motor neuron pool excitability is seen best by the results of Sefton et al¹⁸ who found changes in spinal reflex excitability of the soleus, along with measures of static balance, to accurately classify 86% of participants with CAI. Also, studies documenting changes in spinal reflex excitability of the soleus muscle between those with and without CAI lend further support towards the contention that persistent changes in spinal reflex excitability of the soleus is a key factor in the development of CAI.

McVey and colleagues¹³⁶ compared the soleus, tibialis anterior and fibularis longus H:M ratio bilaterally in a group of subjects with CAI. The H:M ratio of the soleus and fibularis longus were smaller in the injured limb compared to the uninjured leg. Although these findings were an important step forward in demonstrating the presence of AMI in those with CAI, they did not incorporate a control group.¹³⁶ Not including a control group may result in an inaccurate conclusion for whether actual changes occur in the involved limb because bilateral alterations that are caused by changes in spinal reflex excitability have been observed in those with CAI.¹¹⁸

Bowker et al¹³⁷ compared the soleus H:M ratio between three different groups of subjects (CAI, Coper, and healthy-control). Participants included in the Coper group were required to have a history of an acute lateral ankle sprain, but not report any residual symptoms associated with the ankle sprain. Researchers have advocated for the comparison of a Coper group because a Coper is thought to resemble a successful recovery after an acute ankle sprain.¹³⁸ The soleus H:M ratio was lower in the leg of the CAI group compared to the Coper and healthy-control groups, whereas the H:M ratio in the Coper group was similar to that of the control group.¹³⁷ The larger H:M ratio seen in the Coper group compared to the CAI group highlights the importance of reestablishing recruitment of the soleus muscle after an acute ankle sprain. The researchers also emphasized the importance of maintaining adequate motor neuron pool excitability of the soleus when considering the role of the soleus in controlling single-limb balance.

Indeed, researchers have found that changes in spinal reflex excitability of the soleus are associated with postural control alterations in subjects with CAI. Sefton et al¹³⁹ evaluated changes in H:M ratio, pre-synaptic and post-synaptic inhibition during double-

and single-limb stance in a group of subjects with CAI and healthy-controls. The H:M ratio was not different between limbs or groups, but the authors did observe changes in pre-synaptic and post-synaptic inhibition between groups. More specifically, the healthy-control subjects were able to suppress their pre-synaptic inhibition when transitioning from double- to single-limb balance. The participants with CAI were unable to modulate their pre-synaptic inhibition when changing stances. Modulating pre-synaptic inhibition is hypothesized to be necessary to control for changes in the environment. Therefore, the lack of modulation observed in the CAI group provides a possible rationale for the difficulty patients with CAI have interacting with the environment.

In a series of investigations, Kim et al^{140,141} examined the modulation of the H:M ratio of the soleus and fibularis longus when transitioning from prone-to-bipedial, bipedal-to-unipedal, and prone-to-unipedal in a group of subjects with CAI and a healthy control group. Results from these investigations demonstrated as the body position became more difficult, the soleus and fibularis longus H:M ratio decreased in healthy subjects.¹⁴² Conversely, subjects with CAI presented with less modulation for the soleus and fibularis longus compared to the healthy control group when going from prone-to-unipedal.¹⁴¹ In subjects with CAI, a moderate and positive correlation as found between the altered down-regulation of the fibularis longus and single-limb balance, indicating less modulation is associated with worse postural control.¹⁴¹ Whereas moderate and positive correlations between modulation of the soleus H:M ratio and self-reported function related to activities of daily living and physical activity were found.¹⁴⁰

Furthermore, research investigating the efficacy of balance training has shown improvements in motor neuron pool excitability of the soleus in subjects with CAI.

Sefton et al¹⁴³ compared outcomes before and after a 6-week balance-training program in a group of subjects with CAI to a healthy-control group. The balance-training program required participants to balance on a platform containing a marble maze. The level of difficulty progressed by raising the center support height when the participants were able to complete the maze 8-times in 3 minutes or less. In addition to improved dynamic balance and joint position sense, the researchers found the 6-week balance-training resulted in significantly higher H:M ratios and pre-synaptic inhibition of the soleus during a single-limb stance in subjects with CAI compared to the healthy-control group. The higher H:M ratio after the training program indicates that participants with CAI were able to recruit a higher percentage of available motor neurons compared to the healthy-control group. The greater pre-synaptic inhibition during a single-limb stance suggests that subjects with CAI might be able to respond more accurately by dampening an unwanted perturbation while balancing compared to healthy controls.

Strength

Decreased strength of the surrounding ankle musculature has been purported as a potential contributing factor to the development of CAI because early reports demonstrated a significant proportion of individuals presenting with residual symptoms following an acute lateral ankle sprain had decreased evtor muscle strength.^{144,145} This led authors to conclude that a loss of peroneal muscle strength would predispose an individual to develop residual symptoms because the peroneal muscle group would not be strong enough to counteract the ankle from inverting and moving into an injurious position when making contact with the ground.^{144,146} However, the decreased peroneal muscle strength found in these early reports should be taken with caution as the authors

evaluated muscle strength based on manual muscle testing. Manual muscle testing is useful when used in the clinic; however, manual muscle testing can be less accurate and result in a subjective interpretation of strength. Therefore, a considerable amount of attention has been given to determine if a deficit in eversion ankle strength is the cause of ankle instability.

Tropp¹⁴⁷ was the first to compare eversion isokinetic peak torque using a Cybex isokinetic dynamometer. Compared to the un-involved limb, the involved limb had lower concentric eversion peak torque values at $30^\circ/\text{sec}^{-1}$ and $120^\circ/\text{sec}^{-1}$.¹⁴⁷ The findings from Tropp,¹⁴⁷ along with follow-up investigations comparing eccentric¹⁴⁸⁻¹⁵⁰ and eccentric/concentric ratios,¹⁵¹ support the initial hypothesis that decreased evector ankle strength is an important factor in the development of residual symptoms after an acute lateral ankle sprain. However, a considerable amount of disagreement exists within the literature that disputes the concern for a decrease in evector ankle strength among those with CAI.^{114,152-159} In particular, Lentell et al^{154,155} compared concentric eversion peak torque at $0^\circ/\text{s}$, $30^\circ/\text{s}$, $90^\circ/\text{s}$, $150^\circ/\text{s}$ and $210^\circ/\text{s}$ between the involved and un-involved limb in subjects with unilateral CAI. There was no significant bilateral difference in peak torque at any velocity causing the authors to conclude eversion strength might not be a primary concern when treating those with CAI.^{154,155} Furthermore, Kaminski et al¹⁵² performed an extensive investigation comparing isometric, concentric and eccentric peak torque values at $0^\circ/\text{s}$, $30^\circ/\text{s}$, $60^\circ/\text{s}$, $90^\circ/\text{s}$, $120^\circ/\text{s}$, $150^\circ/\text{s}$ and $180^\circ/\text{s}$ between subjects with and without CAI. The results from this study demonstrated that there is no difference strength regardless of the type of muscle contraction or velocity between subjects with unilateral CAI when compared to the control group.¹⁶⁰ The inconsistent results for

whether those with CAI suffer from decreased evertor ankle strength indicates that other factors related to muscle function might be more important. For instance, previous authors examining subjects with CAI have found a difference peroneal reaction time.¹⁶¹ In addition, when considering prior research demonstrating those with CAI strike the ground with a more inverted foot, timing of muscle activation might also be an important factor.¹⁴⁶ Indeed, researchers have observed a delay in the onset of peroneal muscle activation while walking^{162,163} and during a jump-landing.¹⁶⁴

Given the debate over whether eversion ankle strength predisposes an individual to experience the residual symptoms associated with CAI, it is reasonable to suspect that if strength deficits do occur around the ankle, they likely occur in other muscle groups. Research by Ryan¹⁶⁵ documented a deficit in inversion ankle strength of the involved limb versus the un-involved limb in subjects with CAI. Decreased inversion ankle strength seems paradoxical with the mechanism of injury and symptoms associated with CAI; however, later investigations found similar findings.^{151,156} Authors speculated that a reduction in inverter ankle strength likely develops in those with CAI because of selective inhibition.^{156,165} The theory of selective inhibition was conceptualized by Swearingen and Dehen¹⁶⁶ when they speculated that following damage to a joint, a reflex mechanism is triggered that inhibits muscles that are capable of increasing the tensile stress on damaged ligaments. Although Wilkerson et al¹⁵⁶ only observed a decrease in concentric ankle inversion strength, they speculated that if the ankle invertors were inhibited that they would also exhibit decreased eccentric strength. Wilkerson et al¹⁵⁶ further suggested that decreased eccentric strength contributes to the decreased single-limb balance associated with CAI. More specifically, during single-limb balance, the

ankle invertors have to work eccentrically to counteract a lateral postural sway. Therefore, reduced eccentric inversion ankle strength would not be able to prevent excessive lateral postural sway during a single-limb balance task, resulting in loss of balance.^{37,156} Unfortunately, authors comparing eccentric inversion ankle strength have failed to identify any significant differences associated CAI.^{114,158}

The mechanism associated with an ankle sprain has likely contributed to the little attention placed on examining the relationship of dorsiflexion and plantarflexion strength in the literature. Based on the available evidence, dorsiflexion strength deficits are not associated with CAI.^{147,159,167,168} Early investigations by Tropp¹⁴⁷ and Schrader¹⁶⁸ failed to identify concentric or eccentric torque deficits between limbs in subjects with CAI or compared to healthy controls. In addition to peak torque, Porter et al¹⁵⁹ compared time-to-peak torque between a group of CAI subjects and healthy controls. They did not find a significant difference in time-to-peak torque or peak torque between groups; findings that were later confirmed by Gribble et al.¹⁶⁷ Yet, this relationship may need further investigation because a retrospective investigation identified decreased dorsiflexion strength to be one of several predictors of sustaining an ankle sprain among physically active adults.¹⁶⁹ Conversely, the evidence for plantarflexion torque deficits associated with CAI is inconclusive. One set of authors did not find a difference in torque values between groups; other researchers found an increase in plantarflexion strength in the injured limb,¹⁷⁰ while other groups have observed decreased isometric¹⁷⁰, concentric^{38,167} and eccentric¹⁵⁸ plantarflexion torque between a group of subjects with CAI and healthy controls. Despite the inconclusive findings, Hubbard et al³⁸ found reduced plantarflexion strength to explain approximately 10% of CAI group membership. Given the amount of

variance plantarflexion defined in group membership and the important role the plantarflexor's have in controlling balance, plantarflexion torque should be considered when attempting to understand the mechanisms of CAI.

Joints of the lower extremity do not work in isolation. Function or dysfunction at one joint can have an effect throughout the lower extremity. Most notably, changes in hip abduction and adduction moments during the swing phase of gait can cause alterations in the placement of the foot on initial contact, rendering the ankle more vulnerable to injury or 'giving-way'.¹⁷¹ Therefore, researchers have started to examine if changes in hip musculature are associated with CAI. Friel et al¹⁷² compared isometric hip abductor and hip extension strength in between subjects with and without CAI. Compared to healthy-control group, subjects with CAI had decreased isometric hip abduction strength. Because the hip abductors are essential for maintaining pelvic stability in the frontal plane during the stance phase of gait, Friel et al¹⁷² speculated that the weak hip abductors observed in those with CAI might cause the subtalar joint to be more inverted at the time of initial contact. Several other authors have shown changes in muscle recruitment patterns¹⁷³⁻¹⁷⁷ and sensation¹⁷⁵ of the hip musculature; providing preliminary evidence that proximal changes in hip musculature might be associated with CAI. Furthermore, a prospective investigation recently found hip extension strength as a predictor of an ankle injury in youth soccer athletes.¹⁷⁸

The only other group¹⁶⁷ to examine the relationship of hip strength and CAI failed to identify any differences. More specifically, Gribble et al¹⁶⁷ compared concentric knee extension and flexion and hip abduction and extension peak torque at 60°/s between those with and without CAI. Despite not finding a difference in hip strength, they did find

concentric knee extension and flexion peak torque was significantly lower in the CAI subjects relative to the healthy controls. Given this is currently the only investigation that has directly examined force production at the knee; it is difficult to draw any direct conclusions. However, the reduced force production observed at the knee is consistent with studies highlighting the potential for quadriceps dysfunction to be associated with CAI. Previous authors examining knee function have seen changes in quadriceps activation patterns,¹⁷⁹ knee kinematics¹⁸⁰ and force attenuation¹⁸¹ during functional activities. Considering the role of the quadriceps in mitigating knee joint degeneration, further investigation is warranted understand the impact decreased knee strength has on CAI.

Mechanical Alterations of CAI

Dorsiflexion Range of Motion

Mechanism

Dorsiflexion of the talocrural joint requires the talus to glide posteriorly, the distal fibula to glide superior and posteriorly relative to the tibia, and the proximal fibula to glide inferior and anteriorly on the tibia. An ankle sprain can disrupt the normal arthrokinematics of the talocrural or tibiofibular joints.^{94,182} Studies indicate the fibula shifts anteriorly^{77,183,184} or posteriorly^{185,186} relative to the tibia after an ankle sprain. The disagreement among the literature on the location of the fibula is likely the result of the multiple measurement techniques used.^{77,183,184} Adding to the confusion, Hubbard et al⁷⁷ found that only half of the subjects with CAI had an anteriorly displaced fibula, indicating that not everyone with CAI has a positional fault of the fibula.

Rather, consistent evidence suggests the talus is positioned anteriorly relative to the tibia after an acutely sprained ankle and in those with CAI.¹⁸⁷⁻¹⁸⁹ Specifically, when the lateral ligament complex is severely damaged the talus translates anteriorly 1mm, internally rotates 5.7°, and superiorly translates 0.2mm relative to the intact contralateral limb.¹⁸⁹ Earlier studies observing a reduced posterior talar glide support the rationale of an anteriorly placed talus in subjects with a history of lateral ankle sprains. Denegar et al¹⁸² enrolled a group of subjects who sprained their ankle in the previous 6 months and found a restricted posterior talar glide in the involved limb compared to the uninjured leg. Moreover, after a single session of anterior-to-posterior talocrural joint mobilization, Vicenzino et al¹⁹⁰ demonstrated a 50% improvement in posterior talar glide in subjects with CAI. Increased posterior talar glide indicates the talus was likely shifted anteriorly before the anterior-to-posterior joint mobilization was applied.

A positional fault of the talus can keep the talocrural joint from reaching a closed-packed or stable position and rendering the ankle vulnerable to inverting more easily during dynamic activities.³⁷ This caused early studies to propose that restricted dorsiflexion range of motion might be a risk factor for an ankle sprain, however, no study has found decreased dorsiflexion to be a significant predictor of injury.¹⁹¹⁻¹⁹³ Instead, reduced dorsiflexion range of motion appears to be a consequence of joint damage. Therefore, this section will examine deficits in dorsiflexion range of motion observed in participants with CAI using static measures and during dynamic activities.

Static Measures of Limited Dorsiflexion

When controlling for age and gender, Tabrizi et al¹⁹⁴ reported adolescent patients with an ankle injury had 6.4° less open-kinetic chain dorsiflexion than the control group

with the knee extended and 9.4° less open-kinetic chain dorsiflexion with the knee flexed. Similar findings were seen in adolescent and young-adult dancers who reported having a previous lower extremity injury.¹⁹⁵ The results from these investigations should be taken with caution as they included a wide variety of lower extremity overuse injuries, ankle ligament ruptures, and fractures.^{194,195} Denegar et al¹⁸² compared bilateral open-kinetic chain dorsiflexion range of motion in four different positions in a group of subjects diagnosed with an ankle sprain in the previous 6 months. Despite a decreased posterior talar glide in the involved limb, no difference in dorsiflexion range of motion was noted between limbs for any position. The authors attributed the similar dorsiflexion range of motion between limbs to an overstretching of the joint capsule caused by the swelling. Whereas the altered arthrokinematics found might be more important in limiting motion during the open-kinetic chain phase of dynamic activities such as during the swing phase of gait or prior to landing from a jump.

In contrast, various investigators started to examine closed-kinetic chain dorsiflexion range of motion using the Weight-Bearing Lunge Test (WBLT). The WBLT is performed by having the participant stand over a tape measure that is secured to the floor and perpendicular to a wall. The objective of the WBLT is to determine the maximum distance individuals are able to lunge forward, tap the anterior aspect of their knee on the wall, without lifting their heel off the ground. Therefore, lower values on the WBLT equate to decreased dorsiflexion range of motion. Terada et al¹⁹⁶ examined the relationship between open- and closed-kinetic chain dorsiflexion range of motion in a group of CAI subjects and found a positive and weak correlation between the two.¹⁹⁶ The weak correlation observed indicates measurements of open- and closed-kinetic chain

dorsiflexion range of motion provide different information. Hoch et al were the first group of researchers to utilize WBLT to identify dorsiflexion deficits in a cohort of CAI participants. Specifically, they found that participants with CAI had lower scores on the WBLT compared to a group of age-matched healthy-controls. The authors speculated that the decreased closed-kinetic chain dorsiflexion range of motion was the result of changes in the arthrokinematics of the ankle. Subsequent studies^{43,197} demonstrating improved scores on the WBLT after repetitive bouts of talocrural joint mobilization provide justification for changes in ankle arthrokinematics as the cause of the lower values on the WBLT.

Dynamic Activities

Along with static measurements, impaired dorsiflexion range of motion has been observed during dynamic activities. Limited dorsiflexion range of motion has been seen while walking and running after an ankle sprain. Using 3-D motion analysis, Drewes et al¹⁹⁸ compared the sagittal plane ankle kinematics while jogging barefoot in a group of participants with CAI to an age-matched healthy-control group. Participants with CAI were found to have significantly less dorsiflexion range of motion during the stance phase of the gait cycle. More specifically, participants with CAI had decreased sagittal plane motion from 9% to 25% of the gait cycle and at the point of peak dorsiflexion range motion relative to the healthy-control group.¹⁹⁸

Brown et al⁷⁴ first allocated participants with a previous ankle sprain into one of three categories: 1) a mechanically unstable group; 2) a functionally unstable group; or 3) a Coper group. While walking, the mechanically unstable group demonstrated less ankle sagittal plane displacement than the functionally unstable group and Coper group. Using

the same cohort of participants, Brown et al¹⁹⁹ performed a follow-up investigation examining the sagittal plane motion during the terminal swing phase of walking. The functionally unstable group had limited dorsiflexion range of motion 250 milliseconds prior to initial contact compared to the mechanically unstable group when walking.¹⁹⁹ Whereas the mechanically unstable group had greater dorsiflexion prior to contact compared to the Coper and functionally unstable group.¹⁹⁹ Collectively, these findings suggest that individuals develop different movement patterns at the ankle while walking after an ankle sprain.

These previous investigations had participant walk and jog barefoot, a novel task for many individuals and, therefore, may have influenced the results. Chinn et al²⁰⁰ examined sagittal plane ankle kinematics while walking and jogging shod on a treadmill. Relative to the healthy-controls, those with CAI exhibited reduced dorsiflexion range of motion from 42 to 51% of the gait cycle while walking and rom 54 to 68% of the gait cycle while jogging.²⁰⁰

Other researchers have examined sagittal plane ankle kinematics during jump-landing tasks. A positional fault of the ankle joint prior to landing from a jump is thought to make an unstable ankle more susceptible to a recurrent injury. Delahunt et al²⁰¹ compared the sagittal plane ankle motion during a single-leg drop jump in a group of subjects with CAI to an age-matched healthy-control group using 3-D motion analysis. Participants with CAI were found to reach a less dorsiflexed position within the first 200 milliseconds after landing from a single-jump compared to the healthy control.²⁰¹ Interestingly, there were no differences in sagittal plane motion prior to initial contact.

The authors²⁰¹ hypothesized these results suggest participants with CAI are less efficient at controlling their ankle motion after contact, rather than prior to initial contact.

In another study, Brown et al¹⁹⁹ compared the sagittal plane ankle kinematics from a drop jump between three groups of participants: 1) a mechanically unstable group; 2) a functionally unstable group; and 3) a Coper group. Brown et al¹⁹⁹ found the mechanically unstable group had less plantarflexion (more dorsiflexion) at initial contact and at maximum than the Coper and functionally unstable group. No differences were found between the Coper and functionally unstable group at any time point. The increased dorsiflexion range of motion found at initial contact within the mechanically unstable group likely reflects their attempt at positioning their ankle in more stable position to prevent any excessive movement and subsequent injury.

Whereas the previous studies compared the group averages, other investigators have compared the inter-trial variability in sagittal plane motion prior to landing from a single-leg drop. Kipp et al⁷⁸ found participants with CAI to have greater sagittal plane inter-trial variability compared to the healthy-control group. The greater inter-trial variability indicates CAI individuals have a different sagittal plane ankle movement pattern each time they land from a jump. This varied movement pattern from trial-to-trial might increase the risk of experiencing episodes of ‘giving-way’ or recurrent joint injury.

Gait Mechanics

It has been proposed that disruption to the lateral ligament complex after an ankle sprain can lead to inappropriate positioning of the ankle joint during the transition from swing phase to the stance phase of while walking. If an unloaded ankle joint is mal-positioned upon weight-acceptance when walking an increased subtalar inversion torque

may occur, increasing the risk of an individual to sustaining a recurrent joint injury or experience an episode of ‘giving-way’.²⁰² As a result, numerous investigations have examined joint kinematics, kinetics and muscle activity while walking in patients with CAI.

Joint Kinematics

Monaghan et al²⁰³ first compared the frontal plane ankle kinematics while walking barefoot using 3-D motion capture in a group of subjects with CAI to a group of healthy-controls. More specifically, they examined the frontal plane ankle kinematics 100ms prior to heel strike and 200ms post heel strike. It was concluded that participants with CAI had a more inverted foot position throughout the entire time period. The authors²⁰³ suggested that an altered foot position during the time period before heel strike prevents an individual from being able to properly absorb the forces applied to the lower extremity when walking.

Delahunt et al²⁰¹ later confirmed individuals with CAI have a more inverted position of the ankle joint before, at, and immediately after heel strike compared to healthy-controls. In addition to comparing the patterns of lower limb 3-D joint kinematics while walking on a treadmill between those with and without CAI, the authors also examined the vertical foot-floor clearance. Interesting, the authors²⁰¹ found the participants with CAI exhibited a decreased in vertical foot-floor clearance compared to the healthy-control group. This decreased vertical foot-floor clearance seen while walking in participants with CAI might create a predisposition causing them to experiencing an inadvertent contact with the ground causing them to trip and fall when walking, creating a serious event.

In a series work,^{74,199} 3-D motion analysis at the ankle and knee was performed on 3 groups of participants differentiated based on ankle injury history and ligamentous laxity while walking. Specifically, participants with a history of an ankle sprain were separated into three groups: 1) a mechanically unstable group; 2) a functionally unstable group; and 3) a Coper group. Frontal and sagittal plane ankle kinematics were only examined 250ms before heel strike. Data from this work^{74,199} demonstrated the mechanically unstable group had less ankle sagittal plane displacement compared to the functionally unstable group, and both the mechanically and functionally unstable group had more ankle frontal plane displaced than the Coper group.⁷⁴ Furthermore, the mechanically unstable group had greater maximum foot external rotation and were more dorsiflexed while walking than both the functionally unstable and Coper groups.¹⁹⁹ The decreased sagittal plane ankle motion and increased dorsiflexion observed in the mechanically unstable group suggests that they position to their ankle in a more stable position to increase reliance on bony stability rather than ligamentous stability.⁷⁴ Additionally, the greater maximum foot external rotation suggests that individuals with CAI might externally rotate their foot to increase the vertical foot-floor clearance while walking to avoid any inadvertent contact with the ground and thus episodes of instability.¹⁹⁹

While these previous investigations provide unique insight into the joint position of the ankle and knee prior to weight-acceptance in participants with CAI, few authors^{199,201,203} expanded the investigations to examine if participants with CAI displayed deferment movement patterns throughout the entire gait cycle. Chinn et al²⁰⁰ compared sagittal and frontal plane ankle kinematics throughout the entire gait cycle

between participants with and without CAI. Results demonstrated participants with CAI were less dorsiflexed from 42 to 51% of the gait cycle (stance phase).²⁰⁰ Interestingly, No differences were found in the frontal plane ankle kinematics.²⁰⁰ The authors²⁰⁰ concluded that an anteriorly displaced talus likely prevented participants with CAI from reaching a closed-packed position while walking. Furthermore, the disparity between these results and the earlier investigations is that Chinn et al²⁰⁰ had participants walk in custom-made shoes. Whereas the earlier investigations had participants walk barefoot.^{201,203}

A limitation of these prior studies is that all of them considered the foot as a rigid segment. De Ridder et al²⁰⁴ argued modeling the foot as a rigid segment ignores the complexity of the foot and therefore might miss subtle changes occurring within the foot while walking. De Ridder and colleagues²⁰⁴ compared the stance phase kinematics of subjects with CAI, Copers, and controls during walking using a multisegmented foot model. Results from this study revealed the medial forefoot was in a more inverted position during the stance phase of walking in both the CAI and Coper group compared to the healthy-control group.²⁰⁴

While identifying differences in joint ankle sagittal and frontal plane joint ankles when walking has provided useful insights into understanding the consequences of CAI, previous authors have examined the shank-rearfoot joint coupling in participants with CAI. Drewes et al²⁰⁵ analyzed this relationship using an analysis termed continuous relative phase (CRP). Briefly, CRP compresses 4 variables (angular displacement and velocity of the proximal and distal segments) into 1 measure.²⁰⁵ Results demonstrated CAI participants were more out of phase than the healthy controls during the terminal swing phase. More specifically, participants with CAI had more rearfoot inversion and

tibial external rotation compared to the healthy-control group.²⁰⁵ This indicates these segments are less coordinated as the foot is being positioned prior to initial contact.

The use of CRP to assess the intersegment coupling has been previously criticized for its normalization techniques across the entire gait cycle.²⁰⁶ Therefore, Herb et al²⁰⁶ examined this relationship between the shank and rearfoot using stride-to-stride vector coding. Vector coding has been argued to be a more useful measure to examine this relationship because it uses on the angular position of the two segments, which allows for better inference on the original segmental position.²⁰⁶ Herb et al²⁰⁶ found the CAI group had greater combined motion between the rearfoot and shank during the early swing phase of gait, but less combined motion during the late swing phase. Furthermore, the authors²⁰⁶ examined the stride-to-stride variability of these measures and found the CAI group had less variability during the stance phase of gait. Taken together these findings indicate individuals with CAI have a lack of coordination between the rearfoot and shank during immediately after toe off. However, individuals with CAI reduce the movement between these two segments to become more rigid before heel contact and throughout the stance phase. This rigid pattern likely reflects their attempt at increasing ankle joint stability to prevent further injury or 'giving-way'.

Terada et al²⁰⁷ later confirmed CAI is associated with decreased stride-to-stride variability by examining the temporal structure of the sagittal and frontal plane ankle kinematics. It was determined that the CAI group had decreased frontal plane ankle kinematics compared to the control group. The authors²⁰⁷ concluded that this decreased frontal plane motion at the ankle is reflective of a more rigid movement pattern caused by a less adaptable sensorimotor system.

Kinetics

Monaghan et al²⁰³ compared kinetic data relating to the period from 100ms heel strike to 200ms post heel strike between those with and without CAI. The authors²⁰³ found differences between groups when examining the frontal plane ankle joint moments and forces. Specifically, it was determined that CAI participants exhibited an evertor moment throughout the 200ms period post heel strike whereas the healthy control participants had an invertor moment during this time frame. Furthermore, the authors²⁰³ observed periods of concentric power generation after heel strike in participants with CAI as opposed to the control group where an eccentric power generation was observed during these same time periods. Collectively, these changes in joint moments and power likely occur as a result of the different movement patterns while walking observed previously.²⁰³

Other authors^{208,209} compared the center of pressure (COP) trajectories between participants with and without CAI. Hopkins et al²⁰⁸ examined the COP trajectories during the stance phase of while walking from pressure measurements collected from insoles impeded with a grid of sensors. Analysis of the COP trajectories indicated that the COP trajectories were more laterally deviated at initial contact and from 25% to 90% of the stance phase compared to the healthy-controls.²⁰⁸ Likewise, Koldenhoven et al²⁰⁹ examined the COP trajectories using a similar in-shoe plantar pressure measurement system in participants with and without while waling. They found that the CAI participants had a laterally deviated COP throughout the entire stance phase of gait compared to the healthy counterparts.²⁰⁹ The laterally deviated COP trajectories found in both of these studies indicate CAI individuals spend more time on the lateral side of their

foot compare to uninjured individuals. As a result, this laterally deviated COP trajectory might predispose individuals with CAI to experience an episode of ‘giving-way’ or recurrent joint injury if the COP moves outside of their base of support. In addition to the COP trajectories, Koldenhoven et al²⁰⁹ examined the peak pressure, pressure-time integral, time-to-peak pressure, contact area, and contact time. Interestingly, the CAI group an increase in peak pressure and pressure-time integral of the lateral forefoot. Increased time to peak pressure and amount of pressure over time on the lateral forefoot suggests participants with CAI have a might have to over supinate prior to toe off to provide stability within the foot for propulsion.

Chapter 3: Health-Related Quality of Life in Young, Middle, and Older-Aged Adults With and Without Chronic Ankle Instability

Introduction

Lateral ankle sprains are the most common lower extremity musculoskeletal injury among young physically active populations.³ A 5-year review of the National Collegiate Athletic Association (NCAA) injury surveillance program indicates the incidence rate of a lateral ankle sprain is 0.495 per 1000 athlete-exposures.⁷ In addition to the high incidence rate among physically active populations, it is important to recognize the high incidence rate among the general population. Based on a 4-year review of the National Electronic Injury Surveillance System (NEISS), Waterman et al⁴⁷ reported the incidence rate of a lateral sprain among people reporting to an emergency department in the USA is 2.15 per 1000 person-years. Indeed, this high incidence rate observed in the emergency department can cause immense financial burden placed on the health care system.³⁶ Further contributing to the problem, at least 1 in 3 individuals will experience residual symptoms that can persist years after the initial injury,⁹ such as recurrent injury and repetitive ‘giving-way’ or otherwise known as chronic ankle instability (CAI).³⁷ CAI is associated with mechanical and functional impairments that contribute to a pattern of inactivity early in life^{13,210} and the onset of post-traumatic ankle osteoarthritis.¹⁵ Consequently, those with CAI report having lower health-related quality of life (HRQoL).¹⁰

HRQoL is an encompassing term used to coalesce information from several health domains including physical, mental and social.⁶⁷ Thus, HRQoL reflects an individual’s satisfaction with life or overall well-being.⁶⁷ Capturing HRQoL can improve

the quality of care provided by the clinician because it advances the understanding of how patients' experiences, expectations, beliefs, and perceptions are affected by their health condition.⁶⁷ Therefore, the importance of evaluating HRQoL has increased among healthcare professionals.²¹¹ Owing to the multiple health domains that HRQoL incorporates, self-reported surveys are classified as either generic or region specific. Generic outcome instruments are nonspecific to a body region and are broad to provide a glimpse into an individual's overall health status.⁶⁷ In contrast to global outcome tools, region specific instruments are useful in providing HRQoL about a specific region of the body that may be affected by an injury.⁶⁷

Based on a systematic review with meta-analysis, there is moderate to strong evidence indicating long-term symptoms caused by an acute ankle sprain can be detrimental to both global and region-specific HRQoL.¹⁰ Arnold et al¹¹ used the Short Form-36 (SF-36) to compare global HRQoL between a group of subjects CAI and healthy-controls. The authors found the group of subjects with CAI had lower subscale and composite scores relative to the healthy-controls.¹¹ The lower scores obtained in the previous investigation, along with follow-up studies,^{9,10,12} indicate individuals with CAI report having decreased global HRQoL. Likewise, those with CAI often report greater limitations as assessed by ankle and foot HRQoL outcomes. Several region specific instruments have been used to identify the self-reported functional impairments at the ankle;¹⁰ however, the Foot and Ankle Disability Index (FADI) offers additional information compared to other region-specific instruments because it incorporates information related to the severity of ankle pain.^{70,212} As such, research indicates CAI

patients routinely report lower scores on the FADI, suggesting lower ankle reported function.¹⁰

The current literature has primarily focused on the HRQoL among adolescents and young-adults.¹⁰ Unfortunately, long-term follow-up investigations indicate a significant proportion of individuals never fully recover. After 6.5 years, approximately 40% of individuals with a previous ankle sprain report residual symptoms in the involved limb.⁵⁵ Konradsen et al⁵⁴ followed patients for 7 years and noted 32% of people reported having chronic symptoms of pain, swelling, and recurrent injury. More importantly, of those respondents, 72% were functionally impaired by their ankle.⁵⁴ More recent reports have utilized the Patient-Reported Outcomes Measurement Information System (PROMIS) to compare global HRQoL between middle-aged (40-64 years old) athletes and non-athletes. The PROMIS is a “National Institutes of Health Roadmap Initiative” and contains a bank of questions designed and validated to measure symptoms and health associated with a variety of chronic conditions. In a series of work, Simon and Docherty^{213,214} found former Division I athletes reported worse scores related to physical function, depression, fatigue, sleep disturbances, and pain interference compared to age-matched non-athletes. Further, those athletes who participated in a Division I collision sport presented with worse scores on all 8 subscales.²¹⁴ Although these reports did not examine the influence of previous injury, it is well documented that a significant proportion of individuals sustain a lower extremity injury while participating in collegiate athletics,³ which certainly contributes to the HRQoL former athletes report having.^{213,214}

These emerging data provide promising evidence that developing CAI at an early age can lead to worse global and region-specific HRQoL throughout the lifespan.

However, there is currently no investigation that has evaluated both global and region-specific HRQoL in middle-aged and older-aged adults with CAI. Understanding the influence of CAI on global and region-specific HRQoL as individuals age may offer a better indication of the long-term self-reported deficits associated with CAI and help direct future rehabilitation studies targeting an older population.

Therefore, the aim of this investigation is to compare global and region-specific HRQoL in young-, middle-, and older-aged adults with or without CAI. We hypothesize: 1) Participants with CAI will self-report having worse region-specific and global HRQoL compared healthy-controls; 2) Region-specific and global HRQoL will be worse in the middle-aged adults compared to the younger-aged adults; the older-aged adults will have worse scores compared to both groups; 3) Younger-, middle-, and older-aged adults with CAI will self-report having worse region-specific and global HRQoL compared to their age-matched healthy counterpart.

Methods

Study Design

We utilized a cross-sectional case control study design. The independent variables were Injury (CAI or healthy-control) and Age (younger-, middle-, and older-aged adults) whereas the dependent variables were global (PROMIS-43) and region-specific (FADI-ADL and FADI-Sport) HRQoL outcome instruments.

Participants

Sixty participants with self-reported CAI and 40 healthy-control participants were recruited from a large regional university and the surrounding community. Based on age,

participants were classified into three age categories: 1) younger-aged adults (age: 18-35, n = 31); middle-aged adults (age: 36-59, n = 25); and older-aged adults (age: 60+, n = 11). All participants read and signed an informed consent that was approved by the University of Kentucky institutional review board.

Inclusion criteria for younger-aged adults with CAI were based on criteria set by the International Ankle Consortium for identifying individuals with CAI.⁵⁶ Specifically, younger-aged adults with CAI were required to have: 1) a previous history of an acute lateral ankle sprain which resulted in swelling, pain and temporary loss of function; 2) repeated episodes of ‘giving-way’ and/or recurrent sprain; and 3) perceived instability determined by a score of \geq ‘5’ on the Ankle Instability Instrument (AII) and/or \geq ‘11’ on the Identification of Functional Ankle Instability (IdFAI). There is currently no standard used to identify middle- and older-aged adults with CAI. Therefore, middle- and older-aged adults with CAI were identified according to the presence of having: 1) experienced an acute lateral ankle sprain that caused swelling, pain and temporary loss of function before the age of 35 years-old; 2) repeated episodes of ‘giving-way’ and/or recurrent ankle sprains; and 4) perceived instability determined by a score of \geq ‘5’ on the AII and/or \geq ‘11’ on the IdFAI. The AII and IdFAI have been shown as reliable and valid in assessing patient-reported functional limitations in those with CAI. In the event participants reported a bilateral history of ankle sprains, the limb with the greatest self-reported functional limitations according to the AII and IdFAI were used as the test limb.

Participants allocated to the healthy-control group were required to report not having sustained an acute lateral ankle sprain, no ‘giving-way’, and score ‘0’ on the AII and IdFAI.

All participants were free from any: 1) diagnosed balance, vestibular or respiratory disorder; 2) history of low back pain in the previous 6 months; 3) previous history of fracture or surgery in the lower extremity; 4) history of seizures; 5) history of concussion in the past 6 months; 6) history of neurological injuries or diseases; 7) use of any assistive-walking device; and/or previous history of any self-reported musculoskeletal or neurovascular injuries and disorders in the lower extremity within the previous 6 months other than an lateral ankle sprain.

Instrumentation

Foot and Ankle Disability Index

The FADI is a region-specific outcome instrument designed to measure activity limitations and participation restrictions associated with foot and ankle conditions.⁷⁰ The FADI consists of two subscales: 1) Activities of Daily Living (FADI-ADL) and Sport (FADI-Sport). Both scales are scored on a 5-point Likert scale with '0' representing *no difficulty at all* and '4' signifying *unable to do*. Scores are transformed into percentages with 100% equating to no self-reported functional limitations. Test-retest reliability for the FADI and FADI-Sport is 0.89 and 0.85, respectively.⁷⁰

Patient-Reported Outcomes Measurement Information System (PROMIS)

The PROMIS is a NIH Roadmap for Medical Research Initiative with the goal of developing and validating a bank of items for the clinical research community to evaluate global HRQoL for the general population and to those with chronic conditions.²¹⁵⁻²¹⁸ The conceptual framework for designing the bank of items was based on 3 generic areas of health: 1) physical health; 2) mental health; and 3) social health. Based on that framework, items were further sub-categorized into 7 domains of HRQoL: 1) physical

function; 2) pain interference; 3) fatigue; 4) sleep disturbance; 5) anxiety; 6) depression; and 7) ability to participate in social roles & activities.²¹⁹

Items were selected based on an extensive literature review, a panel of expert reviewers, cognitive interviews, and focus groups with patients diagnosed with specific diseases.²¹⁹ Based on the final pool of items, those that produced the greatest information in each domain were selected and used to design several short forms of varying lengths.²¹⁹

Each item has five response options ranging in values from 1 to 5. The total score from each short-form is calibrated by converting the raw score into a *T*-score with the mean of the US general population equal to 50 and a standard deviation fixed at 10. Higher scores for sleep, anxiety, depression, fatigue and pain interference represent poorer health, whereas higher scores for physical function and ability to participate in social roles & activities corresponding with better health.^{218,219}

Experimental Procedures

Participants reported to the laboratory for a single testing session. After reading and signing the informed consent, participant's completed electronic version of the FADI and PROMIS-43. Participants were instructed to complete both instruments based on the directions at the top of each document. The primary investigator did not provide any additional explanation unless the participant asked for clarification. After completing both surveys, the primary investigator scored both survey instruments for analysis based on the established guidelines.

Statistical Analysis

Separate 2x3 between-group analysis of variance models were conducted to explore the impact of Injury (CAI vs. healthy-control) and Age groups (young, middle, and old) on anthropometric information and for each dependent variable. A Bonferroni post hoc analysis was used in the event of any significant differences. The *a priori* alpha level was set a $p \leq 0.05$.

All statistical analyses were performed using IBM SPSS Statistics, version 23 (IBM, Corp., Armonk, NY, USA).

Results

Participant demographics and injury characteristics are listed in Table 3.1 and Table 3.2. The interaction effect between Injury and Age group, along with simple main effects, was not statistically significant for height, weight and BMI. There was a statistically significant age main effect for age ($F_{2,94} = 475.57$, $p = 0.001$, partial $E^2 = 0.908$, observed power = 1.00). As expected, post hoc comparisons using a Bonferroni test indicated that participants allocated to the middle-aged group (46.2 ± 7.5 , $p = 0.001$) and older-aged group (67.2 ± 5.9 , $p = 0.001$) were older than those in the younger-aged group (24.0 ± 3.4). Likewise, those in the older-aged group were significantly older than those in the middle-aged group ($p = 0.001$).

Group means and standard deviations for each dependent variable are given in Table 3.3.

Foot and Ankle Disability Index

The interaction effect between Injury and Age group was not statistically significant for the FADI-ADL or FADI-Sport ($p > 0.05$).

There was a statistically significant Injury main effect for the FADI-ADL ($F_{2, 82} = 27.54, p < 0.001, \text{partial } E^2 = 0.266, \text{observed power} = 0.99$) and FADI-Sport ($F_{2, 82} = 29.24, p < 0.001, \text{partial } E^2 = 0.278, \text{observed power} = 1.00$), indicating participants with CAI scored lower on the FADI-ADL (92.6 ± 7.1 vs. 100.00 ± 0.0) and FADI-Sport (82.2 ± 6.5 vs. 100.00 ± 0.0) compared to the healthy-control group.

Patient-Reported Outcome Measurement Information System

The interaction effect between Injury and Age group was not statistically significant for any PROMIS dependent variables ($p > 0.05$).

There was a statistically significant Injury main effect for the Physical Function ($F_{2, 92} = 6.43, p = 0.013, \text{partial } E^2 = 0.064, \text{observed power} = 0.70$) and Pain Interference ($F_{2, 100} = 3.785, p = 0.05, \text{partial } E^2 = 0.039, \text{observed power} = 0.48$) subscales. These results indicate participants with CAI self-reported having worse physical function (53.68 ± 5.9) compared to the healthy-control group ($57.55 \pm 3.8, p = 0.013$). Further, participants with CAI self-reported having greater pain interference (44.85 ± 5.84) compared to the healthy-control group ($42.18 \pm 3.4, p = 0.05$).

There was a statistically significant Age main effect for Anxiety ($F_{2, 100} = 2.986, p = 0.05, \text{partial } E^2 = 0.060, \text{observed power} = 0.56$) and Social ($F_{2, 100} = 3.047, p = 0.05, \text{partial } E^2 = 0.061, \text{observed power} = 0.57$) subscales. Post hoc comparisons using a Bonferroni test failed to identify any significant pairwise comparisons between Age categories ($p > 0.05$).

Discussion

The purpose of our investigation was to compare global and region-specific HRQoL between those with and without CAI across the lifespan. We hypothesized

participants with CAI would self-report having worse region-specific and global HRQoL compared healthy-controls. Secondly, region-specific and global HRQoL would be worse in the middle-aged adults compared to the younger-aged adults; the older-aged adults would have worse scores compared to both groups. Lastly, younger-, middle-, and older-aged adults with CAI will self-report having worse region-specific and global HRQoL compared to their age-matched healthy counterpart. Our primary finding was participants with CAI, regardless of their age, reported having greater functional limitations as a consequence of their ankle, worse overall physical function, and greater pain interference compared to the healthy-control group. However, there were no significant interactions for Injury and Age group for any main outcome measure.

Regional HRQoL outcome instruments are designed to provide a better understanding of the self-reported functional limitations caused by a particular condition or injury.⁶⁷ The FADI is a region-specific HRQoL questionnaire intended to characterize the level of difficulty individuals have experienced in the past 7 days because of their ankle during broad spectrum activities such as walking on even or uneven ground, walking up and down stairs, running, and jumping.⁷⁰ In our study, we observed lower scores on the FADI-ADL and FADI-Sport in the CAI group compared to the healthy-control group, irrespective of their age. The lower scores on the FADI indicate those with CAI have a harder time performing activities of daily living and tasks related to physical activity because of deficiencies at the ankle. Thus, lingering symptoms after ankle sprain impact an individual's ability to interact with their surrounding, regardless of their age.

This is the first investigation to examine region-specific HRQoL in participants with CAI between different age groups. To date, the majority of the evidence examining

the region-specific HRQoL associated with CAI has been in younger-aged adults. Houston et al¹⁰ undertook a systematic review with meta-analysis to evaluate region-specific HRQoL instruments between those with and without CAI. Despite the heterogeneity of outcome tools included, the authors¹⁰ found convincing evidence that CAI individuals report having a lower HRQoL relative to healthy-controls and compared to a Coper group.¹⁰ The results from this systematic review indicated CAI is associated with the development of unique impairments that cause individuals with CAI to report having functional limitations because of their ankle. Indeed, researchers²²⁰ have demonstrated static and dynamic balance contribute to scores on the ADL subscale of the Foot and Ankle Ability Measure (FAAM); while dorsiflexion range of motion, eversion strength and static balance were found to explain a significant portion of the variance for the sport subscale of the FAAM.²²⁰ Although we did not examine the mechanical and sensorimotor impairments associated with CAI in this current investigation, there is reason to believe that the lower FADI-ADL and FADI-Sport scores observed were the result of a combination of the mechanical and sensorimotor insufficiencies that are associated with CAI.³⁷

In addition to being limited by their ankle during activities of daily living and exercise, participants with CAI also reported having lower levels of specific aspects of physical quality of life as measure via the PROMIS-43. This is consistent with the work by Arnold et al¹¹ who noted scores on the physical component of the Short-Form 36 (SF-36), but not the mental component, were lower in a group of younger-aged adults with CAI compared to age-matched healthy-controls. Additionally, Houston et al¹² reported decreased scores on the Disablement in the Physically Active Scale in a group of

younger-aged participants with CAI relative to their healthy counterpart. These cumulative findings,¹⁰⁻¹² along with those presented in the current study, suggest CAI significantly and negatively impacts the overall physical quality of life of individuals.

The exact reason why participants with CAI reported having overall worse physical quality of life compared to the uninjured participants in the current study is unknown. One potential explanation might be that because participants with CAI reported pain interfered with their day-to-day activities and ability to attend social events (Table 3.3). While the extent of the influence of pain associated with development CAI is widely debated among researchers,²²¹ there is evidence to suggest that residual pain after an ankle joint injury can interfere with quality of life of individuals. Early reports indicated patients could experience lingering ankle pain for as long as 7 years after an acute lateral ankle sprain.^{54,55} Hiller et al⁵⁸ surveyed almost 200 individuals with chronic musculoskeletal ankle disorders and found over half (63%) had to modify or limit their activity. Furthermore, pain was the most common complaint compared to weakness, swelling, 'giving-way' and instability, suggesting that pain was the most common reason why individuals had to modify or limit their activity.⁵⁸ Moreover, Arnold et al¹¹ observed that participants with CAI reported having greater overall bodily pain and indicated that the increased bodily pain was likely the cause of the decreased scores on the physical component of the SF-36 reported by participants with CAI. Therefore, it is reasonable to speculate that the increased pain interference reported by participants in the current study likely contributed to the decreased physical HRQoL. Further research is needed to better understand how pain with movement affects the physical HRQoL in patients with CAI.

Although we observed differences between those with and without CAI, we did not find region-specific or global HRQoL to change with advancing age in participants with CAI. This is not in agreement with previous research examining the influence on the number of ankle injuries on global HRQoL measured using the SF-8.²²² Specifically, Bruce et al²²² found age and history of sustaining at least one injury to the ankle negatively impacted the physical quality of individuals. Additionally, Simon and Docherty^{213,214} surveyed former division 1 athletes (age 40-60 years old) using the computer adaptive version of the PROMIS and found that former athletes reported having greater difficulty performing activities of daily living and exercise compared to age-matched non-athletes. The authors concluded that this decreased global HRQoL was because the majority (70%) of the former division 1 respondents said that they had sustained at least 1 significant injury during their career and were 2.1 times more likely to continue participating with an injury or illness compared to non-athletes. The high prevalence of respondents noting they had a history of a severe injury and the hastened return to activity reported by the former Division 1 athletes may have caused poor healing to occur at the time of the injury. Given the hastened return to activity before adequate healing can occur seen after an ankle sprain^{6,7} it was surprising that we did not observe a difference between younger-, middle- and older-aged adults with CAI compared to their age-matched healthy counterpart.

The lack of differences across age categories between those with and without CAI may be attributed to a shift in their frame of reference in which to compare their HRQoL against. Given that the majority of individuals sustain an ankle sprain as an adolescent or young-adult⁴⁷ and can develop CAI within a year after the initial injury,^{223,224} it is

plausible that people with CAI as a young adult may learn to cope with their functional limitations over time by adjusting the environment that they interact with as they progress into middle-age and older adulthood. For example, to prevent their ankle from ‘giving-way’ when running across uneven ground, individuals with CAI might begin to exercise on more level surfaces. As a result, individuals with CAI may undergo a mental recalibration of their physical expectations as they come to terms with the functional limitations imposed on them.^{225,226} This mental recalibration of an individual’s standards, values, and priorities is known as a response shift.^{225,226} A response shift has been shown to interfere with the ability to detect changes in a patient’s health accurately. Specifically, a response shift can occur in patients with low back pain,²²⁷ after knee surgery,²²⁸⁻²³⁰ and with terminal illness where an individual’s physical health deteriorates, yet their self-reported HRQoL remains stable.^{227,231} The idea that an individual with CAI can be subjected to a mental recalibration of their physical expectations and now have a new frame of reference to compare the health status might help to explain why we did not see a detectable deficiency in HRQoL in those with CAI.^{225,226} However, more research is needed to understand the influence of a response shift in HRQoL outcome tools for individuals with CAI before we can make this conclusion definitively.

Limitations

This study is not without limitations. First, we instituted an inclusion criteria that middle- and older-aged participants with CAI to self-report having sustained their first ankle sprain before the age of 35, which does introduce recall bias. Secondly, by requiring middle- and older-aged participants to self-report having sustained their first ankle sprain before the age of 35 we had hoped to identify individuals who had

developed CAI as a young-adult. While the duration of symptoms reported by the middle- and older-aged adults with CAI was higher in each group, it is reasonable to speculate that some of the middle- and older-aged participants may not have started to experience symptoms of CAI until they were older. If participants didn't develop characteristics of CAI until they were older, they may not have experienced as many functional limitations as someone who has had CAI their entire adult life. We are among the first to consider CAI across multiple age groups, yet there is not a standard for identifying middle- and older-aged adults with CAI. We applied the most contemporary published guidelines for defining CAI, but these are based on literature using exclusively young adults. There is some concern that our criteria fit as well for middle-aged and older adults. Therefore, there is a clear need to develop and determine valid and reliable methods to assess the level of functional instability in middle- and older-aged adults. Lastly, our sample size in the middle- and older-aged groups was considerably smaller compared to the younger-aged group. Therefore, the results of this study may be threatened by a Type 2 error and should be taken with caution. We hope to build upon the work to this point in an effort to reduce this potential source of error.

Conclusion

At least 1 in 3 individuals will experience residual symptoms following an ankle sprain, which will manifest into CAI. On the basis of these data, CAI is associated with lower region-specific compared to healthy-controls. Specifically, participants with CAI scored worse on the FADI-ADL and FADI-Sport compared to their healthy counterparts. The consequence of these findings is individuals with CAI appear to have a harder time completing activities of daily living and tasks associated with exercise because of

lingering symptoms from their ankle sprain. Furthermore, it was found that participants with CAI reported having worse overall physical quality of life compared to the healthy-control group. This decreased physical quality of life is likely attributed to the increase in pain interference reported by those with CAI. Increase in pain can prevent individuals from wanting to participate in physical activity or attend social events and therefore likely experience a lower overall physical quality of life. Research is needed to better understand how lingering pain from an ankle sprain translates into worse overall physical quality of life.

Table 3.1: Participant demographics for all six groups

	Younger-Aged Adults (Mean \pm SD)		Middle-Aged Adults (Mean \pm SD)		Older-Aged Adults (Mean \pm SD)		Main Effect Injury		Main Effect Age		Interaction	
	CAI n = 31	Healthy- Control n = 27	CAI n = 18	Healthy- Control n = 8	CAI n = 11	Healthy- Controls n = 6	F	p-value	F	p-value	F	p-value
Age (years)	24.2 \pm 3.7	23.8 \pm 3.0	45.4 \pm 7.0	46.5 \pm 8.4	67.5 \pm 5.8	66.8 \pm 6.6	0.00	0.97	475.5	<0.001*	0.17	0.84
Height (cm)	166.6 \pm 9.4	169.6 \pm 9.5	167.9 \pm 12.0	170.1 \pm 9.8	173.4 \pm 7.4	170.1 \pm 13.0	0.08	0.77	0.81	0.44	0.61	0.54
Weight (kg)	72.2 \pm 14.1	69.1 \pm 17.0	79.4 \pm 18.9	75.5 \pm 12.4	78.5 \pm 15.4	80.1 \pm 14.5	0.22	0.63	2.62	0.07	0.16	0.85
BMI (kg/m ²)	26.0 \pm 4.5	23.8 \pm 4.6	28.4 \pm 7.5	26.0 \pm 3.1	25.9 \pm 3.3	27.5 \pm 2.1	0.72	0.39	2.08	0.13	0.96	0.38

*Indicates significant differences between age groups ($p < 0.05$)

Abbreviations: **CAI** = Chronic ankle instability; **cm** = centimeters; **kg** = kilograms

Table 3.2: Participant injury characteristics for all six groups

	Younger-Aged Adults (Mean \pm SD)		Middle-Aged Adults (Mean \pm SD)		Older-Aged Adults (Mean \pm SD)	
	CAI	Healthy-Control	CAI	Healthy-Control	CAI	Healthy-Controls
AII	5.7 \pm 1.5	0.0 \pm 0.0	4.7 \pm 2.3	0.0 \pm 0.0	4.7 \pm 2.8	0.0 \pm 0.0
IdFAI	17.45 \pm 3.3	0.0 \pm 0.0	12.2 \pm 7.6	0.0 \pm 0.0	10.9 \pm 8.9	0.0 \pm 0.0
CAIT	17.5 \pm 4.8	0.0 \pm 0.0	19.9 \pm 7.7	0.0 \pm 0.0	20.0 \pm 6.7	0.0 \pm 0.0
# of LAS	3.0 \pm 3.6	0.0 \pm 0.0	3.2 \pm 3.5	0.0 \pm 0.0	1.6 \pm 0.7	0.0 \pm 0.0
First LAS (years)	6.0 \pm 4.5	0.0 \pm 0.0	30.0 \pm 39.8	0.0 \pm 0.0	47.1 \pm 20.3	0.0 \pm 0.0
Most Recent LAS (months)	33.0 \pm 34.2	0.0 \pm 0.0	121.6 \pm 114.5	0.0 \pm 0.0	270.6 \pm 248.0	0.0 \pm 0.0
Duration of Symptoms (years)	4.9 \pm 3.7	0.0 \pm 0.0	10.7 \pm 10.4	0.0 \pm 0.0	22.0 \pm 31.2	0.0 \pm 0.0
# of 'giving-way' in past 6 months	4.3 \pm 5.1	0.0 \pm 0.0	2.8 \pm 5.0	0.0 \pm 0.0	3.5 \pm 7.3	0.0 \pm 0.0

Abbreviations: **CAI** = Chronic ankle instability; **AII** = Ankle instability index; **IdFAI** = Identification of Functional Ankle Instability; **CAIT** = Cumberland ankle instability tool; **LAS** = lateral ankle sprain;

Table 3.3: Group means and standard deviations for the patient reported outcomes for all six groups

	Younger-Aged Adult (Mean ± SD)		Middle-Aged Adult (Mean ± SD)		Older-Aged Adult (Mean ± SD)		Main Effect Injury		Main Effect Age		Interaction	
	CAI	Healthy- Control	CAI	Healthy- Control	CAI	Healthy- Control	F	p-value	F	p-value	F	p-value
Foot and Ankle Disability Index (%)												
FADI-ADL	91.2±7.6	100.0±0	93.3±5.6	100.0±0	93.4±8.9	100.0±0	28.4	<0.001 [#]	0.34	0.70	0.34	0.70
FADI-Sport	78.4±15.0	100.0±0	82.3±17.7	100.0±0	88.5±15.4	100.0±0	30.6	<0.001 [#]	0.92	0.40	0.92	0.40
Patient-Reported Outcome Measurement Information System												
Phys. Func.	54.1±6.1	58.1±2.6	53.6±3.6	57.0±4.6	53.0±6.8	54.7±6.1	6.43	0.01 [#]	1.27	0.28	0.33	0.72
Anxiety	48.4±7.3	47.0±8.2	44.5±4.3	44.8±6.7	43.0±4.8	44.3±5.9	0.00	0.99	2.98	0.05*	0.30	0.74
Depression	42.9±6.6	43.1±6.1	43.1±4.0	43.9±9.4	42.7±5.6	40.5±3.3	0.06	0.80	0.44	0.64	0.29	0.74
Fatigue	47.2±8.0	44.4±8.3	42.3±6.2	45.6±7.1	44.2±6.6	40.1±7.7	0.43	0.51	1.56	0.21	1.43	0.24
Sleep	48.7±7.4	45.3±8.1	45.4±5.9	48.7±7.0	47.8±4.6	41.3±5.5	1.7	0.19	0.76	0.46	2.46	0.09
Social	60.1±7.2	62.1±4.9	62.2±3.9	60.9±10.1	57.8±7.4	55.8±7.7	0.05	0.81	3.04	0.05*	0.88	0.41
Pain Inter.	45.2±6.5	41.8±2.8	43.4±4.4	43.2±5.5	45.9±5.8	42.4±3.3	3.7	0.05 [#]	0.14	0.86	0.81	0.44

[#]Indicates significant differences between injury (p < 0.05)

*Indicates significant differences between age groups (p < 0.05)

Abbreviations: **CAI** = Chronic ankle instability; **FADI** = Foot and ankle disability index; **ADL** = Activities of daily living; **Phys. Func.** = physical function; **Inter.** = Interference

Chapter 4: Sensorimotor and Mechanical Outcomes in Young, Middle, and Older-Aged Adults With and Without Chronic Ankle Instability

Introduction

Ankle sprains are the most common lower extremity injury among young physically active populations and have a high incidence rate among the general population.^{3,36,47} An estimated 23,000 ankle sprains occur daily with an economic burden of approximately \$2 billion in accumulated health care cost each year in the USA.⁴⁷ With over half of all ankle sprains occurring during the early stages of life,⁴⁷ the majority of individuals with a history of a traumatic ankle joint injury will develop chronic ankle instability (CAI) as a young-adult.^{9,53,57} CAI is an encompassing term used to describe the persistent pain, swelling, activity limitations, and recurrent joint injury commonly seen after an ankle sprain.^{37,56,232} These lingering symptoms have been suggested to contribute to the lower health-related quality of life^{9-12,220} and decreased physical activity levels^{59,210} reported by young-adults with CAI.

It is well established within the literature that various sensorimotor insufficiencies contribute to the development of CAI in young-adults.^{18,37,120} Specifically, those with CAI have worse static^{119,121} and dynamic balance,^{122,128,131} decreased sagittal plane torque throughout the lower extremity,^{167,178} and diminished spinal reflex excitability of the soleus muscle.^{136,137,139,141} In addition to the sensorimotor insufficiencies, mechanical restrictions at the ankle can occur in those with CAI,³⁷ primarily, a loss in open^{78,198} and closed-kinetic chain dorsiflexion range of motion (DF-ROM).¹³¹ Together the mechanical and sensorimotor insufficiencies previously observed in young-adults with CAI have been linked to the early decrease in their health-reported quality of life and self-reported

function.^{140,220} Therefore, CAI is considered a multi-factorial pathology that has immediate consequences in early adulthood

While the mechanical and sensorimotor impairments found in young-adults with CAI are thought to result in the development of CAI, similar impairments have been shown to contribute to the loss of independence^{21,28,29,233} and increase the risk of serious injury later in life.^{21,33-35,233,234} Specifically, static postural control,^{19-21,233-235} the integrity of the spinal reflex system,²²⁻²⁵ lower extremity strength^{21,26} and DF-ROM²⁶ have all been seen to decrease with age. Given the majority of individuals develop CAI as a young-adult; the mechanical and sensorimotor impairments associated with CAI may compound the effect of aging. As a result, people with a history of a traumatic ankle joint injury early in life might be at an increased risk of greater decreases in their health and mobility as they get older compared to their age-matched healthy counterpart. However, majority of the empirical evidence aimed at understanding the consequence of CAI is in younger-aged adults with CAI.⁴⁰

Therefore, the aim of this investigation is to compare static and dynamic postural control, spinal reflex excitability, lower extremity strength, and DF-ROM in younger-, middle- and older-aged adults with and without CAI. We hypothesized: 1) participants with CAI will have decreased sensorimotor and mechanical outcome measures compared to healthy-controls; 2) sensorimotor and mechanical outcome measures will be decreased in middle-aged adults compared to the younger-aged adults; the older-aged adults will have decreased sensorimotor and mechanical outcome measures compared to both groups; 3) younger-, middle-, and older-aged adults with CAI will have decreased mechanical and sensorimotor outcome measures compared to their age-matched healthy

counterpart. This study will advance our understanding of CAI by describing the physical mal-adaptations that persist later in life. A better understanding of these mal-adaptations will be valuable in designing novel and unique programs that are capable of addressing functional deficiencies in CAI patients of all ages.

Methods

Study Design

This was a cross-section case control design requiring participants to report to the research laboratory for a single testing session. All methodological research protocols were approved by the University of Kentucky Institutional Review Board.

Participants

Sixty participants with self-reported CAI and 40 healthy-control participants were recruited from a large regional university and the surrounding community. Based on age, participants were classified into three age categories: 1) younger-aged adults (age: 18-35, n = 31); middle-aged adults (age: 36-59, n = 25); and older-aged adults (age: 60+, n = 11). All participants read and signed an informed consent that was approved by the University of Kentucky institutional review board.

Inclusion criteria for younger-aged adults with CAI were based on criteria set by the International Ankle Consortium for identifying individuals with CAI.⁵⁶ Specifically, younger-aged adults with CAI were required to have: 1) a previous history of an acute lateral ankle sprain which resulted in swelling, pain and temporary loss of function; 2) repeated episodes of ‘giving-way’ and/or recurrent sprain; and 3) perceived instability determined by a score of ≥ 5 on the Ankle Instability Instrument (AII) and/or ≥ 11 on the Identification of Functional Ankle Instability (IdFAI). There is currently no standard

used to identify middle- and older-aged adults with CAI. Therefore, middle- and older-aged adults with CAI were identified according to the presence of having: 1) experienced an acute lateral ankle sprain that caused swelling, pain and temporary loss of function before the age of 35 years-old; 2) repeated episodes of ‘giving-way’ and/or recurrent ankle sprains; and 4) perceived instability determined by a score of \geq ‘5’ on the AII and/or \geq ‘11’ on the IdFAI. The AII and IdFAI have been shown as reliable and valid in assessing patient-reported functional limitations in those with CAI.^{212,236,237} In the event participants reported a having bilateral ankle sprain, the limb with the greatest functional limitations according to the AII and IdFAI was used as the test limb. Participants allocated to the healthy-control group were required to report not having sustained an acute lateral ankle sprain, no ‘giving-way’, and score ‘0’ on the AII and IdFAI.

All participants were free from any: 1) diagnosed balance, vestibular or respiratory disorder; 2) history of low back pain in the previous 6 month’s; 3) previous history of fracture or surgery in the lower extremity; 4) history of seizures; 5) history of concussion in the past 6 month’s; 6) history of neurological injuries or diseases; 7) use of any assistive-walking device; and/or previous history of any self-reported musculoskeletal or neurovascular injuries and disorders in the lower extremity within the previous 6 months other than an lateral ankle sprain.

Instrumentation

Static Postural Control

Center of pressure (COP) trajectories in the anteroposterior (AP) and mediolateral (ML) directions were measured using a Bertec force platform (Bertec FP6090-15-2000; Bertec Inc., Columbus, OH) integrated with Cortex 5.5 motion capture software (Motion

Analysis Corporation, Santa Rosa, CA) at a sampling rate of 100Hz. The COP data were filtered using a low pass, fourth order Butterworth filter set at a cutoff frequency of 5 Hz.²³⁸ The COP velocity data were used in the calculation of the mean of time-to-boundary (TTB) minima (sec) for the ML and AP direction. The TTB variables were calculated using a custom MATLAB file (Mathworks, Inc. Natick, MA) using a previously described method.²³⁹

Spinal Reflex Excitability

Electromyography (EMG) signals were collected using two pre-gelled Ag/AgCL EMG recording electrodes (EL503, BIOPAC Systems, Inc.) placed 1.75 mm apart and positioned in line with the muscle fibers approximately 2 finger widths distal to the gastrocnemius muscle.²⁴⁰ The ground electrode was placed over the contralateral medial malleolus.^{240,241} Both areas were shaved, abraded with fine sandpaper, and cleaned with isopropyl alcohol wipes.

A Digitimer DS7AH constant current stimulator (Digitimer Ltd., Hertfordshire, England) delivered a 1-ms square wave stimulus through a 4mm shielded disk-shaped stimulating electrode (EL254S; BIOPAC Systems, Inc., Goleta CA, USA) located over the popliteal fossa.²⁴⁰ A 7-mm carbon-impregnated dispersive pad was placed over the ipsilateral quadriceps.²⁴⁰ A 16-bit converter (MP150, BIOPAC Systems, Inc., Goleta CA, USA) was used to process analog-to-digital signal conversion. EMG signals were sampled at 2000Hz and amplified at a gain of 1000 (EMG100C, BIOPAC Systems, Inc., Goleta CA, USA). Acqknowledge BIOPAC Software (BIOPAC version 3.7.3) was used to visualize the signals and manipulate the stimuli.

Isometric strength

Ankle, knee and hip strength was assessed through maximal voluntary isometric contractions (MVIC) using a BTE evaluator (BTE™ Evaluator, BTE, Hanover, MD) portable load cell with attachments designed for handheld dynamometry.

Experimental Procedures

Static Postural Control

Static postural control was measured during an eyes-open single-limb balance task (Figure 4.1). Participants were asked to stand barefoot on the involved limb in the middle of the force platform for 20-seconds. Participants were instructed to cross their arms across their chest while keeping their foot flat on the force plate. Participants were given three practice trials and then instructed to perform three test trials with their eyes-open. Trials were discarded and repeated if: 1) the non-testing limb made contact on the force platform or the stance limb; 2) participants hopped or took a step with the stance limb; 3) removed their hands from their chest; and/or 4) they lifted their arms from their chest. Lower TTB values represent greater postural instability.²⁴²

Dynamic Postural Control

Dynamic postural control was measured using the Star Excursion Balance Test (SEBT).¹²² The SEBT was originally designed as a lower extremity reach test performed on an eight-directional star pattern constructed by metric tape measures secured to the floor. However, recent work by Hertel et al¹²⁶ has advocated for a reduction in the number of reach directions because of the amount of redundancy when all eight-directions are performed. Therefore, the anterior (SEBT-A), posteromedial (SEBT-PM)

and posterolateral (SEBT-PL) reach directions were measured (Figure 4.2).^{122,131} The SEBT has excellent inter- and intra-rater reliability.²⁴³

Participants were instructed to stand barefoot in the center of the star pattern with their hands on their waist.¹²² While maintaining a single-limb stance on the involved limb, participants were instructed to reach maximally in the designated reach direction with the non-stance limb by lightly touching the line and returning to the starting position.¹²² For the SEBT-A direction the most distal portion of the participant's first toe was placed at the center of the star. For the SEBT-PM and SEBT-PL reach directions the participant's heel was placed at the center of the star. Participants were given four practice trials in each reach direction.¹²⁴ Three test trials were recorded for each reach direction. Trials were discarded and repeated if the individual: 1) touched heavily or came to a rest at the point of touchdown; 2) participants hopped or took a step with the stance limb; and/or 3) lifted or shifted any part of the foot of the stance limb. The maximum distance reached in each direction was recorded in centimeters and normalized to the length of the participant's stance limb.¹²⁷ Leg length was measured as the distance from the anterior superior iliac spine to the most distal portion of the medial malleolus.¹²⁷ The normalized average for each direction was used for statistical analysis. Lower normalized reach distance equates to decreased dynamic postural control.¹²²

Spinal Reflex Excitability

Spinal reflex excitability (Figure 4.3) was performed using a previously published protocol for eliciting the Hoffman reflex (H-reflex) and muscle response (M-response).^{132,244} The soleus muscle was targeted because: it is a muscle used to help maintain upright postural control;^{245,246} and prior studies have demonstrated both older

adults²²⁻²⁵ and younger-aged adults with CAI have alterations in the soleus muscle H-reflex.^{136,137,139,141,143} Participants were prone on a standard height plinth with their involved knee flexed and supported by a pillow placed underneath their ankle.^{141,142} The stimulating electrode was shifted to find the location that elicited the largest peak-to-peak twitch response at a constant stimulus in the Soleus.^{132,137,240,244} Once this location was found the electrode was secured and used for all testing trials. Next, the stimulus intensity was increased or decreased with 10 seconds of rest between trials until the maximum peak-to-peak H-reflex (H_{max}) was identified.²⁴⁴ Three trials were measured and recorded. To determine the maximum M-response (M_{max}), the stimulation was increased in increments of 10.0 mA until the peak-to-peak amplitude of the M-wave plateaued.^{132,137,244} Three M_{max} trials were measured and recorded. The average H_{max} was normalized to M_{max} to calculate the $H_{max}:M_{max}$ and was used for statistical analysis.¹³² Lower $H_{max}:M_{max}$ ration indicate decreased spinal reflex excitability of the soleus.¹³²

Lower Extremity Torque

Participants were asked to remove his/her shoes and were positioned on a standard examination table. For each testing, participants were positioned in accordance to previously published data for testing isometric force.²⁴⁷ Participants were instructed to provide resistance for 5-seconds, ramping up during the first 3-seconds, then providing a maximal effort for the final 2-seconds.²⁴⁸ The participant was given one practice trial and then three test trials were recorded. Participants were provided a 30-second rest interval between trials.²⁴⁸

To assess ankle dorsiflexion torque (Figure 4.4), participants laid supine with their hip, knee and ankle at 0°.²⁴⁷ Two straps placed over the lower leg and thighs were used to

prevent any accessory motion. The handheld dynamometer was placed proximal to the metatarsophalangeal joint.²⁴⁷ Participants were instructed to pull their ankle against the handheld dynamometer. Good test-retest reliability has been demonstrated.²⁴⁹

Plantarflexion torque (**Figure 4.4**) was assessed with the participant in a prone position with their head supported by their arms. The participant's hip, knee and ankle were placed at 0°. Two straps were placed over the lower leg and thighs to prevent any accessory motion. The hand held dynamometer was located over the metatarsal heads on the plantar side of the foot.²⁴⁷ Participants were instructed to push their ankle against the dynamometer. Good test-retest reliability has been demonstrated.²⁴⁹

Knee extension torque (**Figure 4.5**) was evaluated with the participant seated on the edge of an examination table with their hips and knees flexed to 90°; and their arms resting on their chest.²⁵⁰ A strap was placed over their lap to limit accessory motion. The portable load cell was placed behind the involved limb. One end of the portable load cell was attached to a stabilizing strap attached approximately 5.08cm above the medial malleoli of the participant's involved limb.²⁵⁰ The opposite end of the portable cell was fixed to the examination table.²⁵⁰ Participants were instructed to perform a maximal voluntary isometric knee extension. Good test-retest reliability has been demonstrated.²⁵⁰

Hip abduction torque (**Figure 4.6**) was evaluated with participants placed in a sideline position.²⁵¹ A pillow was placed between the limbs to ensure the two limbs were in neutral position and the both knees were fully extended.²⁵¹ A strap was placed over the waist of the participant to limit accessory motion. A second strap was used to hold the handheld dynamometer 5.08 cm proximal to the lateral joint line.²⁵¹ Participants were

instructed to push into the dynamometer with their involved limb. Good test-retest reliability has been demonstrated.²⁵¹

Hip extension torque (Figure 4.6) was assessed with the participant in a prone position.²⁵² The hip was placed in neutral position and the knee flexed to 30°. ²⁵² A strap was placed over the waist to limit accessory motion. The handheld dynamometer was placed over the distal thigh, just proximal to the popliteal fossa. A second strap was used to hold the dynamometer in place and the participants were instructed to extend their hip upwards against the dynamometer. Good test-retest reliability has been demonstrated.²⁵¹

Peak force for each test trial was recorded in pounds (lbs) and converted to Newton's (N) and the average for each strength assessment was calculated. To calculate peak torque the length of the femur, lower leg and foot was recorded and used as the moment arm. The femur was measured as the distance from the greater trochanter to the lateral aspect of the knee joint. The length of the lower leg was measured as the distance from the lateral joint line to the most distal aspect of the lateral malleolus. Foot length was measured as the distance from the posterior lateral malleolus to the metatarsal heads. The length of the femur was used in the calculation of hip abduction and extension torque, the length of the lower leg was used for knee extension torque, and the length of the foot was used for dorsiflexion and plantarflexion torque. The average maximal force output (N) was multiplied by the moment arm (m) and normalized to each participant's body weight (kg) and expressed as Nm/kg. The average Nm/kg was used for all statistical analysis. Lower values correspond with decreased torque.

Open-Kinetic Chain Dorsiflexion Range of Motion

Open-kinetic dorsiflexion range of motion was assessed with the participants seated on the edge of a standard plinth with their knees flexed to 90° (Figure 4.7).¹⁸² The thigh was secured to the table by Velcro straps for stabilization. The bubble inclinometer was placed over the fifth metatarsal of the foot using a Velcro strap. With the ankle placed in neutral (0°) participants were asked to actively dorsiflex the ankle maximally. Once the participant reached their end range of motion, ankle dorsiflexion was recorded. The average of three measures were recorded and used for statistical analysis. Lower values represent decreased DF-ROM.

Weight-Bearing Lunge Test

Closed-kinetic chain dorsiflexion range of motion was assessed using the weight-bearing lunge test (WBLT) (Figure 4.7).²⁵³ The WBLT was performed using a previously published protocol.^{131,253} A standard metric tape measure was used to secure to the floor perpendicular to a wall. Participants placed their hands on the wall to help maintain balance and with their feet in a tandem stance over the tape measure. Participants performed a forward lunge until the anterior aspect of their involved knee touched the wall. Participants were gradually moved further away from the wall in 1cm increments until they could no longer touch the wall with their anterior knee and their heel flat on the floor.^{131,253} The maximum distance from the wall was recorded in cm. Three trials were recorded and the average was used for statistical analysis. Lower values represent decreased DF-ROM.²⁵³

Statistical Analysis

Separate 2x3 between-group analysis of variance models were conducted to explore the impact of Injury (CAI vs. healthy-control) and Age groups (young, middle,

and old) on anthropometric information and for each dependent variable. A Bonferroni post hoc analysis was used in the event of any significant differences. The *a priori* alpha level was set a $p \leq 0.05$

All statistical analyses were performed using IBM SPSS Statistics, version 23 (IBM, Corp., Armonk, NY, USA).

Results

Participant demographics and injury characteristics are listed in Table 4.1 and Table 4.2. The interaction effect between Injury and Age group, along with simple main effects, was not statistically significant for height, weight and BMI. There was a statistically significant Age group main effect for age ($F_{2, 94} = 475.57$, $p = 0.001$, partial $E^2 = 0.908$, observed power = 1.00). As expected, post hoc comparisons using a Bonferroni test indicated that participants allocated to the middle-aged group (46.2 ± 7.5 , $p = 0.001$) and older-aged group (67.2 ± 5.9 , $p = 0.001$) were older than those in the younger-aged group (24.0 ± 3.4). Likewise, those in the older-aged group were significantly older than those in the middle-aged group ($p = 0.001$).

Static Postural Control

Group means and standard deviations for all of the static postural control variables are given in Table 4.3. The interaction effect between Injury and Age group was not statistically significant for any main outcome variable ($p > 0.05$). Likewise, there was not a statistically significant Injury main effect for any main outcome variable ($p > 0.05$). There was a statistically significant main effect for Age group for the TTbAP mean of minima ($F_{2, 86} = 9.55$, $p < 0.0001$, partial $E^2 = 0.193$, observed power = 0.97), TTbAP S.D. of minima ($F_{2, 86} = 7.44$, $p < 0.001$, partial $E^2 = 0.157$, observed power = 0.93), and

TTBAP absolute minimum ($F_{2, 86} = 9.55$, $p = 0.004$, partial $E^2 = 0.127$, observed power = 0.85).

TTBAP mean of minima (sec)

Post hoc comparisons indicated the TTBAP mean minima was greater in the younger aged (5.862 ± 1.8) compared to the middle-aged (4.27 ± 1.2 , $p = 0.002$) and older-aged participants (4.02 ± 1.1 , $p = 0.007$). There was no difference between the middle-aged and older-aged participants ($4.27 \pm$ vs. $4.0 \pm$, $p = 0.99$).

TTBAP S.D. of minima (sec)

Post hoc comparisons indicated the TTBAP S.D. of minima was lower in the middle-aged group compared to the younger-aged group (3.55 ± 1.2 vs. 5.68 ± 2.6 , $p = 0.002$). There was no difference between the younger-aged group and older-aged group (5.68 ± 2.6 vs. 4.01 ± 1.2 , $p = 0.106$) or between the middle-aged and older-aged group (3.55 ± 1.2 vs. 4.01 ± 1.2 , $p = 0.99$).

TTBBAP absolute minimum (sec)

Post hoc comparisons indicated the TTBAP absolute minimum was lower in the older-aged participants compared to the younger-aged participants (0.86 ± 0.21 vs. 1.1 ± 0.31 , $p = 0.016$). There was no difference between the middle-aged and older-aged participants (0.98 ± 0.33 vs. 0.86 ± 0.31 , $p = 0.99$) or between the middle-aged and younger-aged participants (0.98 ± 0.33 vs. 1.1 ± 0.31 , $p = 0.060$).

Dynamic Postural Control

Means and standard deviations for each reach direction of the SEBT are given in Table 4.4. The interaction effect between Injury and Age group was not statistically

significant for any main outcome variable ($p > 0.05$). Likewise, there was not a statistically significant Injury main effect for any main outcome variable ($p > 0.05$).

There was a statistically significant main effect for Age group for the SEBT-PM ($F_{2, 99} = 10.33$, $p < 0.0001$, partial $E^2 = 0.182$, observed power = 0.98) and SEBT-PL ($F_{2, 99} = 12.77$, $p < 0.001$, partial $E^2 = 0.216$, observed power = 0.99) reach directions.

Posteromedial (% LL)

Post hoc comparisons indicated the SEBT-PM reach direction was lower in the older-aged adults (67.2 ± 10.7) compared to the younger-aged adults (81.0 ± 10.6 , $p < 0.001$) and middle-aged adults (76.4 ± 10.9 , $p = 0.033$). There was no difference between the younger-aged and middle-aged adults (81.0 ± 10.6 vs. 76.4 ± 10.9 , $p = 0.264$).

Posterolateral (%LL)

Post hoc comparisons indicated the SEBT-PL reach distance was lower in the older-aged adults (54.6 ± 11.0) compared to the younger-aged adults (74.0 ± 13.5 , $p < 0.001$) and compared to the middle-aged adults (70.2 ± 14.4 , $p = 0.001$). There was no difference between the middle-aged and younger-aged adults (70.2 ± 14.4 vs. 76.4 ± 10.9 , $p = 0.264$).

Spinal Reflex Excitability

Means and standard deviations for $H_{\max}:M_{\max}$ ratio are provided in (Table 4.5) . The interaction effect between Injury and Age group was not statistically significant ($p > 0.05$). There was no significant Injury main effect ($p > 0.05$). There was a statistically significant main effect for Age group ($F_{2, 88} = 3.446$, $p = 0.037$, partial $E^2 = 0.019$, observed power = 0.631).

Post hoc comparisons indicated the $H_{\max}:M_{\max}$ ratio was lower in older-aged adults compared to the younger-aged adults (0.44 ± 0.26 vs. 0.67 ± 0.21 , $p = 0.039$). There was no difference between the middle-aged and younger-aged adults (0.60 ± 0.44 vs. 0.67 ± 0.21 , $p = 0.600$) or between the middle-aged and older-aged adults (0.60 ± 0.44 vs. 0.44 ± 0.26 , $p = 0.661$).

Lower Extremity Torque

Means and standard deviations for each torque measurement are given in Table 4.6. The interaction effect between Injury and Age group was not statistically significant for any main outcome variable ($p > 0.05$).

There was a statistically significant Injury main effect for Dorsiflexion ($F_{2, 97} = 4.682$, $p = 0.033$, partial $E^2 = 0.049$, observed power = 0.572), Plantarflexion ($F_{2, 85} = 5.945$, $p = 0.017$, partial $E^2 = 0.063$, observed power = 0.675), and Hip Extension ($F_{2, 95} = 4.810$, $p = 0.031$, partial $E^2 = 0.037$, observed power = 0.446).

There was a significant Age group main effect for Dorsiflexion ($F_{2, 97} = 4.984$, $p = 0.009$, partial $E^2 = 0.099$, observed power = 0.800), Plantarflexion ($F_{2, 85} = 2.914$, $p = 0.05$, partial $E^2 = 0.002$, observed power = 0.557), and Hip Extension ($F_{2, 85} = 5.536$, $p = 0.005$, partial $E^2 = 0.111$, observed power = 0.105).

Dorsiflexion Torque (Nm/Kg)

Post hoc comparisons indicated the CAI group had decreased Dorsiflexion torque compared to the healthy-control group (0.30 ± 0.09 vs. 0.39 ± 0.14 , $p = 0.033$). Regardless of Injury group, the post hoc comparisons indicated the older-aged participants had decreased dorsiflexion torque compared to the younger-aged groups (0.27 ± 0.08 vs. 0.37 ± 0.13 , $p = 0.008$). There was no difference between the younger-aged and middle-

aged participants (0.37 ± 0.13 vs. 0.33 ± 0.11 , $p = 0.442$) or between the middle-aged and older-aged participants (0.33 ± 0.11 vs. 0.27 ± 0.08 , $p = 0.376$).

Plantarflexion Torque (Nm/Kg)

Post hoc comparisons indicated the CAI group had decreased Plantarflexion torque compared to the healthy-control group (0.53 ± 0.14 vs. 0.63 ± 0.19 , $p = 0.017$). Regardless of Injury group, post hoc comparisons indicated the older-aged participants had decreased Plantarflexion torque compared to the younger-aged participants (0.51 ± 0.13 vs. 0.63 ± 0.18 , $p = 0.05$). There was no difference between the younger-aged and middle-aged participants (0.63 ± 0.18 vs. 0.57 ± 0.15 , $p = 0.99$) or between the middle-aged and older-aged participants (0.57 ± 0.15 vs. 0.51 ± 0.13 , $p = 0.495$).

Hip Extension Torque (Nm/Kg)

Post hoc comparisons indicated the CAI group had decreased Hip Extension torque compared to the healthy-control group (1.47 ± 0.55 vs. 1.73 ± 0.69 , $p = 0.031$). Regardless of Injury group, post hoc comparisons indicated the older-aged participants had decreased Hip Extension torque compared to the younger-aged participants (1.35 ± 0.62 vs. 1.88 ± 0.60 , $p = 0.010$). There was no difference between the younger-aged and middle-aged participants (1.88 ± 0.60 vs. 1.57 ± 0.59 , $p = 0.111$) or between the middle-aged and older-aged participants (1.57 ± 0.59 vs. 1.35 ± 0.62 , $p = 0.860$).

Open-Kinetic Chain Dorsiflexion Range of Motion

Means and standard deviations are given in Table 4.7. The interaction effect between Injury and Age group was not statistically significant ($p > 0.05$). There was no significant Injury or Age group main effect ($p > 0.05$).

Weight-Bearing Lunge Test

Means and standard deviations are given in Table 4.7. The interaction effect between Injury and Age group was not statistically significant for any main outcome variable ($p > 0.05$). There was no significant Age group main effect ($p > 0.05$). There was a significant Injury main effect ($F_{2, 99} = 4.664$, $p = 0.034$, partial $E^2 = 0.048$, observed power = 0.570).

Post hoc comparisons indicated the CAI group and decreased WBLT scores compared to the healthy-control group (7.25 ± 3.4 vs. 9.27 ± 3.5 , $p = 0.033$).

Discussion

Chronic ankle instability is associated with multiple mechanical and sensorimotor insufficiencies that are linked to early decrease in health and self-reported function in younger-aged adults.^{37,140,220} Little empirical evidence exists on whether these common mechanical and sensorimotor factors persist as individuals with CAI get older.⁴⁰ Therefore, the aim of this investigation was to compare the common mechanical and sensorimotor measures reported in CAI participants in younger-, middle-, and older-aged adults with and without CAI. We hypothesized the middle-aged adults would have decreased mechanical and sensorimotor outcomes compared to the younger-aged adults; while the older adults would have greater mechanical and sensorimotor deficiencies compared to both groups. Several age-related differences were observed in the current investigation including static and dynamic balance, spinal reflex excitability, and ankle (plantarflexion and dorsiflexion) and hip extension torque were all lower in the older-aged adults compared to the younger-aged adults. Secondly, we hypothesized that the mechanical and sensorimotor factors would be worse in the CAI group compared to the

healthy-control group. Our results support this hypothesis as participants with CAI had decreased dorsiflexion range of motion and ankle (plantar flexion and dorsiflexion) and hip extension torque compared to the healthy-control group. Lastly, we hypothesized younger-, middle-, and older-aged adults with CAI would have decreased mechanical and sensorimotor outcome measures compared to their age-matched healthy counterpart. Our results do not support this hypothesis because we did not observe any significant interaction for Injury (CAI & healthy-control) and Age (young, middle, and older) for any of the selected dependent variables.

Age-Related Differences

Age-related changes using spatiotemporal measures of single-limb balance have been previously shown. Slobounov et al²⁰ used a composite score to measure the spatiotemporal characteristics of the AP and ML trajectories in older-aged adults and found decreases in the spatiotemporal characteristic with advanced age. Additionally, van Wegen et al¹⁹ observed reduced spatiotemporal measures in older-adults (age 55-69 years old) in the AP direction compared to younger-aged adults (age 25-38 years old). Our results are in agreement with these earlier investigations as we found the middle-aged and older-aged participants had lower TTB mean minima in the AP direction compared to the younger-aged adults (Table 4.3). While the earlier investigations have compared between younger- and older-aged adults, our results provide evidence suggesting balance can begin to change as early as the 4th decade of life. Furthermore, the lower TTB mean minima in the AP direction observed in the middle-and older-aged participants indicates they were using a less ideal strategy to balance because they were balancing closer to the edge of their base of support compared to the younger-aged participants. The implication

of these results is that the middle-aged and older-aged adults have less time to respond to an unanticipated perturbation and are at an increased risk of falling because they might not have enough time to make a postural correction. However, it is important to recognize all of the participants included in the present investigation were able to complete the single-limb balance task. Therefore, more research is needed to understand the consequence of these findings.

The lower TTB mean in the AP direction found in the current study might be explained by age-related changes occurring within the muscle spindle. Muscle spindles are intrafusal fibers that are sensitive to changes in muscle length and are involved in controlling posture. Various investigators²⁵⁴⁻²⁵⁶ have suggested aging results in several morphological changes to the muscle spindles that can impair their sensitivity and therefore the information relayed to the central nervous system. Because of the important role the soleus has in maintaining upright postural control,^{245,246} older-aged individuals might have to lean forward or slightly flex their knee to increase the tension and sensitivity of the muscle spindles within the soleus muscle. This compensation likely places an individual's COP closer to the edge of their base of support and might help to account for the lower TTB mean minima in the AP direction observed in the current study. However, we did not examine the joint kinematics of participants as they balanced and more research is needed to confirm this hypothesis.

Along with lower average TTB minima, we found the middle-aged participants had smaller TTB standard deviations in the AP direction (Table 4.3). Early studies^{19,20} demonstrated older-aged adults had smaller TTB standard deviations compared to younger-aged adults. Additionally, researchers²⁵⁷ determined patients with Parkinson's

disease exhibit similar alterations in the TTB standard deviations compared to healthy-controls. Examining the standard deviations can provide additional information about the amount of variability within the TTB profile.²⁴² Smaller TTB standard deviations are thought to be reflective of diminished variability caused by neuromuscular dysfunction.²⁴² Madhavan and Shields²⁵⁸ demonstrated older-aged individuals have increased EMG activity in the plantar flexors and dorsiflexors compared to younger-aged adults when balancing. This increased co-activation is hypothesized to improve joint stability and increase sensitivity in the muscle spindles.²⁵⁸ However, this increased co-activation could lead to a more rigid postural control system and reduce the variability within COP oscillations. The consequence of this is the potential for individual's to lose the flexibility to adapt to an unanticipated perturbation and be at an increased risk of falling when balancing. This is supported by previous studies demonstrating larger TTB standard deviations are associated with improve postural control.⁹² More research is needed to examine the role co-activation of the surrounding ankle musculature has on measures of TTB variability.

Additionally, we found age-related decreases in dynamic postural control measured with the SEBT (Table 4.4). Primarily, we found the older-aged participants produced a shorter reach distance in the posteromedial direction of the SEBT compared to the younger-aged adults; as well as, in the posterolateral reach direction relative to the younger- and middle-aged adults (Table 4.4). Previous research using the Y Balance Test has shown differences in all 3 distances between middle-aged (age 45-60 years old) and older-aged (age 70-80 years old) adults.²⁵⁹ Other researchers have implemented the Berg Balance Scale²⁶⁰ and Functional Reach Test^{261,262} to demonstrate decreases in dynamic

balance in older-aged adults. However, the differences in methodology and participant demographics between these earlier studies²⁶⁰⁻²⁶² and the present investigation make it difficult to make comparisons. Of note, we did not find a difference in any direction of the SEBT between the younger-aged and middle-aged participants (Table 4.4). This lack of differences is not in agreement with previous research using the SEBT. Specifically, Bouillon and Baker²⁶³ found middle-aged (age 40-54 years old) women reached a shorter distance in the anteromedial, medial, and posteromedial directions compared to younger-aged (age 23-39 years old) women. These findings suggest dynamic balance can begin to deteriorate as early as 40 years old.

The SEBT is a dynamic postural control task requiring an individual to maintain a single-limb stance and maximally reach with their contralateral limb in different directions.¹²² Therefore, this test challenges an individual to move to the edge of their base of support without falling. The lower reach distances by the older-aged participants in the current investigation suggest they remained closer to the center of their base of support (Table 4.4). Given the limited investigations to have implemented the SEBT to identify dynamic balance deficits in older-aged adults makes it hard to determine the exact cause for the older-aged participants to remain over the center of their base of support.

Robinson and Gribble²⁶⁴ reported hip flexion of the stance limb accounted for approximately 88% of the variance for the posteromedial and 95% of the posterolateral reach direction of the SEBT. These findings indicate that greater reach distance on the posteromedial and posterolateral directions is equated with greater hip flexion. Therefore, considering older-aged participants have a greater reliance on proximal hip musculature

to balance,²⁶⁵ it is reasonable to speculate that decreased hip strength might help to explain the decreased reach performances observed in the current study. Although we did not measure hip flexion strength, we did find older-aged participants had decreased hip extension torque. However, research focusing on the SEBT has largely been focused in younger-aged adults, making it difficult to conclude whether hip function contributes to the performance of the SEBT in older-aged adults. Rather, other impairments associated with a reduction in balance such as reaction time,²³³ vestibular and oculomotor function,^{21,234} and fear of falling²⁶⁶ might explain why older-aged adults do not reach as far on the SEBT.

In addition, we found the $H_{\max}:M_{\max}$ ratio of the soleus muscle was lower in the older-aged participants compared to the younger-aged participants (Table 4.5). The literature examining age-related changes in $H_{\max}:M_{\max}$ ratio of the soleus muscle has mainly focused on understanding its relationship with postural control. Specifically, Koceja et al²³ demonstrated that elderly subjects were unable to modulate the soleus H-reflex when transitioning from a prone to standing position, whereas younger-aged participants depressed the soleus H-reflex when standing. Angulo-Kinzler et al²² compared the soleus H-reflex gain between younger-aged and older-aged participants and reported the older-aged participants did not modulate the gain of the reflex when transitioning to a standing position. This lack of down modulating the H-reflex amplitude was found to be associated with greater postural sway in older adults.²³

The mechanism leading to the reduction in modulating a down-regulation of the H-reflex has been explained by changes in presynaptic inhibition.²⁶⁷ While previous studies demonstrated a relationship between changes in $H_{\max}:M_{\max}$ ratio of the soleus

muscle to be related to static postural, it would be easy to speculate that the decreased $H_{\max}:M_{\max}$ ratio of the soleus muscle observed in the current study might partially explain the decreased balance observed as well in the current study. However, it is difficult to make those conclusions because methodology used in the current investigation and those used previously.^{22-25,267} Therefore, the functional consequence of the age-related decreases in $H_{\max}:M_{\max}$ in the current study remains speculative.

Finally, this study demonstrated older-aged participants had decreased sagittal plane isometric peak torque at the ankle and hip compared to the younger-aged adults. Specifically, the older-aged adults had decreased isometric plantar flexion, dorsiflexion and hip extension peak torque compared to the younger-aged participants (Table 4.6). Reduced isometric peak torque suggests the older-aged participants produced less force compared to the younger-aged adults. These findings are in agreement with previous studies demonstrating decreases in sagittal plane strength in older-aged adults for the leg extensors,²⁶⁸⁻²⁷⁰ plantar flexors,²⁷¹⁻²⁷³ dorsiflexors.^{272,273} Decreases in ankle plantar flexion and dorsiflexion strength have been shown to be correlated several age-related changes in physical function including static balance,^{17,274,275} walking speed,²⁷⁴ stair ascent,²⁷⁶ and increased risk of falling²⁷⁷. Similarly, decreases in hip extension strength have been correlated with impaired gait mechanics,^{278,279} as well as, static²⁶⁵ and dynamic balance.²⁸⁰ Therefore, the decreased dorsiflexion, plantar flexion and hip extension observed in the current study likely have negative age-related consequences that could impact older-aged individuals ability to perform day-to-day activities. More research is needed to better understand the impact the decreased sagittal plane ankle and hip strength found in the present study.

Injury Differences

Along with age-related decreases, we hypothesized that the CAI group would have worse mechanical and sensorimotor outcome measures compared to the healthy-control group. According to the results, the participants with CAI had decreased dorsiflexion range of motion, specified by the decreased scores on the WBLT (Table 4.7). Hoch et al¹³¹ examined dorsiflexion range of motion using the WBLT in younger-aged adults (age 18-35 years old) with and without CAI and reported lower scores in the CAI group relative to their healthy counterpart. In addition, restricted dorsiflexion range of motion has been observed during functional activities such as landing from a jump.²⁰¹ The decreased dorsiflexion range of motion found in the present study could be caused by an anteriorly displaced talus. Wikstrom et al¹⁸⁸ compared the location of the talus between those with and without CAI using radiographic images. The participants with CAI were found to have an anteriorly displaced talus relative to the tibia compared to the healthy-control group.¹⁸⁸ Limited dorsiflexion range of motion is a significant concern because of its implications in the performance of the anterior reach direction of the SEBT,²⁸¹ a test that has been associated with an increase risk of re-injury.²⁸² Furthermore, reduced dorsiflexion range of motion is associated with a jump-landing strategy using reduced joint flexion that attenuated forces less efficiently.²⁸³ This could increase the risk of injury further up the kinetic chain, as well as, alter the loading patterns experienced at the ankle. While these early reports into the consequences of limited dorsiflexion range of motion examined only younger-aged participants, the results from the current investigation add to the literature by demonstrating limited dorsiflexion is associated with CAI irrespective of an individual's age.

Results from this study also demonstrated participants with CAI had decreased isometric dorsiflexion and plantar flexion (Table 4.6) peak torque compared to the healthy-control group. Decreased isometric peak torque suggests participants with CAI produced less force compared to the healthy-control group. We examined sagittal plane ankle torque rather than the frontal plane because of CAI appears to be more associated with sagittal plane ankle strength compared to frontal plane strength deficits. Specifically, Hubbard et al³⁸ found decreased plantar flexion peak torque of the involved limb in a group of subjects with CAI compared to a healthy-control group and decreased plantar flexion-to-dorsiflexion peak torque compared to a healthy control group. They further found decreased plantar flexion peak torque of the involved limb in a group of subjects with CAI compared to a healthy-control group and decreased plantar flexion-to-dorsiflexion peak torque compared to a healthy control group. In addition, Gribble et al¹⁶⁷ compared concentric ankle (plantar flexion and dorsiflexion) peak torque between limbs of participants with CAI and to a group of healthy-controls, and reported decreases in concentric plantar flexion peak torque between limbs and groups; however, no difference between groups or limbs was found for dorsiflexion peak torque. Therefore, the results from the current investigation further demonstrate CAI is associated with decreases in sagittal plane torque.

Furthermore, this study demonstrated participants with CAI had decreased isometric hip extension peak torque compared to the healthy-control group (Table 4.6). The results from the current investigation provide further support for previous investigations identifying proximal neuromuscular alterations in those with CAI compared to healthy-controls.^{177 173,176,284} The functional consequence of this decreased

hip extension torque might be related to the recurrent joint injury associated with CAI. Recent work from our laboratory has demonstrated hip strength significantly contributes to the performance of the SEBT in younger-aged adults with CAI.²⁸⁵ Given the SEBT has been shown to be a predictor of an ankle sprain,²⁸² decreased hip extension strength in participants with CAI might contribute to the recurrent joint injury commonly associated with CAI. This is further supported by De Ridder et al¹⁷⁸ who found decreased hip strength was a significant predictor for an acute lateral ankle sprain in youth soccer players. However, conflicting evidence exist in the literature for whether strength deficits in sagittal plane hip extension are associated with CAI. Specifically, previous researchers^{38,167} have failed to identify hip extension deficits between limbs of participants with CAI and compared to a healthy-control group. Therefore, future work is needed to confirm if strength deficits in the proximal hip musculature are associated with CAI and their functional consequence.

We did not find a significant interaction for Injury (CAI & healthy-control) and Age group (young, middle, old) for any dependent variable. It is well known that aging brings a progressive decline in postural control,^{19,20,233,235} integrity of the spinal reflex system,²²⁻²⁵ lower extremity strength²⁴⁷ and range of motion,²⁸⁶ all of which have a significant impact on the self-reported function,^{28-30,287} health-related quality of life and risk of serious injury in older-aged adults.^{25,33-35} Given the common sensorimotor and mechanical alterations that are associated with aging and CAI,^{21,37,233,234} we hypothesized participants younger-, middle-, and older-aged participants with CAI would have greater deficits compared to their age-matched healthy counterpart. However, results from this study failed to identify group differences (CAI & healthy-control) in any age cohort.

We can speculate a few possible explanations for the lack of Injury differences among different age categories. First, because this is the first investigation to examine the impact of CAI in middle-aged and older-aged participants, it is unknown if the same mechanical and sensorimotor insufficiencies known to be associated with CAI in younger-aged adults continue to persist later in life. Rather, the middle-aged and older-aged participants might have learned to compensate for these impairments over time and now have developed new neuromuscular alterations.

An alternative explanation might be because of the unknown etiology of CAI³⁷ and its relationship with the development of post-traumatic ankle osteoarthritis (PTOA).²⁸⁸ CAI is a multifactorial and heterogeneous pathology.^{37,64,65} For example, some patients with CAI might have decreased balance whereas others experience mechanical restrictions. Because of the multifactorial and heterogeneous nature of CAI, researchers have been unable to identify the specific impairments associated with CAI that cause PTOA. Therefore, we included a wide-range of mechanical and sensorimotor impairments in hopes of identifying those that might contribute to age-related changes rather than the development PTOA. However, because we did not find group differences (CAI & healthy-control) among different age categories, it is reasonable to speculate that some combination of the mechanical and sensorimotor impairments included into this study are associated with the development of PTOA rather than the aging process. Indeed, Hubbard et al²⁸⁹ found decreased isometric ankle strength, double-limb static balance, and increased ankle joint stiffness in patients with unilateral ankle osteoarthritis compared to age-matched healthy-controls. Therefore, other factors known to be associated with CAI in younger-aged adults such as delayed peroneal reaction time¹⁶¹ or

altered joint position sense²⁹⁰ might be important factors in middle-aged and older-aged adults with CAI.

Limitations

This study is not without limitations. The primary limitation of this study is the small sample size of middle-aged (n = 26) and older-aged (n = 17) participants enrolled. A post hoc analysis showed that majority of the variables that were not statistically different were associated with low statistical power (observed power <0.5 for all variables). Conversely, the variables that were found to be significantly different were considered to have strong statistical power (observed power >0.9). Therefore, the small sample size included in this study raises the concern of an increased risk of Type II error and the results should be taken with caution.

Our overall aim of this investigation was to understand the long-term consequences of developing CAI as a young-adult. However, there is currently no established guidelines to identify middle-aged and older-aged participants who developed CAI as a young-adult. Therefore, we developed our inclusion criteria using the previously established guidelines set by the International Ankle Consortium and further required participants to have sustained an acute ankle sprain before the age of 35-years old.⁵⁶ Certainly, asking participants when they first sprained their ankle and the duration of symptoms is subject to recall bias. More research is needed to develop more effective ways to identify middle-aged and older-aged participants with CAI.

This study included a broad spectrum of mechanical and sensorimotor impairments known to be associated with CAI in younger-aged adults.³⁷ Other sensorimotor factors such as delayed muscle reaction time,¹⁶¹ altered activation

patterns,^{76,177,201} or supraspinal alterations^{241,244,291} are associated with CAI. Likewise, measures related to mechanical instability were not included in this study.³⁷ Therefore, future studies should determine whether these impairments are present in middle-aged and older-aged adults with CAI.

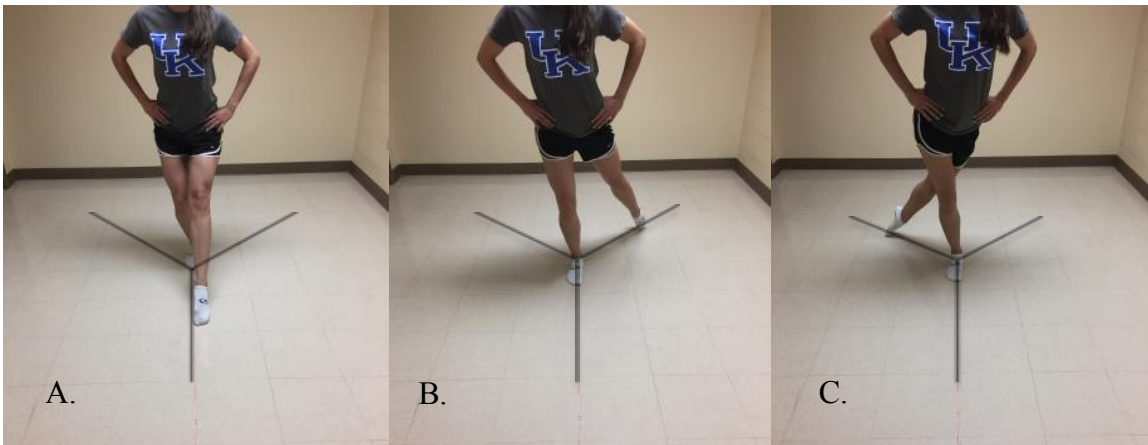
Conclusions

The aim of this investigation is to compare static and dynamic postural control, spinal reflex excitability, lower extremity strength, and DF-ROM in younger-, middle- and older-aged adults with and without CAI. Results demonstrated older-aged adults had decreased static and dynamic postural control, sagittal plane ankle and hip isometric peak torque, and spinal reflex excitability compared to younger-aged adults. While participants with CAI had decreased dorsiflexion range of motion and ankle and hip extension strength compared to healthy-controls.

Figure 4.1: Eyes-open static postural control



Figure 4.2: Star Excursion Balance Test



Abbreviations: **A.** Anterior reach direction; **B.** Posteromedial reach direction; **C.** Posterolateral reach direction

Figure 4.3: Spinal reflex excitability

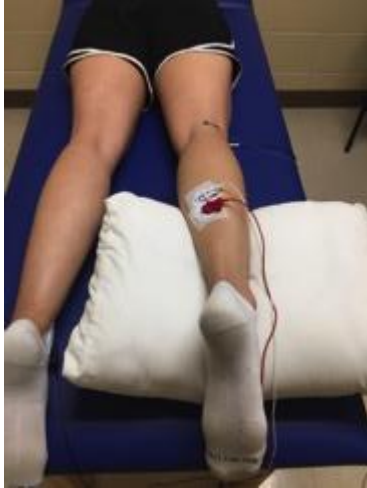
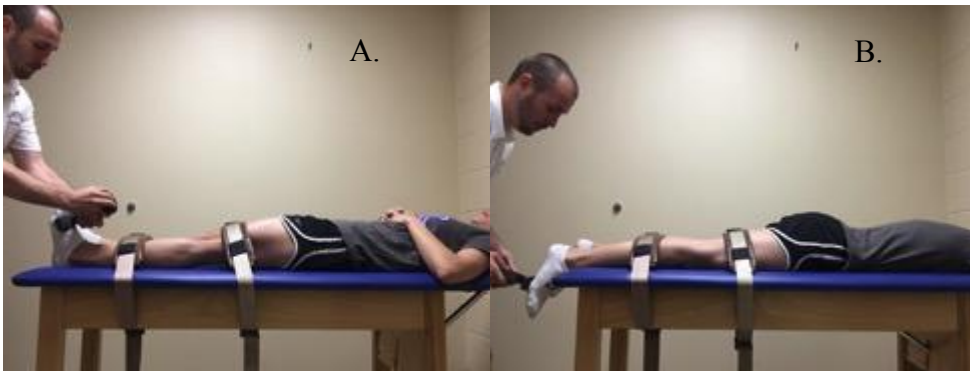


Figure 4.4: Dorsiflexion and plantarflexion torque

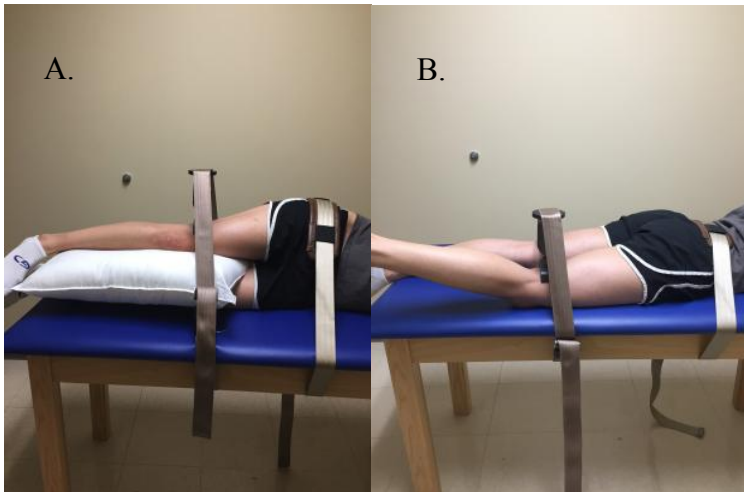


Abbreviations: **A.** Dorsiflexion Torque Position; **B.** Plantarflexion Torque Position

Figure 4.5: Knee extension torque

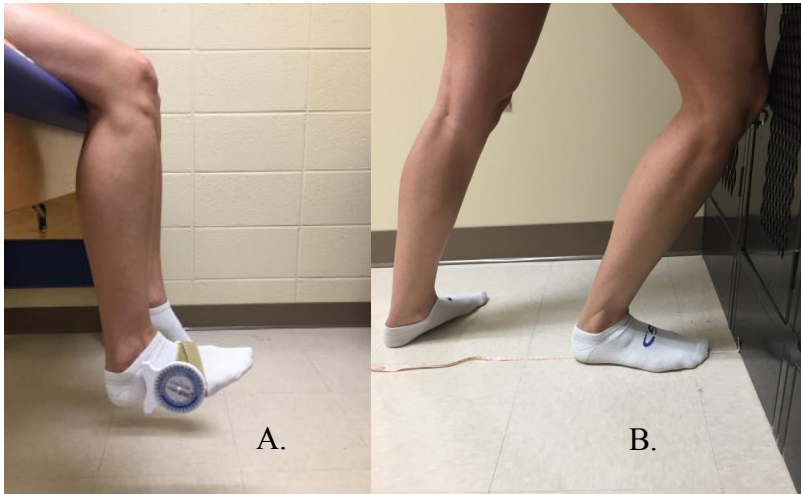


Figure 4.6: Hip abduction and extension torque



Abbreviations: **A.** Hip abduction; **B.** Hip extension

Figure 4.7: Open- and closed-kinetic chain dorsiflexion range of motion



Abbreviations: **A.** Open-kinetic chain dorsiflexion; **B.** Weight-bearing Lunge Test

Table 4.1: Participant demographics for all six groups

	Younger-Aged Adults (Mean \pm SD)		Middle-Aged Adults (Mean \pm SD)		Older-Aged Adults (Mean \pm SD)		Main Effect Injury		Main Effect Age		Interaction	
	CAI n = 31	Healthy- Control n = 27	CAI n = 18	Healthy- Control n = 8	CAI n = 11	Healthy- Controls n = 6	F	p-value	F	p-value	F	p-value
Age (years)	24.2 \pm 3.7	23.8 \pm 3.0	45.4 \pm 7.0	46.5 \pm 8.4	67.5 \pm 5.8	66.8 \pm 6.6	0.00	0.97	475.5	<0.001*	0.17	0.84
Height (cm)	166.6 \pm 9.4	169.6 \pm 9.5	167.9 \pm 12.0	170.1 \pm 9.8	173.4 \pm 7.4	170.1 \pm 13.0	0.08	0.77	0.81	0.44	0.61	0.54
Weight (kg)	72.2 \pm 14.1	69.1 \pm 17.0	79.4 \pm 18.9	75.5 \pm 12.4	78.5 \pm 15.4	80.1 \pm 14.5	0.22	0.63	2.62	0.07	0.16	0.85
BMI (kg/m ²)	26.0 \pm 4.5	23.8 \pm 4.6	28.4 \pm 7.5	26.0 \pm 3.1	25.9 \pm 3.3	27.5 \pm 2.1	0.72	0.39	2.08	0.13	0.96	0.38

*Indicates significant differences between age groups ($p < 0.05$)

Abbreviations: **CAI** = Chronic ankle instability; **cm** = centimeters; **kg** = kilograms

Table 4.2: Participant injury characteristics for all six groups

	Younger-Aged Adults (Mean ± SD)		Middle-Aged Adults (Mean ± SD)		Older-Aged Adults (Mean ± SD)	
	CAI	Healthy-Control	CAI	Healthy-Control	CAI	Healthy-Controls
AII	5.7 ± 1.5	0.0 ± 0.0	4.7 ± 2.3	0.0 ± 0.0	4.7 ± 2.8	0.0 ± 0.0
IdFAI	17.45 ± 3.3	0.0 ± 0.0	12.2 ± 7.6	0.0 ± 0.0	10.9 ± 8.9	0.0 ± 0.0
CAIT	17.5 ± 4.8	0.0 ± 0.0	19.9 ± 7.7	0.0 ± 0.0	20.0 ± 6.7	0.0 ± 0.0
# of LAS	3.0 ± 3.6	0.0 ± 0.0	3.2 ± 3.5	0.0 ± 0.0	1.6 ± 0.7	0.0 ± 0.0
First LAS (years)	6.0 ± 4.5	0.0 ± 0.0	30.0 ± 39.8	0.0 ± 0.0	47.1 ± 20.3	0.0 ± 0.0
Most Recent LAS (months)	33.0 ± 34.2	0.0 ± 0.0	121.6 ± 114.5	0.0 ± 0.0	270.6 ± 248.0	0.0 ± 0.0
Duration of Symptoms (years)	4.9 ± 3.7	0.0 ± 0.0	10.7 ± 10.4	0.0 ± 0.0	22.0 ± 31.2	0.0 ± 0.0
# of 'giving-way' in past 6 months	4.3 ± 5.1	0.0 ± 0.0	2.8 ± 5.0	0.0 ± 0.0	3.5 ± 7.3	0.0 ± 0.0

Abbreviations: **CAI** = Chronic ankle instability; **AII** = Ankle instability index; **IdFAI** = Identification of Functional Ankle Instability; **CAIT** = Cumberland ankle instability tool; **LAS** = lateral ankle sprain;

Table 4.3: Group means and standard deviations for all the postural control variables for all six groups

	Younger-Aged Adult (Mean \pm SD)		Middle-Aged Adult (Mean \pm SD)		Older-Aged Adult (Mean \pm SD)		Main Effect Injury		Main Effect Age		Interaction	
	CAI	Healthy- Control	CAI	Healthy- Control	CAI	Healthy- Control	F	p-value	F	p-value	F	p-value
TTBML abs. minimum (s)	0.58 \pm 0.3	0.75 \pm 0.4	0.62 \pm 0.4	0.53 \pm 0.6	0.43 \pm 0.3	0.29 \pm 0.3	0.038	0.84	2.26	0.11	1.03	0.36
TTBAP abs. minimum (s)	1.1 \pm 0.3	1.1 \pm 0.3	1.0 \pm 0.2	0.9 \pm 0.4	0.8 \pm 0.2	0.9 \pm 0.2	0.092	0.76	5.80	0.004*	0.39	0.67
TTBML mean of minima (s)	3.8 \pm 2.2	5.1 \pm 3.0	3.7 \pm 1.7	3.4 \pm 3.2	3.7 \pm 1.7	2.2 \pm 1.1	0.038	0.84	3.02	0.5	1.02	0.36
TTBAP mean of minima (s)	5.9 \pm 1.8	5.7 \pm 1.8	4.5 \pm 1.3	4.0 \pm 1.2	3.7 \pm 1.1	4.3 \pm 1.0	0.010	0.95	9.55	<0.001*	0.33	0.71
TTBML S.D. of minima (s)	3.5 \pm 1.9	4.6 \pm 2.8	3.3 \pm 1.3	3.1 \pm 2.6	2.9 \pm 1.9	2.4 \pm 1.0	0.077	0.78	2.26	0.11	0.95	0.39
TTBAP S.D. of minima (s)	5.8 \pm 2.7	5.4 \pm 2.5	3.8 \pm 1.3	3.3 \pm 1.0	3.5 \pm 1.3	4.4 \pm 0.7	0.001	0.98	7.44	0.001*	0.37	0.68

#Indicates significant differences between injury ($p < 0.05$)

*Indicates significant differences between age groups ($p < 0.05$)

Abbreviations: **CAI** = Chronic ankle instability; **abs.** = absolute; **S.D.** = Standard deviation; **s** = second; **TTBAP** = time-to-boundary anteroposterior; **TTBML** = time-to-boundary mediolateral

Table 4.4: Group means and standard deviations for the star excursion balance test for all six groups

	Younger-Aged Adult (Mean \pm SD)		Middle-Aged Adult (Mean \pm SD)		Older-Aged Adult (Mean \pm SD)		Main Effect Injury		Main Effect Age		Interaction	
	CAI	Healthy- Control	CAI	Healthy- Control	CAI	Healthy- Control	F	p-value	F	p-value	F	p-value
SEBT-A (%LL)	62.2 \pm 6.6	64.9 \pm 5.0	62.3 \pm 7.4	64.9 \pm 6.2	59.4 \pm 3.8	60.2 \pm 6.2	1.81	0.18	2.34	0.10	0.13	0.87
SEBT-PM (%LL)	78.1 \pm 10.0	84.2 \pm 10.6	76.2 \pm 12.0	76.8 \pm 8.7	66.7 \pm 8.8	68.0 \pm 14.5	1.08	0.30	10.3	<0.001*	0.65	0.52
SEBT-PL (%LL)	71.1 \pm 15.0	77.1 \pm 11.1	69.4 \pm 15.1	72.1 \pm 13.2	54.3 \pm 11.3	55.0 \pm 13.7	0.97	0.32	12.7	<0.001*	0.29	0.74

#Indicates significant differences between injury ($p < 0.05$)

*Indicates significant differences between age groups ($p < 0.05$)

Abbreviations: **CAI** = Chronic ankle instability; **SEBT** = Star excursion balance test; **A** = anterior; **PM** = posteromedial; **PL** = posterolateral

%LL = Percent leg length

Table 4.5: Group means and standard deviations for spinal reflex excitability for all six groups

	Younger-Aged Adult (Mean \pm SD)		Middle-Aged Adult (Mean \pm SD)		Older-Aged Adult (Mean \pm SD)		Main Effect Injury		Main Effect Age		Interaction	
	CAI	Healthy- Control	CAI	Healthy- Control	CAI	Healthy- Control	F	p-value	F	p-value	F	p-value
H _{max} :M _{max} ratio	0.6 \pm 0.1	0.7 \pm 0.1	0.6 \pm 0.5	0.4 \pm 0.2	0.4 \pm 0.2	0.4 \pm 0.3	0.96	0.32	3.44	0.03*	1.45	0.24

#Indicates significant differences between injury ($p < 0.05$)

*Indicates significant differences between age groups ($p < 0.05$)

Abbreviations: **CAI** = Chronic ankle instability

Table 4.6: Group means and standard deviations for the strength variables of the six groups

	Younger-Aged Adult (Mean ± SD)		Middle-Aged Adult (Mean ± SD)		Older-Aged Adult (Mean ± SD)		Main Effect Injury		Main effect Age		Interaction	
	CAI	Healthy- Control	CAI	Healthy- Control	CAI	Healthy- Control	F	p-value	F	p-value	F	p-value
Dorsiflexion (Nm/kg)	0.32±1.0	0.42±0.1	0.31±1.0	0.34±0.1	0.25±0.7	0.29±0.1	4.68	0.03 [#]	4.98	0.009*	0.90	0.41
Plantarflexion (Nm/kg)	0.57±0.1	0.69±0.2	0.54±0.1	0.64±1.0	0.47±0.08	0.55±0.2	5.94	0.01 [#]	2.91	0.05*	0.00	0.99
Knee Extension (Nm/kg)	2.11±0.4	2.4±0.8	2.2±0.8	2.4±1.0	1.8±0.5	1.7±0.3	1.32	0.25	1.75	0.18	0.26	0.77
Hip Abduction (Nm/kg)	1.7±0.4	2.0±0.6	1.8±0.6	1.8±0.5	1.5±0.3	1.65±0.1	1.23	0.27	1.48	0.23	0.37	0.68
Hip Extension (Nm/kg)	1.6±0.4	2.0±0.6	1.4±0.5	1.6±0.6	1.2±0.6	1.4±0.7	4.81	0.03 [#]	5.54	0.005*	0.33	0.71

[#]Indicates significant differences between injury (p < 0.05)

*Indicates significant differences between age groups (p < 0.05)

Abbreviations: **CAI** = Chronic ankle instability; **Nm/kg** = Newton meter/kilogram

Table 4.7: Group means and standard deviations for ankle dorsiflexion range of motion for all six groups

	Younger-Aged Adult (Mean ± SD)		Middle-Aged Adult (Mean ± SD)		Older-Aged Adult (Mean ± SD)		Main Effect Injury		Main Effect Age		Interaction	
	CAI	Healthy- Control	CAI	Healthy- Control	CAI	Healthy- Control	F	p-value	F	p-value	F	p-value
OKC-DF (°)	11.4±4.3	12.8±6.5	11.6±5.5	11.7±5.9	8.9±3.7	11.5±3.2	1.23	0.27	0.82	0.44	0.27	0.76
WBLT (cm)	7.7±3.5	9.4±4.0	7.2±3.8	9.6±3.1	6.7±2.6	8.1±3.5	4.66	0.03 [#]	0.67	0.51	0.12	0.88

[#]Indicates significant differences between injury (p < 0.05)

*Indicates significant differences between age groups (p < 0.05)

Abbreviations: **CAI** = Chronic ankle instability; **OKC-DF** = Open kinetic chain dorsiflexion; **WBLT** = Weight bearing lunge test; **cm** = centimeter

Chapter 5: Spatiotemporal Gait Mechanics in Young, Middle, and Older-Aged Adults With and Without Chronic Ankle Instability

Introduction

Musculoskeletal injury rates are rising; with rates for lateral ankle sprain being the highest among young physically active individuals.³ Though young-adults with an acute ankle sprain can return to normal activity quickly,⁷ at least 1 in 3 people experience residual symptoms after returning to their normal activity.^{9,51,53} Most notably, individuals complain of an increase sensation of ankle joint instability, episodes of ‘giving-way’ and recurrent joint injury; collectively described as chronic ankle instability (CAI).⁵⁶ The term CAI is often used to describe these residual impairments and has garnered international attention from researchers and health care professionals because of the physical and social impacts it has on an individual early in life.^{36,56} Therefore, further study into the long-term implications of developing CAI as a young-adult is warranted.

Gait deviations have been previously described in CAI patients. During walking, participants with CAI have been found to have a more inverted position of the forefoot,^{204,292} rearfoot,²⁰⁵ and ankle,^{163,203} a more externally rotated shank²⁰⁵ and decreased sagittal plane motion^{163,199,200} at various time points throughout the gait cycle. Changes in gait patterns are not constrained to the ankle as alterations in sagittal plane motion at the knee, and hip have been found in participants with CAI.²²³ Furthermore, Terada et al²⁰⁷ observed less stride-to-stride variability in frontal ankle kinematics, whereas Herb et al²⁰⁶ found less stride-to-stride variability in the shank-rearfoot coupling. It is hypothesized that individuals with CAI walk with a more rigid movement pattern to minimize the risk of their ankle ‘giving-way’ or sustaining a recurrent injury.

These changes in sagittal and frontal plane motion and rigid movement patterns found during walking could influence the spatiotemporal gait patterns displayed by individuals with CAI. Gigi et al²⁹³ recently found participants with CAI walked slower, took smaller and wider steps, and spent less time during single-limb support compared to the healthy control group. Additionally, the authors²⁹³ found these alterations were significantly associated with the lower health-related quality of life reported by participants with CAI. These findings indicate that alterations in spatiotemporal gait mechanics contribute to the early decrease in health of individuals with CAI. However, the age-related effect of developing these spatiotemporal gait patterns is unknown because the majority of the current evidence regarding gait patterns in patients with CAI is on younger-aged adults. Understanding the age-related consequences of these spatiotemporal gait patterns associated with CAI is important because similar alterations have been identified as significant predictors of subsequent disability later in life. Investigators have found decreased gait velocity²⁹⁴⁻²⁹⁶ and stride length^{296,297} and increases in step width^{296,297} and duration of double-limb stance²⁹⁵ are predictors of fall risk and mobility impairments later in life.²⁹⁸⁻³⁰⁰ Subsequently, there is a reason to believe that these early spatiotemporal alterations observed in young adult populations with CAI might pose a potential contribution to greater mobility impairments in those with ankle sprain history later in life.

Therefore, the purpose of this investigation is to compare the spatiotemporal gait patterns in younger-, middle-, and older-aged adults with and without CAI. We hypothesize: 1) participants with CAI will have decreased spatiotemporal gait variables compared to healthy-controls; 2) middle-aged participants will have decreased

spatiotemporal gait variables compared to younger-aged adults; the older-aged adults will have decreased spatiotemporal gait mechanics compared to both groups; and 3) younger-, middle- and older-aged adults with CAI will have decreased spatiotemporal gait variables compared to their age-matched healthy counterpart. Understanding the long-term impact of CAI on the spatiotemporal patterns will aid in the development of more efficient rehabilitation program for patients with CAI of all ages.

Methods

Study Design

This was a cross-section case control design requiring participants to report to the research laboratory for a single testing session. All methodological research protocols were approved by the University of Kentucky Institutional Review Board.

Participants

Sixty participants with self-reported CAI and 40 healthy-control participants were recruited from a large regional university and the surrounding community. Based on age, participants were classified into three age categories: 1) younger-aged adults (age: 18-35, n = 31); middle-aged adults (age: 36-59, n = 25); and older-aged adults (age: 60+, n = 11). All participants read and signed an informed consent that was approved by the University of Kentucky institutional review board.

Inclusion criteria for younger-aged adults with CAI were based on criteria set by the International Ankle Consortium for identifying individuals with CAI.⁵⁶ Specifically, younger-aged adults with CAI were required to have: 1) a previous history of an acute lateral ankle sprain which resulted in swelling, pain and temporary loss of function; 2) repeated episodes of 'giving-way' and/or recurrent sprain; and 3) perceived instability

determined by a score of \geq '5' on the Ankle Instability Instrument (AII) and/or \geq '11' on the Identification of Functional Ankle Instability (IdFAI). There is currently no standard used to identify middle- and older-aged adults with CAI. Therefore, middle- and older-aged adults with CAI were identified according to the presence of having: 1) experienced an acute lateral ankle sprain that caused swelling, pain and temporary loss of function before the age of 35 years-old; 2) repeated episodes of 'giving-way' and/or recurrent ankle sprains; and 4) perceived instability determined by a score of \geq '5' on the AII and/or \geq '11' on the IdFAI. The AII and IdFAI have been shown as reliable and valid in assessing patient-reported functional limitations in those with CAI. In the event participants reported a bilateral history of ankle sprains, the limb with the greatest self-reported functional limitations according to the AII and IdFAI was used as the test limb.

Participants allocated to the healthy-control group were required to report not having sustained an acute lateral ankle sprain, no 'giving-way', and score '0' on the AII and IdFAI.

All participants were free from any: 1) diagnosed balance, vestibular or respiratory disorder; 2) history of low back pain in the previous 6 month's; 3) previous history of fracture or surgery in the lower extremity; 4) history of seizures; 5) history of concussion in the past 6 month's; 6) history of neurological injuries or diseases; 7) use of any assistive-walking device; and/or previous history of any self-reported musculoskeletal or neurovascular injuries and disorders in the lower extremity within the previous 6 months other than an lateral ankle sprain.

Instrumentation

Spatiotemporal gait parameters were used measured using a GAITRite® (CIR Systems, Inc. Havertown, PA USA) electronic walkway with an active area of approximately 7.32 m long and 0.61 m wide. Data were sampled at 120 Hz and processed using GAITRite Platinum software v.4.7.7 (CIR Systems, Inc., Havertown, PA USA). The GAITRite System has been shown to a valid and reliable measurement for gait parameters.^{301,302}

Experimental Procedures

Participants were asked to walk un-assisted with their shoes off across the electronic walkway at their normal self-selected pace. Participants initiated and terminated their walk 3 meters before and after the walkway to avoid any acceleration/de-acceleration effects. Participants were given three practice trials and performed 5 test trials. Trials were discarded and repeated if the participant: 1) stopped or slowed down on the walkway; 2) tripped or took a double-step; and/or 3) did not keep their eyes looking forward.

Spatiotemporal data were collected for both the involved and uninvolved limbs making a total of 16 different dependent variables. Table 5.1 provides a description of each main outcome variable used.

To control for the potential influence of height, step length and stride length for both limbs were normalized to each participant's limb length. Limb length was measured as the distances from the anterior superior iliac spine to the most distal portion of the medial malleolus. Therefore values for step length and stride length are expressed as a percentage of limb length (%LL).

Data from all 5-test trials were averaged together and used for statistical analysis.

Statistical Analysis

Separate 2x3 between-groups analysis of variance was conducted to explore the impact of Injury (CAI & healthy-control) and Age group (young, middle, old) on anthropometric information and for each dependent variable. A Bonferroni post hoc analysis was used in the event of any significant differences. The *a priori* alpha level was set a $p \leq 0.05$ for comparisons of anthropometric information. However, to reduce the risk of a Type 1 error based on the number of outcomes collected simultaneously during the gait task, a Bonferroni correction was made based on the number of dependent variables collected to set the new alpha level at $p \leq 0.003$ for all spatiotemporal comparisons.

All statistical analyses were performed using IBM SPSS Statistics, version 23 (IBM, Corp., Armonk, NY, USA).

Results

Participant demographics and injury characteristics are listed in Table 5.2 and Table 5.3. The interaction effect between age and group, along with simple main effects, was not statistically significant for height, weight and BMI. The statistically significant age main effect for age ($F_{2, 94} = 475.57$, $p = 0.001$, partial $E^2 = 0.908$, observed power = 1.00) confirms our Age cohorts. Post hoc comparisons using a Bonferroni test indicated that participants allocated to the middle-aged group (46.2 ± 7.5 , $p = 0.001$) and older-aged group (67.2 ± 5.9 , $p = 0.001$) were older than those in the younger-aged group (24.0 ± 3.4). Likewise, those in the older-aged group were significantly older than those in the middle-aged group ($p = 0.001$).

Group means and standard deviations for each dependent variable are given in Table 5.4 and Table 5.5. The interaction effect between age and group was not statistically significant for any main outcome variable ($p > 0.003$). There was no significant group or age main effect ($p > 0.003$) for any main outcome variable.

Discussion

The aim of this investigation was to compare the spatiotemporal gait patterns between those with and without CAI and across age categories. We hypothesized that 1) participants with CAI would have decreased spatiotemporal gait variables compared to healthy-controls; 2) middle-aged participants would have decreased spatiotemporal gait variables compared to younger-aged adults; while older-aged adults will have decreased spatiotemporal gait mechanics compared to both groups; and 3) younger-, middle- and older-aged adults with CAI would have decreased spatiotemporal gait variables compared to their age-matched healthy counterpart. Based on the test for statistical significance, the results do not support our hypotheses. Specifically, the results determined that spatiotemporal gait patterns are not different Age cohorts (young, middle, old) or between Injury groups (CAI & healthy-controls).

The lack of difference between age categories indicates spatiotemporal gait mechanics do not change with age (Table 5.4 & Table 5.5). Previous studies have reported an increase in age is associated with decreased walking speed and stride length and an increase in stride width and double support time.^{27,297,303,304} Specifically, comfortable walking speed has been shown to decline at a rate of 0.2% per year up until the sixth decade of life and 1.6% per year after that.³⁰⁵ Because of this steady decline in speed, self-selected gait velocity is considered a useful marker in the surveillance of health and

functional status in older adults.³² Additionally, Hageman and Blanke²⁹⁷ compared gait patterns of healthy younger-aged women (age 20-35 years old) to a group of healthy older-aged women (age 60-84 years old). They found the older-aged women walked slower and took smaller steps compared to the younger-aged women.²⁹⁷ In another study, individuals made shorter and broader strides with advanced age.³⁰³ These studies collectively suggest that spatiotemporal gait patterns change with age. Changes in gait patterns occur with advanced age because of subtle changes in musculoskeletal function such as an increased joint stiffness, decreased strength and impaired balance.^{21,233,304} Other researchers³⁰⁶ have suggested that older-aged adults have an increased fear of falling making them walk slower and take smaller steps to increase their double-limb support time, and, therefore have a safer and more stable gait patterns.

The disparity between these studies and the current investigation might be explained by the demographics of participants examined. Earlier investigations^{303,304} examining the spatiotemporal gait parameters between different age cohorts included older-aged participants that were almost 10 years older than the upper age limit of participants included in the current investigation. Jansen et al³⁰⁷ compared the temporal gait patterns between younger (age 20-29 years old) and older adults (age 60-69 years old) and reported no differences between groups. This is further supported by follow-up studies demonstrating discrete spatiotemporal gait variables are not different between age cohorts.^{308,309} Therefore, our results support those previously demonstrating spatiotemporal gait patterns in otherwise healthy adults do not change until late adulthood.

No group differences were identified for any spatiotemporal measure used in this study (Table 5.4 & Table 5.5). The lack of group differences implies CAI is not associated with a change in spatiotemporal gait mechanics. Only one other study has directly examined the spatiotemporal gait patterns associated with CAI. Gigi et al²⁹³ compared the spatiotemporal gait patterns of a group of middle-aged adults with CAI (age 36.7 ± 15.0 years old) to a group of age-matched healthy-controls (age 36.6 ± 13.3 years old). The researchers determined the participants with CAI walked slower, took more steps that were shorter and wider, and spent less time during single-limb stance on the involved limb.²⁹³ The authors hypothesized that the CAI participants displayed this gait pattern, as a way to reduce the amount of time the unstable ankle must maintain a single-limb stance.²⁹³ However, gait velocity alone can influence the several spatiotemporal measures. Because Gigi et al²⁹³ demonstrated differences in gait speed between groups, it's reasonable to speculate that if they had controlled for gait velocity, they might not have seen group differences.

Additionally, we did not observe any significant difference in young, middle, and older-aged adults with CAI compared to their age-matched healthy counterpart (Table 5.4 & Table 5.5). This is the first investigation to examine the age-related effects of CAI on spatiotemporal gait mechanics. Researchers studying other chronic diseases such as end-stage ankle⁶³ and knee^{310,311} osteoarthritis have shown age-related differences in spatiotemporal gait mechanics compared to age-matched healthy controls. When considering these studies examining the effect of osteoarthritis on spatiotemporal gait mechanics, it might be that the spatiotemporal gait patterns in those with CAI may only change if they develop symptomatic post-traumatic ankle osteoarthritis; which might help

to explain the lack of group differences or age-related changes observed in the current study. However, because of the large difference in participant demographics between these studies and the current investigation, it 's hard to draw any direct comparisons and more research is needed to substitute this claim.

However, what can be taken away is a direction for future research. Rather than comparing the discrete averages, researchers have demonstrated age-related changes in the variability of spatiotemporal gait patterns. Specifically, Callisaya et al³¹² found greater intra-individual gait variability for most spatiotemporal gait measures with increasing age. Furthermore, changes in gait variability have been found to be better predictors of decreased health status and increased risk of injury later in life compared to absolute gait measures.^{299,313-316} Therefore, future work should considering comparing the stride-to-stride variability in younger, middle, and older-aged adults with and without CAI

Limitations

This study is not without limitations. The primary aim of this investigation was to examine the long-term effects of developing CAI on the spatiotemporal mechanics. There is currently no standard for identifying middle-aged and older-aged participants with CAI. As a result, we adopted the recommendations set the International Ankle Consortium for identifying younger-aged adults with CAI.⁵⁶ Therefore, research is needed to examine the validity and reliability of the AII and IdFAI for identifying middle-aged and older-aged participants with CAI. Additionally, we required participants with CAI to have sustained their first ankle sprain before the age of 35, which is open to recall bias. Moreover, because CAI is a self-reported pathology we cannot confirm when

the middle-aged and older-aged participants indeed developed CAI. It is reasonable to speculate that the middle-aged and older-aged participants might not have developed CAI until they were older. Further research is warranted in designing more certain inclusion criteria for individuals of all ages with CAI.

Another potential limitation is the sample size. We only included a total of 26 participants in the middle-aged group and 17 in the older-aged group. Post hoc power analysis revealed low to moderate statistical power for both group (observed power >0.910 to <0.183 for all dependent variables) and age (observed power >0.100 to <0.420 for all dependent variables) main effects; along with all the main interactions (observed power >0.121 to <0.341). Certainly, this observed lower power raises concern for a Type II error, and, therefore the results should be taken with caution.

Conclusion

The aim of this investigation was to compare spatiotemporal gait mechanics between those with and without CAI across three different age categories. No age-related differences were observed for any spatiotemporal gait variable. Similarly, the presence of CAI was not associated with a change in any dependent variable compared to the healthy-control, regardless of age. It can be concluded from this investigation that neither age nor CAI impacts the spatiotemporal gait mechanics. Future studies should examine the influence CAI on age-related changes in spatiotemporal gait variability rather than the average of discrete variables.

Table 5.1: Description of spatiotemporal gait parameters

Gait Parameter	Description
Velocity (m/sec)	The linear distance covered per second
Cadence (steps/min)	Number of steps taken per minute.
Step Length (cm)	The anterior-posterior distance from the heel of one print to the heel of the opposite footprint.
Stride Length (cm)	The anterior-posterior distance between heels of two consecutive footprints of the same foot.
Step Width (cm)	The distance from the heel center of one footprint to the line of progression formed by two consecutive footprints of the opposite foot.
Swing Time (%GC)	The swing phase is the time between toe off and until contact is made again with the same foot and is normalized to the %GC.
Stance (%GC)	The stance phase is the time between the initial contact and the last contact of a single footfall and is normalized to the %GC.
Single (%GC)	Single support phase is the time between the last contact of the current footfall to the first contact of the next footfall of the same foot and is normalized to the %GC.
Double (%GC)	Double support phase is the amount of time both feet are in contact with the ground simultaneously throughout the entire gait cycle and is normalized to the %GC.

Abbreviations: %GC = Percent of gait cycle

Table 5.2: Participant demographics for all six groups

	Younger-Aged Adults (Mean \pm SD)		Middle-Aged Adults (Mean \pm SD)		Older-Aged Adults (Mean \pm SD)		Main Effect Group		Main Effect Age		Interaction	
	CAI n = 31	Healthy- Control n = 27	CAI n = 18	Healthy- Control n = 8	CAI n = 11	Healthy- Controls n = 6	F	p-value	F	p-value	F	p-value
Age (years)	24.2 \pm 3.7	23.8 \pm 3.0	45.4 \pm 7.0	46.5 \pm 8.4	67.5 \pm 5.8	66.8 \pm 6.6	0.00	0.97	475.5	<0.001*	0.17	0.84
Height (cm)	166.6 \pm 9.4	169.6 \pm 9.5	167.9 \pm 12.0	170.1 \pm 9.8	173.4 \pm 7.4	170.1 \pm 13.0	0.08	0.77	0.81	0.44	0.61	0.54
Weight (kg)	72.2 \pm 14.1	69.1 \pm 17.0	79.4 \pm 18.9	75.5 \pm 12.4	78.5 \pm 15.4	80.1 \pm 14.5	0.22	0.63	2.62	0.07	0.16	0.85
BMI (kg/m ²)	26.0 \pm 4.5	23.8 \pm 4.6	28.4 \pm 7.5	26.0 \pm 3.1	25.9 \pm 3.3	27.5 \pm 2.1	0.72	0.39	2.08	0.13	0.96	0.38

#Indicates significant differences between injury ($p < 0.05$)

*Indicates significant differences between age groups ($p < 0.05$)

Abbreviations: **CAI** = Chronic ankle instability; **cm** = centimeters; **kg** = kilograms

Table 5.3: Participant injury characteristic for all six groups

	Younger-Aged Adults (Mean \pm SD)		Middle-Aged Adults (Mean \pm SD)		Older-Aged Adults (Mean \pm SD)	
	CAI	Healthy-Control	CAI	Healthy-Control	CAI	Healthy-Controls
AII	5.7 \pm 1.5	0.0 \pm 0.0	4.7 \pm 2.3	0.0 \pm 0.0	4.7 \pm 2.8	0.0 \pm 0.0
IdFAI	17.45 \pm 3.3	0.0 \pm 0.0	12.2 \pm 7.6	0.0 \pm 0.0	10.9 \pm 8.9	0.0 \pm 0.0
CAIT	17.5 \pm 4.8	0.0 \pm 0.0	19.9 \pm 7.7	0.0 \pm 0.0	20.0 \pm 6.7	0.0 \pm 0.0
# of LAS	3.0 \pm 3.6	0.0 \pm 0.0	3.2 \pm 3.5	0.0 \pm 0.0	1.6 \pm 0.7	0.0 \pm 0.0
First LAS (years)	6.0 \pm 4.5	0.0 \pm 0.0	30.0 \pm 39.8	0.0 \pm 0.0	47.1 \pm 20.3	0.0 \pm 0.0
Most Recent LAS (months)	33.0 \pm 34.2	0.0 \pm 0.0	121.6 \pm 114.5	0.0 \pm 0.0	270.6 \pm 248.0	0.0 \pm 0.0
Duration of Symptoms (years)	4.9 \pm 3.7	0.0 \pm 0.0	10.7 \pm 10.4	0.0 \pm 0.0	22.0 \pm 31.2	0.0 \pm 0.0
# of 'giving-way' in past 6 months	4.3 \pm 5.1	0.0 \pm 0.0	2.8 \pm 5.0	0.0 \pm 0.0	3.5 \pm 7.3	0.0 \pm 0.0

Abbreviations: **CAI** = Chronic ankle instability; **AII** = Ankle instability index; **IdFAI** = Identification of Functional Ankle Instability; **CAIT** = Cumberland ankle instability tool; **LAS** = lateral ankle sprain;

Table 5.4: Group means and standard deviations for the spatiotemporal gait variables for the six groups

	Younger-Aged Adult (Mean ± SD)		Middle-Aged Adult (Mean ± SD)		Older-Aged Adult (Mean ± SD)		Main Effect Group		Main Effect Age		Interaction	
	CAI	Healthy- Control	CAI	Healthy- Control	CAI	Healthy- Control	F	p-value	F	p-value	F	p-value
Velocity (m/sec)	1.27±1.1	1.31±1.5	1.32±1.4	1.25±1.7	1.24±1.3	1.27±1.9	0.00	0.98	0.32	0.72	0.10	0.36
Cadence (steps/min)	112.7±7.6	114.5±8.9	117.3±5.1	112.5±9.9	113±10.5	110.5±11.2	0.78	0.37	0.58	0.55	1.33	0.27
Involved Step Length(%LL)	0.76±0.04	0.77±0.05	0.76±0.06	0.74±0.08	0.71±0.06	0.73±0.08	0.03	0.84	2.79	0.06	0.28	0.75
Uninvolved Step Length (%LL)	0.77±0.04	0.77±0.06	0.75±0.06	0.76±0.06	0.71±0.06	0.74±0.1	0.36	0.54	2.52	0.08	0.20	0.81
Involved Stride Length (%LL)	1.54±0.08	1.54±0.11	1.5±0.12	1.5±0.15	1.4±0.12	1.4±0.18	0.15	0.69	2.86	0.06	0.10	0.86
Uninvolved Stride Length (%LL)	1.5±0.08	1.5±0.11	1.5±0.11	1.5±0.14	1.4±0.12	1.4±0.18	0.22	0.63	2.44	0.09	0.30	0.73
Involved Step Width (cm)	10.4±2.5	9.6±1.4	10.1±2.6	10.6±2.7	10.2±2.6	8.7±1.2	1.13	0.29	0.62	0.53	0.86	0.42
Uninvolved Step Width (cm)	10.4±2.5	9.6±1.6	10.4±2.6	10.6±2.8	10.2±2.6	8.9±1.0	1.10	0.29	0.70	0.49	0.56	0.57

#Indicates significant differences between injury ($p < 0.003$) *Indicates significant differences between age groups ($p < 0.003$)
Abbreviations: **CAI** = Chronic Ankle Instability; **m** = Meter; **min** = Minute; **cm** = Centimeter; **%LL** = Percent of leg length

Table 5.5: Group means and standard deviations for the spatiotemporal gait variables for the six groups

	Younger-Aged Adult (Mean \pm SD)		Middle-Aged Adult (Mean \pm SD)		Older-Aged Adult (Mean \pm SD)		Main Effect Group		Main Effect Age		Interaction	
	CAI	Healthy- Control	CAI	Healthy- Control	CAI	Healthy- Control	F	p-value	F	p-value	F	p-value
Involved Swing (%GC)	38.8 \pm 1.3	39.1 \pm 1.3	38.6 \pm 1.7	38.8 \pm 1.6	37.8 \pm 1.5	37.9 \pm 1.3	0.00	0.99	3.61	0.03	0.37	0.68
Uninvolved Swing (%GC)	38.9 \pm 1.0	38.8 \pm 1.6	38.2 \pm 1.6	38.3 \pm 1.5	38.0 \pm 1.1	38.3 \pm 1.5	0.18	0.66	3.57	0.03	0.09	0.91
Involved Stance (%GC)	61.1 \pm 1.3	60.8 \pm 1.3	61.3 \pm 1.7	61.7 \pm 1.6	62.1 \pm 1.5	62.0 \pm 1.3	0.00	0.99	3.59	0.03	0.35	0.17
Uninvolved Stance (%GC)	61.0 \pm 1.0	61.1 \pm 1.6	61.7 \pm 1.6	61.7 \pm 1.5	61.7 \pm 1.6	62.3 \pm 1.0	0.17	0.68	3.58	0.03	0.09	0.90
Involved Single Support (%GC)	38.9 \pm 1.1	38.8 \pm 1.6	38.3 \pm 1.6	38.2 \pm 1.6	38.1 \pm 1.0	37.7 \pm 1.1	0.24	0.62	3.27	0.04	0.04	0.95
Uninvolved Single Support (%GC)	38.7 \pm 1.3	39.1 \pm 1.3	38.6 \pm 1.7	38.3 \pm 1.5	37.8 \pm 1.5	37.9 \pm 1.3	0.00	0.99	3.81	0.02	0.34	0.70
Involved Double Support (%GC)	22.3 \pm 2.1	22.2 \pm 2.8	23.2 \pm 3.3	23.4 \pm 2.9	24.1 \pm 2.4	24.3 \pm 1.8	0.00	0.99	3.34	0.04	0.02	0.98
Uninvolved Double Support (%GC)	22.4 \pm 2.2	22.2 \pm 2.9	23.1 \pm 3.2	23.4 \pm 2.8	23.9 \pm 2.4	24.2 \pm 1.7	0.04	0.82	3.03	0.05	0.09	0.90

#Indicates significant differences between injury ($p < 0.003$)

*Indicates significant differences between age groups ($p < 0.003$)

Abbreviations: **CAI** = Chronic ankle instability; **%GC** = Percent of gait cycle

Chapter 6: Summary

The first purpose of this dissertation was to compare regional and global health-related quality of life using the Foot and Ankle Disability Index and the Patient Reported Outcomes Measurements Information System-43 adult profile between younger-, middle-, and older-aged adults with and without CAI. Similarly, the second purpose of this dissertation was to compare the common mechanical sensorimotor deficits associated with CAI between Injury (CAI vs. healthy-controls) and Age groups (young, middle and old). Specifically, time-to-boundary variables during a static single-limb balance task, reach distances on the Star Excursion Balance Test, spinal reflex excitability of the soleus specific by the $H_{max}:M_{max}$ ratio, sagittal plane torque values of the ankle, knee and hip, open-kinetic chain dorsiflexion range of motion, and the Weight-Bearing Lunge test. The last purpose of this dissertation was to determine if differences exists in spatiotemporal gait parameters while walking at a self-selected pace in younger-, middle- and older-aged adults with and without CAI. To better summarize the findings, the hypotheses from Chapter 1 are revisited:

Hypotheses for Specific Aim 1:

Hypothesis 1: Participants with CAI will self-report having worse region-specific and global HRQoL compared healthy-controls.

Hypothesis 2: Region-specific and global HRQoL will be worse in the middle-aged adults compared to the younger-aged adults; while the older-aged adults will have worse scores compared to both groups.

Hypothesis 3: Younger-, middle-, and older-aged adults with CAI will self-report having worse region-specific and global HRQoL compared to their age-matched healthy counterpart.

Findings: Those with CAI had worse region-specific HRQoL as specified by lower scores on the Foot and Ankle Disability Index (FADI) and Foot and Ankle Disability Index Sport (FADI-Sport) compared to healthy-controls. Furthermore, participants with CAI self-reported having deficits in global HRQoL represented by worse physical function and having pain interfere with their day-to-day activities and attending social events compared to the healthy-control group. We did not find any differences for any region-specific or global HRQoL outcome measure between younger-, middle- and older-aged adults with and without CAI.

Hypotheses for Specific Aim 2:

Hypothesis 4: Participants with CAI will have decreased sensorimotor and mechanical outcome measures compared to healthy-controls.

Hypothesis 5: Sensorimotor and mechanical outcome measures will be decreased in middle-aged adults compared to the younger-aged adults; the older-aged adults will have decreased sensorimotor and mechanical outcome measures compared to both groups.

Hypothesis 6: Younger-, middle-, and older-aged adults with CAI will have decreased mechanical and sensorimotor outcome measures compared to their age-matched healthy counterpart.

Findings: It was determined that participants with CAI had decreased dorsiflexion range of motion compared to the healthy control group, as evidenced by the lower scores on the

Weight-Bearing Lunge Test. Furthermore, participants with CAI had decreased dorsiflexion, plantarflexion and hip extension torque compared to the healthy-control group. Taken together these findings suggest that participants with CAI have mechanical restrictions at the ankle and decreased sagittal plane isometric strength in the surrounding ankle and hip musculature

Regardless of injury history, the results demonstrated age-related differences in static postural control. Specifically, the anteroposterior time-to-boundary mean minima and standard deviations were lower in the middle and older-aged participants compared to the younger-aged group; the anteroposterior absolute minimum was only lower in the older-aged participants compared to the younger-aged adults. These results imply that as early as 40 years old, individuals begin to balance closer to the edge of their boundary of support which leaves individuals less time to respond efficiently to an unanticipated perturbation and increases the risk of falling.

Older-aged participants reached less distance on the posteromedial and posterolateral reach directions of the Star Excursion Balance Test (SEBT) compared to the younger- and older-aged participants, irrespective of injury history. These findings indicated older individuals are unable able to move to the edge of their base of support during dynamic activity and must remain closer to the center of their base of support to maintain balance.

Age differences for the $H_{\text{man}}:M_{\text{max}}$ ratio were found between the younger-aged and older-aged adults. The older aged adults had a lower $H_{\text{man}}:M_{\text{max}}$ ratio of the soleus muscle compared to the younger-aged participants, suggesting spinal reflex excitability

of the soleus muscle is decreased in the older-aged participants compared to younger-aged adults.

Several age differences for sagittal plane isometric peak torque were noted. The older-aged participants exhibited lower dorsiflexion, plantarflexion and hip extension isometric peak torque compared to the younger-aged adults, irrespective of injury history. Reduce sagittal plane isometric torque in the older-aged participants suggests they produced less isometric force compared to the younger-aged adults.

Several differences between Injury (CAI & healthy-control) groups, were observed for sagittal plane isometric peak torque. Participants with CAI have had decreased dorsiflexion, plantarflexion and hip extension isometric peak torque compared to the healthy-control group. Lower sagittal plane isometric peak torque suggests participants with CAI produced less isometric force compared to the healthy-control group.

Participants with CAI had decreased scores on the WBLT compared to the healthy-control group. Decreased scores on the WBLT suggest participants with CAI have decreased dorsiflexion range of motion compared to the healthy-control group.

There were no significant interactions for Injury (CAI & healthy-control and Age (young, middle, old) for any outcome measure included.

Hypotheses for Specific Aim 3:

Hypothesis 7: Participants with CAI will have decreased spatiotemporal gait variables compared to healthy-controls.

Hypothesis 8: Middle-aged participants will have decreased spatiotemporal gait variables compared to younger-aged adults; the older-aged adults will have decreased spatiotemporal gait mechanics compared to both groups.

Hypothesis 9: Younger-, middle- and older-aged adults with CAI will have decreased spatiotemporal gait variables compared to their age-matched healthy counterpart.

Findings: No changes in spatiotemporal gait parameters were observed between Injury (CAI & healthy-control) or Age groups (young, middle, and old).

Synthesis and Application of Results

The aim of the first study in this dissertation was to advance the understanding of CAI on region-specific and global HRQoL across the lifespan. It was determined from this study that those with CAI report experiencing greater difficulty because of their ankle when performing activities of daily living and tasks related to exercise. Therefore, persistent symptoms at the ankle appear to impact an individual's ability to interact with their environment. These findings provide valuable evidence for the importance of seeking formal rehabilitation following an ankle sprain in attempt to prevent lingering symptoms from developing. This study also demonstrated participants with CAI had self-reported having worse overall physical quality of life compared to the healthy-control group. This decreased physical quality of life is likely attributed to the increase in pain interference reported by those with CAI. An increase in pain can prevent individuals from wanting to participate in physical activity or attend social events and therefore likely experience a lower overall physical quality of life. More research is needed to better understand how lingering pain from an ankle sprain translates into worse overall physical quality of life.

Despite not finding differences in region-specific or global HRQoL between Injury (young, healthy-control) across Age groups (young, middle, old), this study provided unique insight into how living with the organismic constraints associated with CAI might re-shape the way an individual view their functional capability as they learn to adapt to their new environment over time. More work is needed to develop more sensitive questionnaires capable better identifying deficits in HRQoL in middle- and older-aged participants with CAI.

The aim of the second study in this dissertation was to determine if middle- and older-aged adults with CAI present with similar mechanical and sensorimotor insufficiencies commonly observed in younger-aged adults with CAI. We hypothesized that the mechanical and sensorimotor outcome measures would be worse with the older-aged groups. Results from the study partially support this hypothesis as we observed age differences in several sensorimotor outcome measures. Specifically, we found the middle-aged and older-aged adults had lower time-to-boundary absolute minimum, mean minima and standard deviations compared to the younger-aged adults. Age-related differences in static postural control are well documented within the literature; however, our results provide additional evidence indicating static balance strategies can begin to change as early as the 4th decade of life. More specifically, the lower TTB mean minima indicate as individuals get older they move their COP trajectories closer to the edge of their boundary of support. The consequence of this is individuals have less time to respond to an unanticipated perturbation while balancing before the COP trajectories would reach the edge of their base of support and keep from falling. Whereas the decreased TTB standard deviations suggest as people age they reduce the number of

degrees of freedom when balancing, likely to increase stability to successfully complete the balance task. The significance of these findings is the development of a less adaptable or more rigid postural control system that would be incapable of correcting for a large perturbation when balancing.

Age differences were found for dynamic static postural control between the younger-aged and older-aged adults. Older-aged participants reached less distance in both the posteromedial and posterolateral reach directions of the SEBT compared to younger-aged and middle-aged adults. Decreased reach distance on the SEBT indicates older-aged participants have to remain closer to the center of their base of support during dynamic activities compared to younger-aged adults. This is the first investigation to demonstrate differences in reach distances between younger-aged and older-aged adults. More research examining which mechanical and sensorimotor factors contribute the most to the performance of the SEBT in the older-aged adults is needed. Because the SEBT requires the use of multiple mechanical and sensorimotor factors, the SEBT may provide greater clinical utility for identifying lower extremity deficits that might cause an increased risk of sustaining a more serious injury later in life.

Several age differences in sagittal plane ankle strength were observed. Older-aged participants had decreased dorsiflexion, plantar flexion and hip extension isometric peak torque compared to the younger-aged adults. The lower isometric peak torque indicates older-aged participants produced less force compared to the younger-aged participants. Age differences in lower extremity strength are well documented within the literature and have been demonstrated as important factors in maintaining an active lifestyle as individuals get older.

In addition to age differences, we observed changes in dorsiflexion range of motion between those with and without CAI. Participants with CAI had decreased scores on the WBLT compared to the healthy-control group. Decreased dorsiflexion range of motion has been previously observed in a cohort of younger-aged adults (age 18-35 years old) compared to age-matched healthy-controls. Restricted dorsiflexion range of motion on the WBLT is likely attributed to the anteriorly displaced talus commonly observed after an ankle sprain. An anteriorly displaced talus prevents the ankle from reaching a closed-packed position and in-turn decreased scores on the WBLT.

Group differences were also seen for sagittal plane isometric peak torque. Participants with CAI had decreased dorsiflexion, plantarflexion and hip extension peak torque compared to the healthy-control group. Lower isometric peak torque values indicate participants with CAI produced less isometric force compared to the healthy-control group. This decreased isometric peak force might account for the less efficient force attenuation previously seen in those with CAI and might increase their risk of sustaining an ankle sprain.

The lack of between differences between younger-, middle-, and older-aged adults with and without CAI might attribute to the unknown association between CAI and the development of ankle post-traumatic osteoarthritis. CAI is a multifactorial pathology arising from combination of mechanical and sensorimotor insufficiencies. It is believed that some combination of these mechanical and sensorimotor outcome measures contribute to the onset of post-traumatic ankle osteoarthritis. Considering of the unknown etiology causing individuals with CAI to develop ankle osteoarthritis and because we did

not enroll participants with diagnosed ankle osteoarthritis, it reasonable to assume that the factors in the current study impact the development of osteoarthritis rather than aging.

Finally, it was determined for this dissertation that spatiotemporal gait mechanics were not different between Injury (CAI & healthy-control) groups or across Age categories (young, middle, and old). Early reports demonstrated differences in spatiotemporal gait patterns between younger-aged and older-aged adults. However, these studies demonstrated age-related changes included participants that were up to 10 years older than the older-aged participants enrolled in the current investigation. Reports including similar age cohorts as we did have demonstrated that spatiotemporal gait patterns do not change with age. Additionally, in Chapter 5 we did not find group differences or any significant group (CAI vs. healthy-control) interaction for any dependent variable related to the walking task. The lack of Injury group (CAI & healthy-control) differences suggests CAI is not associated with a change in spatiotemporal gait mechanics. Furthermore, we did not find a significant interaction for Injury and Age for any spatiotemporal variable. This is the first investigation to examine the age-related influences of CAI on spatiotemporal gait mechanics, making it difficult to draw comparisons to previous studies. However, what can be taken away is a direction for future research. Rather than discrete averages, researchers have demonstrated age-related changes in the variability of spatiotemporal gait patterns, which have been shown to be better predictors of a decrease in in health status and increased risk for injury in late adulthood. Therefore, more work is needed to determine if changes in variability are better indicators of a decrease in mobility compared to absolute measures in those with CAI.

The studies presented in this dissertation provide interesting insight into the presence of CAI on region-specific and global HRQoL, sensorimotor and mechanical outcomes measures, and spatiotemporal gait mechanics in different age cohorts. In Chapter 3 there was evidence of decreased region-specific HRQoL and global HRQoL compared. In addition, Chapter 4 demonstrated evidence of decreased static and dynamic balance, sagittal plane ankle and hip torque, and spinal reflex excitability across different age categories. Results also demonstrated decreased dorsiflexion range of motion and sagittal plane ankle and hip isometric peak torque in the CAI group compared to the healthy-control group. It was determined that there were no differences between younger-, middle-, and older aged adults with and without CAI. Moreover, there is evidence in Chapter 5 that suggests spatiotemporal gait variables are not different between those with and without CAI or across different age categories. Although no significant differences between Injury groups was found, future research should examine the intra-individual variability of the spatiotemporal gait patterns between Injury groups (CAI & healthy-controls) because changes in variability have been shown to be better indicators of health status in older adults.

Despite not finding a significant interaction for any main outcome measure, future work is still needed to examine the age-related changes associated with CAI. Considering that not all individuals with CAI develop symptomatic post-traumatic ankle osteoarthritis, middle-aged and older-aged individuals with CAI likely still experience a difference in their self-reported HRQoL and physical function. Therefore, this dissertation provides the foundation for future work into understanding the impact of middle-aged and older-aged adults with CAI. Additionally, this dissertation provides direction for future

investigations into examining the etiology of post-traumatic ankle osteoarthritis in those with CAI. This is because many of the sensorimotor and mechanical outcome measures examined in this investigation are thought to contribute to the development of post-traumatic ankle osteoarthritis. Because we did not find any significant interaction and enrolling only participants who were asymptomatic from post-traumatic ankle osteoarthritis, it is reasonable to speculate that the dependent variables examined in this dissertation might contribute more to the development of ankle osteoarthritis rather than the aging process. However, more research is needed to substantiate this claim. This is highlighted by the small sample size included in the middle-aged and older-aged participants in this dissertation. We only included a total of 26 participants in the middle-aged group and 17 in the older-aged group. Post hoc power analysis revealed low to moderate statistical power for both Injury and Age main effects; along with all the main interactions. Certainly, this observed lower power raises concern for a Type II error, and, therefore the results and conclusions should be taken with caution.

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Vita

Kyle B. Kosik, MEd, ATC

CONTACT INFORMATION

Office

The University of Kentucky
College of Health Sciences
Wethington Building Room, 214A
Lexington, Kentucky 40517
Phone: (815) 383-8644
E-mail: kyle.kosik@uky.edu

Home

175 North Locust Hill Drive, Apt. # 2504
Lexington, Kentucky 40509

EDUCATION

University of Kentucky

Doctor of Philosophy
Major Area of Study: Rehabilitation Sciences-Athletic Training
Conferred: August 2017

University of Virginia

Master of Education
Major Area of Study: Kinesiology-Athletic Training
Conferred: August 2013

Illinois State University

Bachelor of Science
Major Area: Athletic Training
Conferred: May 2012

CLINICAL EXPERIENCE

Transylvania University, Lexington KY
PRN Athletic Trainer
Summer (2016)

Bluegrass Orthopedics, Lexington KY
PRN Athletic Trainer
Spring (2015)

Virginia Military Institute, Lexington VA
Graduate Assistant Athletic Trainer
Fall (2012) - Spring (2013)

TEACHING EXPERIENCE

University of Kentucky

Guest Lecture

- AT695: Orthopedic Evaluation and Rehabilitation of Lower Extremity (Spring 2016) “Knee Evaluation”
AT 671: Scientific Inquiry Athletic Training II (Spring 2016)
“Pearson Correlation & Linear Regression”

Eastern Kentucky University

Instructor

- ATR 100: Introduction to Athletic Training (Fall 2015)

University of Toledo

Instructor

- KINE 2520: Human Anatomy Laboratory (Fall 2013-Spring 2014)
KINE 2470: Human Anatomy and Physiology II Laboratory (Fall 2013-Spring 2014)

PUBLICATIONS

Published Referred Manuscripts

1. Terada M, **Kosik KB**, McCann RS, Gribble PA. Diaphragm Structural Integrity and Contractility in Individuals with and without Chronic Ankle Instability. *Medicine Science & Sports Exercise*. Epub ahead of print: 2016. doi: 10.1111/sms.12721
2. Gribble PA, Terada M, Beard Q, **Kosik KB**, Lepley AS, McCan RS, Pietrosimone BP, Thomas AC. Prediction of Lateral Ankle Sprains in Football Players Based on Clinical Tests and Body Mass Index. *American Journal of Sports Medicine*, 2015.
3. McCann RS, **Kosik KB**, Beard MQ, Terada M, Pietrosimone BG, Gribble PA. Variations in Star Excursion Balance Test Performance between High School and Collegiate Football Players. *Journal of Strength and Conditions Research*, 2015

Accepted Refereed Manuscripts in Press

1. McCann RS, **Kosik KB**, Terada M, Beard MQ, Buskirk GE, Gribble PA. Associations between Functional and Isolated Performance Measures in Collegiate Women's Soccer Players. *Journal of Sport Rehabilitation*. 2016: In Press.
2. **Kosik KB**, Terada M, Drinkard CP, McCann RS, Gribble PA. An Examination of Corticomotor Plasticity in Individuals With and Without Chronic Ankle Instability. *Medicine & Science in Sports & Exercise*. 2016: In Press.
3. **Kosik KB**, McCann RS, Terada M, Gribble PA. Therapeutic Interventions for Improving Self-Reported Function in Patients with Chronic Ankle Instability: A Systematic Review. *British Journal of Sports Medicine*. 2016: In Press.
4. **Kosik KB**, Gribble PA. The Effect of Joint Mobilization on Dynamic Postural Control in Patients with Chronic Ankle Instability: A Critically Appraised Topic. *Journal of Sports Rehabilitation*. 2016: Accepted November 2016.
5. **Kosik KB**, Terada M, McCann RS, Boland S, Gribble P. Comparison of Two Rehabilitation Protocols on Patient and Disease Oriented Outcomes in Chronic Ankle Instability Individuals. *International Journal of Athletic Therapy & Training*. Submitted May 2016: Accepted November 2016.

Manuscripts Submitted for Publication

1. McCann RS, **Kosik KB**, Terada M, Gribble PA. Landing Kinematics and Isometric Hip Strength of Individuals with Chronic Ankle Instability. *Clinical Biomechanics*. Submitted December 2016: In Review.
2. Terada M, Johnson N, **Kosik KB**, Gribble PA. Associations Between White Matter Integrity of the Brain and Postural Control in Individuals with a History of Ankle Sprain. *Science Report*. Submitted October 2016: In Review
3. McCann RS, **Kosik KB**, Terada M, Gribble PA. Residual Functional Impairments and Activity Limitations at Return to Play from a Lateral Ankle Sprain. *Scandinavian Journal of Medicine and Science in Sports*. Submitted October 2016: In Review.
4. McCann RS, **Kosik KB**, Terada M, Crossett ID, Boldinga B, Gribble PA. Hip Strength and Dynamic Stability of Individuals with Chronic Ankle Instability. *Medicine & Science in Sports & Exercise*. Submitted September 2016: In Review.

5. **Kosik KB**, Terada M, Drinkard CP, McCann RS, Gribble PA. Association Between Corticospinal Inhibition and Dorsiflexion Range of Motion in those with Chronic Ankle Instability. *Clinical Biomechanics*. Submitted August 2016: In Review.
6. McCann RS, Crossett ID, Terada M, **Kosik KB**, Boldinga B, Gribble PA. Hip Strength and Star Excursion Balance Test Deficits of Patients with Chronic Ankle Instability. *Journal of Science and Medicine*. Submitted July 2016: In Review.
7. McCann RS, **Kosik KB**, Terada M, Beard MQ, Buskirk GE, Gribble PA. Acute Lower Extremity Injury Prediction in Collegiate Female Soccer Players. *Journal of Strength and Conditioning Research*. Submitted June 2016: In Review.
8. Terada M, **Kosik KB**, McCann RS, Drinkard CP, Gribble PA. Corticospinal activity during a single-leg stance differs between individuals with and without chronic ankle instability. *Human Movement Science*. Submitted February 2016: In Review.

Manuscripts in Preparation

1. **Kosik KB**, Drinkard CP, McCann RS, Terada M, Gribble PA. Association Between Lower Extremity Biomechanics and Corticospinal Inhibition in Individuals with Chronic Ankle Instability.
2. **Kosik KB**, Drinkard CP, McCann RS, Terada M, Gribble PA. Association Between Corticomotor Plasticity and Postural Control In Individuals with Chronic Ankle Instability.

Published Invited/Non-Referrred Manuscripts

PRESENTATIONS

Papers Presented

1. **Kosik KB**, Terada M, McCann RS, Drinkard CP, Gribble PA. Potential Association Between Corticomotor Plasticity and Postural Control. Presented at the 2016 National Athletic Trainers' Association Annual Meeting & Clinical Symposium. June 2016, Baltimore, MD.

2. McCann RS, Terada M, **Kosik KB**, Bolding BA, Crossett ID, Drinkard CP, Gribble PA. Hip Strategies of Ankle Copers and Chronic Ankle Instability Patients during a Single-Leg Landing. Presented at the 2016 National Athletic Trainers' Association Annual Meeting & Clinical Symposium. June 2016, Baltimore, MD.
3. Bolding BA, McCann RS, Terada M, **Kosik KB**, Crossett ID, Drinkard CP, Gribble PA. **Relationships between Time-to-Stabilization and Isometric Hip Strength in Those With and Without Chronic Ankle Instability**. Presented at the 2016 National Athletic Trainers' Association Annual Meeting & Clinical Symposium. June 2016, Baltimore, MD.
4. Crossett ID, McCann RS, Terada M, **Kosik KB**, Bolding BA, Gribble PA. Associations between Hip Strength and Dynamic Postural Control in Those With and Without Chronic Ankle Instability. Presented at the 2016 National Athletic Trainers' Association Annual Meeting & Clinical Symposium. June 2016, Baltimore, MD.
5. McCann RS, **Kosik KB**, Terada M, Beard MQ, Buskirk GE, Gribble PA. Prediction of Lower Extremity Injury in Collegiate Women's Soccer Players. **Presented at the American College of Sports Medicine Annual Meeting**. May 2016, Boston, MA.
6. **Kosik KB**, Terada M, Drinkard CP, McCann RS, Gribble PA. An Examination of Corticomotor Plasticity in Individuals With and Without Chronic Ankle Instability. Presented at the 10th Annual University of Kentucky Center for **Clinical and Translational Science Spring Conference**. April 2016, Lexington, KY.
7. McCann RS, **Kosik KB**, Terada M, Beard MQ, Buskirk GE, Gribble PA. Prediction of Lower Extremity Injury in Collegiate Women's Soccer Players. **Presented at the 10th Annual University of Kentucky Center for Clinical and Translational Science Spring Conference**. April 2016, Lexington, KY.
8. **Kosik KB**, Terada M, McCann RS, Drinkard CP, Gribble, PA. An Examination of Corticomotor Plasticity in Individuals With and Without Chronic Ankle Instability. Presented at the Southeastern Athletic Trainers' Association Clinical Symposium & Members Meeting. March 2016, Atlanta, GA.
9. **Kosik KB**, Terada M, Gribble PA. Examining the Corticospinal Pathways of the Tibialis Anterior Muscle in Chronic Ankle Instability Individuals in Different Body Positions. Presented at the 6th International Ankle Symposium. October 2015, Dublin, Ireland.

10. **Kosik KB**, Terada M, Beard MQ, Lepley A, McCann RS, Pietrosimone BG, Thomas A, Gribble PA. The influence of physical characteristics and self-reported history on functional performance tests. **Presented at** the National Athletic Trainers' Association Annual Meeting & Clinical Symposium. June 2015, St. Louis, MO.
11. McCann RS, **Kosik KB**, Terada M, Beard MQ, Buskirk GE, Gribble PA. **Associations of the Star Excursion Balance Test and Functional Movement Screen with Isolated Lower Extremity Strength and Range of Motion.** **Presented at** the National Athletic Trainers' Association Annual Meeting & Clinical Symposium. June 2015, St. Louis, MO.
12. Gribble PA, Terada M, Beard MQ, **Kosik KB**, Lepley A, McCann RS, Pietrosimone BG, Thomas A. A novel approach for prediction of lateral ankle sprain in football players using functional testing. **Presented at** the National Athletic Trainers' Association Annual Meeting & Clinical Symposium. June 2015, St. Louis, MO.
13. **Kosik KB**, Terada M, Beard MQ, Lepley A, McCann RS, Pietrosimone BG, Thomas AC, Gribble PA. The influence of physical characteristics and self-reported history on functional performance tests. Presented at the 9th Annual University of Kentucky Center for Clinical and Translational Science Spring Conference. March 2015, Lexington, KY.
14. McCann RS, **Kosik KB**, Quinlevan M, Terada M, Pietrosimone B, Gribble PA. **Differences in star-excursion balance test performance between high school and collegiate football players.** Presented at the National Athletic Trainers' Association Annual Meeting & Clinical Symposium. June 2014, Indianapolis, IN.
15. **Kosik KB**, Pritchard K, Hertel J, Saliba S. Effects of Focal Joint Cooling on Sensory and Mixed Nerves in Patients with Chronic Ankle Instability. Presented at the National Athletic Trainers' Association Annual Meeting & Clinical Symposium. June 2014, Indianapolis, IN.
16. Wilhelm SE, Terada M, Quinlevan ME, **Kosik KB**, McCann RS, Welsch LA, Thomas AC, Gribble PA. Functional Measures as Predictors of Non-Contact vs. Contact Lower Extremity Injury among High School Football Players. Presented at the National Athletic Trainers' Association Annual Meeting & Clinical Symposium. June 2014, Indianapolis, IN.
17. **Kosik KB**, Hawkins JR, Langellier DM, Selkow NM. Illinois State University, Normal IL. Clinical Applications of Cryotherapy among Certified Athletic Trainers. Presented at the National Athletic Trainers Association Annual Meeting & Clinical Symposium. June 2013, Las Vegas, NV.

Invited Presentations

1. Gribble PA & **Kosik KB**. Long-Term Consequences of Lateral Ankle Sprain: Recognizing the Public Health Burden. Presented at the Southeast Athletic Trainers Association Clinical Symposium & Members Meeting. March 2016, Atlanta, GA.
2. Gribble PA, Terada M, **Kosik KB**, McCann RS. Evidence Based Indications for the Repetitive Nature of Ankle Sprains: Preventing and Intervention Pathways. . Presented at the Southeast Athletic Trainers Association Clinical Symposium & Members Meeting. March 2015, Atlanta, GA.

Abstracts Submitted for Consideration

FUNDING ACTIVITIES

Extramural Grants Funded

Source: National Athletic Trainers' Association Doctoral Research Grant

Title: Chronic Ankle Instability and Aging

PI: Kyle B. Kosik, MEd, ATC

Effort: No Salary Support

Period: 2016

Amount: \$2,500

Description: Cross-sectional investigation of static postural control and spinal reflex excitability of the soleus muscle between young, middle-aged and older-aged individuals with and without chronic ankle instability. Secondly, to determine if decline in static postural control and spinal reflex excitability are associated with self-reported function in those with chronic ankle instability.

Source: Southeast Athletic Trainers Association Research Grant

Title: Examination of Corticomotor Plasticity Between Those With and Without Chronic Ankle Instability

PI: Kyle B. Kosik, MEd, ATC

Effort: No Salary Support

Period: 2015

Amount: \$2,000

Description: Compare plastic changes of the corticomotor excitability in patients with and without history of ankle sprains using corticomotor output mapping with TMS; and establish the association between plastic alterations in the motor cortex and self-reported quality of life.

Extramural Grants (Pending)

Extramural Grants (Not Funded)

Source: American College of Sports Medicine Foundation Doctoral Student Research Grant

Title: Chronic Ankle Instability and Aging

PI: Kyle B. Kosik, MEd, ATC

Effort: No salary Support

Period: 2016

Amount: \$5,000

Description: Cross-sectional investigation to examine changes in static postural control and spatiotemporal gait mechanics between young, middle-aged and older-aged individuals with and without Chronic Ankle Instability.

MENTORING

Undergraduate Senior Research Projects

1. Knerr K. The Effects of Proximal Joint Exercises on Dynamic Postural Control in Individuals with Chronic Ankle Instability. Spring 2014. Doctoral Student Mentor (University of Toledo)

Master Student Thesis Advisement

1. Drinkard CP. Potential Association Between Corticospinal Excitability and Ankle Kinematics in Chronic Ankle Instability Individuals. Fall 2014 – Spring 2016. Doctoral Student Mentor (University of Kentucky)

ACADEMIC SERVICE ACTIVITIES

1. College of Health Science Hearing Committee. 2016

PROFESSIONAL SERVICE ACTIVITIES

Manuscript Reviewer

1. International Journal of Sport Physical Therapy. 2015-Present
2. Journal of Sports Rehabilitation. 2015-Present
3. Journal of Athletic Training. 2014-Present
4. Athletic Training and Sports Health Care. 2013-Present

PROFESSIONAL MEMBERSHIP/CERTIFICATIONS

1. American College of Sports Medicine (2015-Present). Membership # 76614
2. Kentucky Board of Medical Licensure (2014-Present). License # AT1243
3. National Athletic Trainers' Association Member, 2012-Present. Certification #: 2000009868
4. American Red Cross CPR/AED for the Professional Rescuer, 2010-Present

HONORS AND AWARDS

1. Illinois State University McGinnis Distinguished Senior, School of Kinesiology and Recreation, 2012
2. Iota Tau Alpha National Honor Society, 2011