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Biomechanics of functional and dynamic tasks in individuals

with chronic ankle instability

By

Jeffrey Daniel Simpson

A Dissertation
Submitted to the Faculty of
Mississippi State University
in Partial Fulfillment of the Requirements
for the Degree of Doctor of Philosophy
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in the Department of Kinesiology

Mississippi State, Mississippi

August 2018
Biomechanics of functional and dynamic tasks in individuals with chronic ankle instability

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Chronic ankle instability (CAI), a pathological condition characterized by repetitive bouts of the ankle giving way, commonly develops following a lateral ankle sprain injury. Individuals with CAI have been shown to exhibit deficits in postural control and alterations in movement dynamics, which have been suggested to be contributing factors to the recurrent injury paradigm. The purpose of this investigation was to conduct a comprehensive biomechanical analyses to examine the influence of CAI on postural control and movement dynamics during a single leg squat, side-cut task, and single leg landing on an inverted surface.

Fifteen participants with CAI and fifteen participants without CAI completed the study following a between-subjects design, with limb serving as the repeated measure during the single leg squat. Each participant completed a single leg squat, side-cut task, and unexpected and expected single leg landings on a tilted surface. Results from the single leg squat and single leg landings on the tilted surface were analyzed using a 2 x 2 mixed-model ANOVA, while results from the side-cut task were analyzed using an
independent samples $t$-test. Statistical significance was considered for all dependent variables when $p < 0.05$.

Individuals with CAI demonstrated impaired postural control, as indicated by reduced time-to-boundary, during the single leg squat compared to controls. Altered ankle joint kinetics and increased sagittal plane hip joint stiffness were observed in the CAI group compared to controls. With regards to the single leg landings on the inverted surface, during the unexpected landing condition the CAI group displayed altered neuromuscular control and ankle kinematics. However, when the landing on the inverted surface as expected, the CAI group exhibited similar motor control strategies to the control group. Findings from this study indicate CAI alters postural control and movement dynamics during functional and dynamic movements, which may be used by researchers and clinicians to develop rehabilitation protocols to restore maladaptive movement patterns in individuals that develop CAI.
DEDICATION

This work is dedicated to my parents, Eddy and Kathy Simpson, who have sacrificed so much to provide me with opportunities that I never thought would be possible. Without their unconditional love and continued support during my academic journey, none of my success would have ever been possible.
ACKNOWLEDGEMENTS

I would like to thank Dr. Adam Knight and Dr. Harish Chander for their constant guidance, wisdom, patience and for sharing their love of biomechanics with me. They have provided me with an opportunity to continue my education and realize my passion for teaching. Their profound mentorship has left a lasting impact and has helped shape me into the educator and scholar that I am today.

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CHAPTER I
INTRODUCTION

The human foot and ankle is one of the most complex areas of the human body, which is collectively formed by numerous bones, ligaments, and articulations. The talocrural, subtalar, and distal tibiofibular joints work congruently to allow joint motion in the three cardinal planes, while passive and active components provide joint stability to the ankle through numerous ligamentous and musculotendinous structures that cross the foot and ankle (Hertel, 2002). These structures act to reinforce the ankle and prevent excessive joint motion that could potentially damage the supporting structures of the foot and ankle (Hertel, 2000; Hubbard & Hertel, 2006).

Ankle sprains, particularly those that damage the lateral ankle ligament complex, are a common orthopedic injury (Doherty et al., 2014c). The ankle complex supports the greatest amount of weight per unit area of any joint in the human body, which contributes to the high rate of ankle sprain injury (Morrison & Kaminski, 2007). Ankle sprains are one of the most prevalent soft tissue injuries sustained in intercollegiate (Roos et al., 2017) and interscholastic athletics (Fernandez, Yard, & Comstock, 2007), accounting for approximately 15% of all reported injuries (Hootman, Dick, & Agel, 2007) This injury frequently occurs during dynamic open kinetic chain movements such as jumping, landing, cutting and rapid center of mass (COM) accelerations (i.e. starting and stopping) because large and rapid impulse loads are imposed to the ankle complex (Doherty et al.,
Furthermore, these movements increase the risk of a lateral ankle sprain because of the potential for the lateral border of the foot to stick to the ground while displacement of the individuals COM continues laterally with respect to the foot, and/or contact another individuals’ foot, unexpectedly forcing the subtalar joint into excessive inversion (Garrick & Requa, 1989; Thacker et al., 1999).

The lateral, or ankle supination sprain, is the most common type of ankle sprain and occurs when the ankle complex is unexpectedly forced into excessive subtalar inversion, or a combination of subtalar inversion, internal rotation and talocrural plantar flexion (Fong et al., 2009; Hertel, 2002). A pathomechanical model published by Fuller suggested an increased supination moment of the subtalar joint as the cause of a lateral ankle sprain (Fuller, 1999). During open kinetic chain movements, supination involves talocrural plantar flexion, subtalar inversion and internal rotation, while in a closed kinetic chain supination involves talocrural dorsiflexion, subtalar inversion and internal rotation (Hertel, 2002; Rockar, 1995). Fuller (1999) described a theoretical relationship between the subtalar joint axis of rotation and the vertical ground reaction force vector acting on the plantar aspect of the foot. Specifically, a vertical ground reaction force vector that is positioned more medially on the plantar aspect of the foot in relation to the subtalar joint axis of rotation can generate a supination moment that could result in damage to the lateral ankle ligament complex (Fuller, 1999).

The peroneus longus and peroneus brevis muscles, which are the primary evertors of the subtalar joint, are responsible for providing dynamic stabilization and helping control ankle inversion displacement and velocity through eccentric muscle actions during inversion perturbations (Hertel, 2002). Therefore, if rapid and/or unexpected
inversion perturbations occur, the muscle spindles of the lateral ankle musculature are
lengthened and activated, initiating a reflexive contraction of the evertors to generate an
eversion moment at the subtalar joint to help stabilize the ankle joint complex (Hertel,
2000; Konradsen, Voigt, & Hojsgaard, 1997). The peroneus longus and peroneus brevis
muscles, which cross the lateral aspect of the ankle complex just posterior to the lateral
malleolus, are the primary dynamic stabilizers during unexpected inversion perturbations
and could become stretched and/or strained during a lateral ankle sprain (Hertel, 2000,
2002; Palmieri et al., 2004). Consequently, damage to the ligamentous and/or
musculotendinous structures that support the lateral aspect of the ankle complex during
an acute lateral ankle sprain can result in joint instability and significant sensorimotor
deficits that directly influence the lateral ankle musculature that provides dynamic frontal
plane stabilization (Hertel, 2008).

Various intrinsic and extrinsic human factors and environmental factors have been
identified to influence the risk of a lateral ankle sprain. Intrinsic factors include evertor
strength deficits, variations in anatomical foot structure, physiological laxity, reduced
range of motion (ROM), postural control and proprioceptive deficits, and a history of a
lateral ankle sprain (Denyer, Hewitt, & Mitchell, 2013; Hertel, 2000; Hubbard & Hertel,
2006; McGuine, Greene, Best, & Leverson, 2000; van Rijn et al., 2008). Extrinsic factors
include prophylactic ankle supports, such as adhesive tape and ankle braces (i.e. semi-
rigid or rigid braces), footwear, support surface conditions, and training interventions
(Ashton-Miller, Ottaviani, Hutchinson, & Wojtys, 1996; Callaghan, 1997; Fu, Fang, Liu,
& Hou, 2014; McGuine & Keene, 2006). Although several preventative measures have
been implemented to reduce the incidence of ankle sprain injuries, it appears that the
The greatest predictor of a lateral ankle sprain is a previous history of a lateral ankle sprain(s) (Doherty et al., 2014c; Roos et al., 2017; Yeung, Chan, So, & Yuan, 1994).

Contrary to the notion that lateral ankle sprains are innocuous injuries that resolve quickly and have no long-term consequences (Hertel, 2008), recurrence rates of lateral ankle sprains exceeding 70% (van Rijn et al., 2008; Yeung et al., 1994) and a plethora of residual symptoms lasting several months post-injury have been reported (Hertel, 2008; McKay, Goldie, Payne, & Oakes, 2001; Smith & Reischl, 1986). Many individuals that sustain an acute lateral ankle sprain will decline proper medical and/or rehabilitative treatment intended to restore concurrent sensorimotor deficits that manifest following acute ankle inversion trauma (Hertel, 2008; Roos et al., 2017). Consequently, an estimated 33% of individuals will suffer from recurrent lateral ankle sprains and the development of chronic ankle instability (Hiller et al., 2011; Tanen, Docherty, Van Der Pol, Simon, & Schrader, 2014). Chronic ankle instability (CAI) is a pathological condition characterized by a variety of residual symptoms resulting in recurrent ankle sprain injuries and/or subjective feelings of the ankle “giving way” during functional and dynamic activities (Hertel, 2002). These recurrent episodes of ankle joint instability during functional and dynamic activities are postulated to manifest from a continuum of functional and/or mechanical insufficiencies that contribute to CAI following an acute lateral ankle sprain (Freeman, 1965a; Hertel, 2002; Tropp, Odenrick, & Gillquist, 1985).

Although empirical definitions and associated factors contributing to CAI have been ambiguous in the literature, the recurrent lateral ankle sprain paradigm has been suggested to manifest from functional and/or mechanical instability (Hertel, 2000; Hubbard & Hertel, 2006). Functional instability (FI) refers to the neuromuscular and
proprioceptive deficits following an acute lateral ankle sprain (Freeman, 1965a; Freeman, Dean, & Hanham, 1965; Hertel, 2000), while mechanical instability (MI) refers to joint motion that exceeds normal physiological limits resulting in ankle joint laxity and abnormal joint mechanics (Hertel, 2002; Hubbard & Hertel, 2006; Tropp et al., 1985). However, FI and MI are not hypothesized to be mutually exclusive of one another and individuals may present with a combination of functional and mechanical deficits. These decrements in ankle stability have been identified to further increase the risk of recurrent lateral ankle sprains in individuals affected by CAI (Hertel, 2002).

Previous research has extensively examined postural stability during functional tasks in individuals with CAI (Arnold, De La Motte, Linens, & Ross, 2009; Hertel, 2008; Hiller et al., 2011; McKeon & Hertel, 2008b, 2008c). Functional tests such as unilateral static standing, the Star Excursion Balance Test (SEBT) and the Y Balance Test™ are methods of assessing sensorimotor impairments in CAI populations (McKeon & Hertel, 2008a; Olmsted, Carcia, Hertel, & Shultz, 2002; Plisky et al., 2009; Wikstrom, Fournier, & McKeon, 2010a). In recent years, research has examined biomechanical movement adaptations during dynamic maneuvers, such as jump-landings, to elucidate postural stability deficits that manifest from sensorimotor impairments in CAI populations (Gribble & Robinson, 2010; Gribble & Robinson, 2009; Wikstrom, Tillman, Chmielewski, Cauraugh, & Borsa, 2007; Wikstrom et al., 2010c; Wright, Arnold, & Ross, 2016). However, other functional tasks that may also evaluate such impairments, such as the single leg squat, have received minimal attention in CAI cohorts (Beazell et al., 2012; Grindstaff, Dolan, & Morton, 2017). The single leg squat is commonly implemented in physical therapy and rehabilitation programs while also being utilized to
screen movement patterns that may be predictive of a lower extremity injury (Dolak et al., 2011; Earl, Monteiro, & Snyder, 2007). In addition, this functional exercise can be used to assess for lower extremity stability and strength deficits that can be extrapolated to predict movement mechanics during dynamic movements such as landing, running, and cutting (Claiborne, Armstrong, Gandhi, & Pincivero, 2006). Therefore, examining biomechanical parameters during a single leg squat exercise in CAI populations may allow researchers and clinicians to develop empirically based physical therapy and rehabilitation programs in order to improve rehabilitation outcomes and hopefully mitigate recurrent lateral ankle sprains in CAI populations.

Although previous research provides evidence of centrally mediated alterations resulting in sensorimotor deficits in individuals affected by CAI (Hass, Bishop, Doidge, & Wikstrom, 2010; Hertel, 2008; Hiller et al., 2011), alterations in supra-spinal features of motor control are suggested to explain alterations in lower extremity biomechanics during unilateral jump-landings (Brown, Bowser, & Simpson, 2012; Caulfield, Crammond, O’Sullivan, Reynolds, & Ward, 2004; Caulfield & Garrett, 2002; Doherty et al., 2016c; Gribble & Robinson, 2010; Gribble & Robinson, 2009; Monaghan, Delahunt, & Caulfield, 2006; Wright et al., 2016). Unilateral jump-landings are often reported as a mechanism of a lateral ankle sprain injury and differences in unilateral landing strategies between CAI and healthy controls has been well investigated (Doherty et al., 2016b). Previous research has shown that individuals affected by CAI demonstrate a proximal movement strategy to execute unilateral jump-landing tasks to compensate for the constraints of ankle joint instability in comparison to healthy controls, who typically use a more distal movement strategy (Brown et al., 2012; Caulfield & Garrett, 2002; Doherty et al., 2016c).
et al., 2016c; Gribble & Robinson, 2010; Gribble & Robinson, 2009; Monaghan et al., 2006).

In regards to rapid change of direction tasks (i.e. cutting and turning), rapid medio-lateral ground reaction forces are imposed to the ankle complex that can generate rapid inversion of the ankle complex resulting in a lateral ankle sprain (Dayakidis & Boudolos, 2006; Koshino et al., 2014; McKay et al., 2001). However, biomechanical movement adaptations in CAI populations during a side-cut task have received little attention in the literature (Dayakidis & Boudolos, 2006; Koshino et al., 2016; Koshino et al., 2014; Suda & Sacco, 2011). Dynamic open kinetic chain movements, such as unilateral landing and rapid change of directions, require substantial feed-forward and feedback neuromuscular control to execute tasks effectively and position lower extremity segments in an advantageous position to attenuate biomechanical loads (Dicus & Seegmiller, 2012; Gribble & Robinson, 2009). The available literature regarding side-cut tasks indicates that kinematic (Koshino et al., 2016; Koshino et al., 2014), ground reaction force (Dayakidis & Boudolos, 2006), and neuromuscular (Suda & Sacco, 2011) alterations arise due to the constraints of ankle joint instability. Therefore, examining biomechanical parameters of a side-cut task warrants further investigation to provide researchers and clinicians with movement adaptations that could potentially contribute to recurrent lateral ankle sprains in CAI populations.

Various methodological approaches have been explored in laboratory investigations to safely replicate the mechanism of a lateral ankle sprain to further our understanding of ankle sprain mechanics (Ha, Fong, & Chan, 2015). A tilt platform/trap door is a commonly used device in ankle stability research. This device creates an
Ankle sprain injuries often occur during dynamic movements, such as landing from a jump, with a rapid and unanticipated inversion moment (Dicus & Seegmiller, 2012; Doherty et al., 2016b). Neuromuscular preparation of the ankle musculature during landing provides rapid joint stabilization to unanticipated inversion perturbations (Hertel, 2002; Konradsen et al., 1997). However, this anticipatory preparation to inversion perturbations is often a major limitation in many laboratory studies that confounds biomechanical outcomes and prohibits researchers from examining the unanticipated
nature of lateral ankle sprain injuries (Dicus & Seegmiller, 2012; Ha et al., 2015; Hertel, 2002, 2008; Konradsen et al., 1997). While much research has used variations of tilt platform/trapdoors to induce inversion stress during standing and walking (Donahue, Docherty, & Riley, 2014; Gruneberg, Nieuwenhuijzen, & Duysens, 2003; Nieuwenhuijzen, Gruneberg, & Duysens, 2002; Shima, Maeda, & Hirohashi, 2005; Vaes, Duquet, & Van Gheluwe, 2002), extrapolating results from studies implementing tilt platform/trapdoors to dynamic movements that usually result in a lateral ankle sprain injury is challenging (Dicus & Seegmiller, 2012; Gruneberg et al., 2003). Implementing experimental designs that discriminate between unanticipated and anticipated landings, especially on a tilted surface that creates a dynamic inversion perturbation upon landing, provides a complete spectrum of landing biomechanics that replicate the actual mechanism of injury and may provide clinical relevance to the recurrent ankle sprain injury paradigm in CAI populations (Dicus & Seegmiller, 2012; Hertel, 2008; Hiller et al., 2011).

The related sensorimotor deficits and pathophysiological mechanisms that results in biomechanical movement adaptations in CAI populations continues to be a primary focus of researchers and clinicians. Extensive research has been conducted examining postural control and motor control strategies during functional and dynamic tasks in CAI cohorts. Substantial differences in static and dynamic postural stability, gait dynamics, and motor control strategies during drop landings in CAI cohorts have been noted, which may explain the high rates of recurrent lateral ankle sprain injury. However, there is a gap in the literature examining the influence of CAI on postural stability during functional exercises, such as a single leg squat, and motor control strategies during a side-cut task.
Furthermore, several studies have explored the underlying biomechanical and neuromechanical factors during inversion perturbations, but have failed to examine feed-forward and feedback motor control strategies during unexpected and expected inversion perturbations using a tilted surface in CAI populations.

**Purpose**

The purpose of this study is to: (1) examine the influence of CAI on postural control during a single leg squat, (2) examine the influence of CAI on motor control strategies during a side-cut task, and (3) examine the influence of CAI on motor control strategies during unexpected and expected inversion perturbations when landing on an inverted surface. Results from this study will further the scientific literature regarding movement adaptations associated with CAI and provide clinical relevance to improve the high rates of recurrent ankle sprain injury in CAI populations.

**Hypotheses**

**Postural Control Hypothesis:**

**Specific Aim 1:** To investigate the influence of CAI on postural control during a single leg squat exercise.

- **H01:** There will be no significant differences in postural control, kinematics, kinetics, and muscle activity during the single leg squat between CAI and control groups.

- **H11:** There will be a significant difference in postural control, kinematics, kinetics, and muscle activity during the single leg squat between CAI and control groups.
Previous research has shown that individuals affected by CAI demonstrate deficits in dynamic postural stability. Functional assessments including the SEBT and the Y Balance Test™, as well as unilateral jump-landings have identified postural stability deficits and altered movement mechanics in individuals with CAI. These deficits are suggested to arise from sensorimotor and mechanical impairments associated with CAI. The single leg squat is a functional exercise commonly implemented in rehabilitation programs, which requires adequate neuromuscular control, stability, and strength. However, this functional exercise has received little attention in the literature as a functional assessment to identify postural stability deficits in CAI populations.

**Side-Cut Task Hypothesis:**

**Specific Aim 2:** To investigate the influence of CAI on motor control strategies during a side-cut task.

- **H02:** There will be no significant differences in kinematics, kinetics, and muscle activity during the side-cut task between CAI and control groups.
- **H12:** There will be a significant difference in kinematics, kinetics, and muscle activity during the side-cut task between CAI and control groups.

Lower extremity biomechanics during jump-landings has been extensively studied in individuals with CAI. Researchers have indicated that alterations to centrally mediated and/or supraspinal mechanisms of motor control in individuals with CAI result in feed-forward and feedback motor control differences during jump-landings that result in recurrent lateral ankle sprains. Rapid change of direction (i.e. side-cut) tasks are also a commonly reported mechanism of lateral ankle sprain injuries, however, less is known
regarding the motor control strategies adopted by individuals with CAI during a rapid change of direction type task.

**Inversion Perturbation Hypothesis:**

**Specific Aim 3:** To investigate the influence of CAI on ankle stability during unexpected and expected landings on an inverted surface.

- \( H_03 \): There will be no significant differences in kinematics, kinetics, and muscle activity during the unexpected and expected landings on an inverted surface between CAI and control groups.
- \( H_{A3} \): There will be a significant difference in kinematics, kinetics, and muscle activity during the unexpected and expected landings on an inverted surface between CAI and control groups.

Previous research provides evidence of proprioceptive and neuromuscular deficits in individuals with CAI resulting in delayed peroneal latency during inversion perturbations. In addition, altered lower extremity kinematics and sensorimotor control in individuals with CAI during jump-landings have also been shown and attributed to recurrent ankle sprain injuries. While the limited literature examining drop landings on an inverted surface in CAI cohorts is limited, the anticipatory motor control strategies during unexpected and expected ankle inversion perturbations in individuals with CAI warrants further investigation. It appears based on previous studies that individuals with CAI demonstrate an altered motor control strategy to further protect the injured ankle from a potentially injurious perturbation.
CHAPTER II
REVIEW OF LITERATURE

Ankle sprains are a common musculoskeletal injury sustained in intercollegiate and interscholastic athletics and the United States military (Doherty et al., 2014c; Fernandez et al., 2007; Hootman et al., 2007). The lateral, or ankle supination sprain, is the most commonly reported type of ankle sprain (Doherty et al., 2014c), which accounted for 7.3% of all reported injuries in National Collegiate Athletic Association (NCAA) athletic competition from 2009 to 2015 and 9.3% of United States military emergency room visits in 2009 (Dada-Laseinde, Canham-Chervak, & Jones, 2009; Roos et al., 2017). Recently, an epidemiological survey of lateral ankle ligament sprains in NCAA athletics identified the highest rates in men’s basketball (11.96 per 10,000 Athlete-Exposures [AE]), women’s basketball (9.50 per 10,000 AEs), women’s soccer (8.36 per 10,000 AEs), and men’s soccer (7.43 per 10,000 AEs; Roos et al., 2017). In addition, this injury also accounts for 51.0% of outpatient military personnel (Dada-Laseinde et al., 2009). Consequently, this creates a substantial financial and clinical burden for many athletes and academic institutions, as well as the United States Department of Defense, resulting in a substantial amount of time lost due to injury and the number of days limited on active military duty (Cameron, Owens, & DeBerardino, 2010; Doherty et al., 2014c; Hootman et al., 2007; Roos et al., 2017; Waterman, Belmont, Cameron, Deberardino, & Owens, 2010).
Once an individual has sustained a lateral ankle sprain, reoccurrence rates of subsequent injury are reported to exceed 70% (van Rijn et al., 2008; Yeung et al., 1994). In order to mitigate time lost due to injury, approximately 45% of athletes will attempt to return to sport within 24 hours without receiving proper medial and/or rehabilitative treatment, further increasing the risk to sustain recurrent lateral ankle sprain (Hertel, 2008; Roos et al., 2017). Moreover, approximately 19% of intercollegiate and 32% of interscholastic athletes that sustain an acute lateral ankle sprain develop a plethora of residual symptoms for several months, or even years, after the initial ankle sprain that progresses into chronic ankle instability (CAI) (Tanen et al., 2014). Previous research has shown that individuals affected by CAI demonstrate substantial sensorimotor and neuromuscular impairments resulting in postural stability decrements and biomechanical movement adaptations during sports related tasks such running, jumping, and landing (Caulfield & Garrett, 2002; Hertel, 2008; Hiller et al., 2011; Koshino et al., 2014; Ross, Guskiewicz, & Yu, 2005; Wikstrom et al., 2007). In addition, the development of CAI can result in long-term sensorimotor deficits and movement adaptations during dynamic sports related tasks, which are likely causative factors that contribute to the high rate of recurrent lateral ankle sprains (Brown et al., 2012; Caulfield & Garrett, 2002; Hertel, 2008; Hiller et al., 2011; Koshino et al., 2014; Monaghan et al., 2006).

The purpose of this chapter will be to: (1) review the anatomy and mechanics of the human ankle complex, (2) review the mechanism(s) of a lateral ankle sprain, (3) review the functional and mechanical contributions to CAI, (4) review previous literature regarding laboratory methodologies that simulate the mechanism of a lateral ankle sprain and their applications to CAI cohorts, (5) review previous investigations regarding
dynamic postural stability in CAI cohorts, and (6) review previous research investigating biomechanical movement patterns during sports related tasks such as jump-landings and side-cut maneuvers in CAI cohorts.

Anatomy of the Ankle Complex

The ankle complex is comprised of numerous bones, ligaments, and articulations, making it one of the most complex areas in the human body. The talocrural, subtalar, and distal tibiofibular joints are the three main joints that make up the ankle complex, which work together to allow triplanar motions of pronation and supination. Furthermore, numerous active and passive structures provide joint stability to the ankle through several ligamentous and musculotendinous structures that cross the foot and ankle to prevent excessive joint motion that could potentially damage the supporting structures. Therefore, the purpose of this section will be to review the anatomy and mechanics of the talocrural, subtalar, and distal tibiofibular joints.

Talocrural Joint

The talocrural joint, which is commonly referred to as the “ankle joint”, is the articulation between the superior aspect of the talus and the distal ends of the tibia (medial malleolus) and fibula (lateral malleolus). The arrangement of the talocrural joint is considered to be a hinge joint, which predominantly allows joint motion in the sagittal plane (i.e. dorsiflexion and plantar flexion) about a medial-lateral axis that passes through the lateral and medial malleoli (Figure 1). Due to the anatomical structure and the axis of rotation at the talocrural joint, there is a greater degree of sagittal-plane motion in plantar flexion than there is dorsiflexion. Moreover, the anatomical structure of the talocrural
joint allows torque transfer from the lower leg to the foot during weight bearing activities (Hertel, 2002).

Figure 1. Anatomy of the talocrural joint and axis of rotation (Hertel, 2002).

The lateral aspect of the talocrural joint receives ligamentous support from the anterior talofibular ligament (ATFL), the posterior talofibular ligament (PTFL), and the calcaneofibular ligament (CFL), while the medial aspect receives ligamentous support from the deltoid ligament (Figure 2) (Hertel, 2002; Hertel, Denegar, Monroe, & Stokes, 1999). Collectively, the deltoid ligament of the talocrural joint is made up of the anterior and posterior tibiotalar, tibiocalcaneal, and tibionavicular ligaments (Golano et al., 2016). The ATFL on the lateral aspect of the talocrural joint prevents excessive anterior displacement, inversion and internal rotation of the talus on the tibia. Consequently, the strain placed on the ATFL increases as the talocrural joint moves into plantar flexion making this the ligament most often injured during a lateral ankle sprain (Hertel, 2002). The ATFL is considered the weakest ligament of the three lateral ligaments that support the talocrural joint, and is the most frequently injured ligament during a lateral ankle
sprain. However, if the force exceeds the tensile strength of the ATFL, the CFL and PTFL can also become damaged during a lateral ankle sprain (Hertel, 2002).

Figure 2. Lateral ligaments of the talocrural joint (1) ATFL, (2) CFL, and (3) PFL (Hertel et al., 1999).

**Subtalar Joint**

The subtalar joint allows joint motion in the frontal plane (i.e. inversion and eversion) and is located inferior to the talocrural joint. In addition, the subtalar joint is divided into anterior and posterior sections that share the same axis of rotation but have separate joint cavities. The anterior portion of the subtalar joint is the articulation between the talus, calcaneous, and navicular, while the posterior portion of the subtalar joint is the articulation between the talus and calcaneous (Figure 3). Similar to the talocrural joint, the subtalar joint also allows for torque transfer from the lower leg onto to the foot during weight bearing activities (Hertel, 2002). The cervical and interosseous ligaments, which cross obliquely, provide ligamentous support to the subtalar joint and form a barrier between the anterior and posterior joints (Golano et al., 2016; Hertel, 2002). The subtalar joint also receives ligamentous support from the CFL, the lateral
talocalcaneal and the fibulotalocalcaneal ligaments. In addition to the ligaments at the talocrural joint, ligaments of the subtalar joint may also become injured during a lateral ankle sprain (Hertel, 2002).

![Figure 3](image.jpg)

*Figure 3.* Anatomy of the subtalar joint and subtalar ligaments (1) Interosseous ligament, (2) cervical ligament, and (3) deep fibers of the extensor retinaculum. (Hertel et al., 1999).

**Distal Tibiofibular Joint**

The distal tibiofibular joint is a syndesmosis joint that is formed by the articulation of the distal aspect of the tibia and fibula (Figure 4). This joint allows for slight separation between the distal tibia and fibula, which is crucial for anterior/posterior talar glide and normal ankle joint mechanics and lower extremity function (Hertel, 2002). The distal tibiofibular joint receives structural support from the interosseous membrane and the anterior and posterior inferior tibiofibular ligaments (Figure 5). Maintaining the structural integrity of this joint critical to form a stable roof for the mortise of the talocrural joint and to allow slight separation of the tibia from the fibula for adequate force transmission up the kinetic chain (Hertel, 2002).
Figure 4. Anatomy of the distal tibiofibular joint (Floyd, 2015).

Figure 5. Ligaments of the distal tibiofibular joint (Norkus & Floyd, 2001).

The anterior and posterior inferior tibiofibular ligaments act to hold the fibula against the tibia, preventing excessive fibular movement and external rotation of the talus. Moreover, the pliable interosseous membrane allows for slight separation of the distal fibula from the distal tibia to allow posterior talar glide during talocrural dorsiflexion. Collectively, these structures are critical for providing adequate stability and providing resistance to lateral fibular displacement at the distal syndesmosis, or the distal tibiofibular joint. The syndesmosis, or high ankle sprain is an injury to the ligaments of the distal tibiofibular joint. The most commonly reported mechanism of a syndesmosis, or a high ankle sprain is excessive subtalar external rotation and talocrural dorsiflexion, either in combination or in isolation (Norkus & Floyd, 2001). Damage to the ligaments of
the distal tibiofibular joint will result in diminished joint integrity, increase the susceptibility of a future injury, provide poor force transmission up the kinetic chain, and reduce talocrural dorsiflexion and plantar flexion range of motion (Hertel, 2002).

**Lateral Ankle Sprain Mechanics**

**Mechanism of Injury**

The primary mechanism of a lateral, or ankle supination sprain, is excessive inversion of the subtalar joint about an externally rotated lower leg during initial ground contact (Fong, Ha, Mok, Chan, & Chan, 2012; Hertel, 2002). However, a combination of talocrural plantar flexion, subtalar inversion and internal rotation coupled with external rotation of the lower leg is also a commonly reported mechanism of injury (Hertel, 2002). Many ankle sprains occur during dynamic open kinetic chain movements such as jumping, landing, cutting and turning because large and rapid impulse loads are imposed to the ankle complex (Dicus & Seegmiller, 2012; Doherty et al., 2016b; Gribble & Robinson, 2009). During these movements, the ankle complex will frequently experience rapid and unexpected joint perturbations that could potentially force the ankle complex into excessive supination resulting in damage to the lateral ankle ligaments (Ashton-Miller et al., 1996; Hertel, 2002). In an open kinetic chain supination consists of talocrural plantar flexion, subtalar inversion and internal rotation, while in a closed kinetic chain supination involves talocrural dorsiflexion, subtalar inversion and internal rotation (Figure 6; Hertel, 2002; Rockar, 1995). The ATFL is considered the weakest ligament of the three lateral ligaments that support the talocrural joint, and is the most frequently injured ligament during a lateral ankle sprain. However, if the force exceeds
the tensile strength of the ATFL, the CFL and PTFL can also become damaged during a lateral ankle sprain (Hertel, 2002).

![Figure 6. Pronation and supination in an open kinetic chain (Hertel, 2002).](image)

The pathomechanics of an acute lateral ankle sprain result from an excessive supination moment of the subtalar joint (Fuller, 1999; Hertel, 2002). A pathomechanical model published by Fuller (1999) described the relationship between the vertical ground reaction force vector acting on the plantar aspect of the foot and the subtalar joint axis of rotation during initial ground contact. The magnitude and position of the vertical ground reaction force vector acting on the plantar aspect of the foot in relation to the subtalar joint axis of rotation may, or may not, cause a supination moment at the subtalar joint. A vertical ground reaction force vector that is positioned directly under the subtalar joint axis of rotation will result in no moment or joint movement. However, ground reaction forces may not be the only factor influencing the moment experienced at the subtalar joint. Moments from muscles, bones, and ligaments should be considered in combination to the vertical ground reaction force vector acting on the subtalar joint. Although the vertical ground reaction force vector may produce supination moments if the location is medial to the subtalar joint axis of rotation, musculotendinous units that cross the lateral aspect of the ankle complex, primarily the peroneus longus and peroneus brevis, may
generate an equal pronation moment to stabilize the ankle complex resulting in no joint movement. Thus, the magnitude of vertical ground reaction force vector and the position in relation to the subtalar joint axis of rotation and the perpendicular distance from the line of action of the force application to the axis of rotation must be known to determine subtalar joint moments (Fuller, 1999).

The location and alignment of the subtalar joint axis across individuals varies widely. Individuals that have a medially deviated subtalar joint axis are more likely to have a pronation moment from the vertical ground reaction force vector, while individuals with a more laterally deviated subtalar joint axis are more likely to have a supination moment from the vertical ground reaction force vector (Fuller, 1999; Hertel, 2002). Damage to the lateral ankle ligament complex is a result of excessive and/or forced supination of the rearfoot. Individuals that have a subtalar joint axis located more lateral in relation to the vertical ground reaction force vector acting on the plantar aspect of the foot during ground contact have the potential to produce greater supination moments of the ankle complex. Consequently, greater magnitudes of the ground reaction force will cause supination moments at the subtalar joint that could potentially force the ankle complex into excessive supination resulting in damage to the lateral ankle ligament complex (Fuller, 1999).

Ankle Musculature

The musculotendinous units that cross the lateral aspect of the ankle complex are responsible for generating joint stiffness to provide dynamic stabilization (Hertel, 2000; Konradsen et al., 1997). The primary evertors of ankle complex, which are the peroneus longus and peroneus brevis, provide dynamic stabilization and help control rapid and/or
excessive supination of the rearfoot to prevent a lateral ankle sprain (Hertel, 2002). Specifically, these muscles help control excessive supination of the rearfoot by contracting eccentrically to produce a pronation moment to stabilize the ankle joint complex. In addition to the lateral musculature of the ankle complex, musculotendinous units that cross the anterior aspect of the ankle complex such as the tibialis anterior, extensor digitorum longus, extensor digitorum brevis, and peroneus tertius also generate joint stiffness and contribute to dynamic stabilization of the ankle complex (Hertel, 2002). More specifically, these muscles also contract eccentrically during excessive supination of the rearfoot to help control the amount and velocity of talocrural plantar flexion, further protecting the lateral ankle ligament complex from injury (Hertel, 2000, 2002).

The peroneus longus and peroneus brevis, which are located in the lateral compartment of the lower leg, receive nerve innervation from the superficial portion of the peroneal nerve (Floyd, 2015). The peroneus longus originates on the head of the proximal fibula and the lateral condyle of the proximal tibia, while the peroneus brevis originates of the middle third of the fibula. Together, the peroneus longus and peroneus brevis begin to share one synovial sheath approximately 4 cm superior to the lateral malleolus and pass posteriorly to the lateral malleolus through the retromalleolar groove, with the peroneus longus being located posterior to the peroneus brevis (Floyd, 2015). The peroneus longus inserts onto the plantar aspect of the base of the first metatarsal and medial cuneiform, while the peroneus brevis inserts onto the base of the fifth metatarsal tuberosity. The primary function of both the peroneus longus and peroneus brevis
primary function is external rotation and eversion of the subtalar joint and plantar flexion of the talocrural joint (Floyd, 2015).

Antagonists to the peroneus longus and peroneus brevis are the tibialis anterior, tibialis posterior, flexor hallucis longus, and flexor digitorum longus. The tibialis anterior originates on the upper two-thirds of the lateral tibia and inserts on the inner surface of the medial cuneiform and the base of the first metatarsal. The primary functions of the tibialis anterior are talocrural dorsiflexion and subtalar inversion. Originating on the posterior surface of the proximal tibia and fibula and inserting onto the inner surfaces of the navicular cuneiform, and the base of the second, third, fourth, and fifth metatarsals, the tibialis posterior main functions are talocrural plantar flexion and subtalar inversion (Floyd, 2015). While the peroneus longus and peroneus brevis function to produce a pronation moment (Heckman, Reddy, Pedowitz, Wapner, & Parekh, 2008), the tibialis posterior functions to produce a supination moment during open kinetic chain movements (Frigg, Valderrabano, Kundert, & Hintermann, 2006).

When the ankle complex is forced into excessive inversion, the peroneus longus and peroneus brevis provide the primary active defense against a lateral ankle sprain (Konradsen et al., 1997). Therefore, if rapid and/or unexpected subtalar inversion occurs, muscle spindles of the peroneus longus and peroneus brevis are lengthened and activated, which subsequently initiates a stretch reflex contraction of the peroneus longus and peroneus brevis to generate an eversion moment that helps stabilize the ankle joint complex (Hertel, 2000, 2002). Previous research has reported that individuals with a previous history of a lateral ankle sprain and/or chronic ankle instability demonstrate substantial sensorimotor deficits that directly influences the ankle musculature during
dynamic ankle inversion perturbations, which may explain the current lateral ankle sprain paradigm (Hertel, 2008). In addition, preparatory activation in the ankle musculature prior to ground contact during ankle inversion perturbations make examining lateral ankle sprain mechanics challenging in laboratory settings. Thus, part of this dissertation project will examine responses in the ankle musculature during expected and unexpected landings on and inverted surface in individuals with and without CAI.

**Chronic Ankle Instability**

Damage to the lateral ankle ligaments can result in a plethora of residual symptoms that continuously develop and affect an individual for months, or even years, after an acute lateral ankle sprain. This pathological condition is known as chronic ankle instability (CAI), which is characterized by a variety of residual symptoms resulting in recurrent lateral ankle sprains and/or repeated episodes of the ankle “giving way” during functional activities (Hertel, 2002). Researchers have hypothesized two theories that contribute to CAI: functional instability and mechanical instability (Freeman, 1965a; Freeman et al., 1965; Hertel, 2000, 2002; Hertel et al., 1999; Hubbard & Hertel, 2006; Tropp et al., 1985). Functional instability refers to the neuromuscular and proprioceptive impairments that manifest following an acute lateral ankle sprain (Freeman, 1965a; Freeman et al., 1965; Hertel, 2000), while mechanical instability refers to ankle joint motion exceeding normal physiological limits, or ankle joint laxity, resulting in altered ankle joint mechanics (Hertel, 2002; Hertel et al., 1999; Hubbard & Hertel, 2006; Tropp et al., 1985). While these two conditions are not postulated to be mutually exclusive of each other, the full spectrum of impairments related to CAI are not adequately described by each condition independently (Hertel, 2002). Thus, Hertel suggested a model that
encompasses both functional and mechanical insufficiencies that likely describes the continuum of insufficiencies that contribute to CAI and the recurrent lateral ankle sprain paradigm (Figure 7; Hertel, 2002).

Figure 7. Functional and mechanical insufficiencies that contribute to CAI. (Hertel, 2002).

**Functional Instability**

Damage to the ligaments of the ankle complex have been shown to result in impairments to the proprioceptive and neuromuscular systems that provide dynamic stabilization to the ankle complex (Hertel, 2000, 2002, 2008). Although there is no clear or widely accepted definition of functional instability in the literature, Freeman and colleagues first proposed a seminal hypothesis of functional instability through findings in a series of investigations conducted in the mid-1960s (Freeman, 1965a, 1965b; Freeman et al., 1965; Freeman & Wyke, 1967). The authors proposed that the proprioceptive and neuromuscular deficits following an acute lateral ankle sprain were a result of damage to the afferent receptors within the injured ligaments and the ankle joint.
capsule. More specifically, Freeman and colleagues described the theory of “articular deafferentation”, which proposed damage to the ankle ligaments disrupted the sensory mechanoreceptors located in the ankle ligaments that resulted in functional (i.e. sensorimotor) deficits (Freeman, 1965a, 1965b; Freeman et al., 1965; Freeman & Wyke, 1967). Furthermore, these impairments were also presumed to limit the central nervous system from generating an accurate perception concerning the position of the ankle joint in space. Therefore, the authors attributed postural control decrements in individuals with lateral ankle sprains to damaged articular mechanoreceptors, resulting in ankle joint proprioception deficits and an increased risk of the ankle joint giving way into excessive supination due to reduced peroneal muscle response to anomalous ankle joint positioning (Freeman, 1965a, 1965b; Freeman et al., 1965; Freeman & Wyke, 1967).

While Freedman’s theory provided initial insight to the sensorimotor deficits in individuals with lateral ankle sprains and/or CAI, this theory only assumes a feedback model of sensorimotor control (Figure 8). In the feedback only model, efferent neuromuscular control deficits are suggested to only be present after damage to the afferent receptors causes a reduction in sensory information regarding ankle joint position. Furthermore, Freedman’s theory did not consider the role the gamma motoneuron system and/or the adaptations to chronic alpha motoneuron inhibition (Hertel, 2000, 2002, 2008). Feed-forward aspects of motor control are critical to consider because it has been well-established that preparatory muscle activity in the lower extremity is present during various open kinetic chain movements such as walking, running, jump-landing and side-cut movements that generally initiate the mechanism of a lateral ankle sprain. Furthermore, if the ankle musculature operated in a feedback only
manner, peroneal muscle response to sudden inversion stress would not be able to react quickly enough to prevent a lateral ankle sprain during ground contact (Hertel, 2002, 2008). Thus, it has been proposed by Hertel that the complete spectrum of functional instability should also consider neuromuscular control by combining aspects of feedback and feed-forward motor control (Figure 9; Hertel, 2002).

![Figure 8](image1.png)

**Figure 8.** The feedback model of sensorimotor control (Hertel, 2008).

![Figure 9](image2.png)

**Figure 9.** The feedback and feedforward model of sensorimotor control (Hertel, 2008).

The proprioceptive and neuromuscular impairments related to functional instability are not postulated to occur independently, but rather, are likely causative factors that create the complex spectrum of CAI (Figure 7; Hertel, 2000, 2002). Injuries

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to the lateral ankle ligaments can result in substantial proprioceptive and neuromuscular deficits, which has also been shown to negatively alter neuromuscular control (Hertel, 2008). Hertel has suggested that alterations to muscle spindle activity, as facilitated through the gamma motoneuron system, is likely the underlying cause to the interconnected symptoms of functional instability (Hertel, 2002). Most notably, prolonged reflexive response times of the peroneal musculature to sudden inversion perturbations and greater postural sway during static standing have been noted, indicating these deficits are related to impaired proprioception, reduced nerve conduction velocity, and/or centrally mediated alterations in neuromuscular motor control strategies (Hertel, 2000, 2002, 2008). Therefore, it appears based on the available literature that altered gamma motoneuron function is likely the underlying cause of the functional impairments that result in the proprioception, neuromuscular and postural control deficits that manifest following a lateral ankle sprain injury (Hertel, 2000, 2002, 2008).

**Mechanical Instability**

Tropp and colleagues were the first suggest the notion that mechanical instability resulted from physiological laxity of the ankle complex after a lateral ankle sprain (Tropp et al., 1985). While anatomical changes to the ankle complex are suggested to occur after an initial ankle sprain, numerous insufficiencies that further increase the risk of recurrent episodes of ankle joint instability and/or ankle sprain injuries have been suggested (Hertel, 2002; Hertel et al., 1999; Hubbard & Hertel, 2006). These mechanical insufficiencies include pathological laxity, arthrokinematic restrictions, synovial and/or degenerative changes that occur independently, or in combination, following injury (Hertel, 2002; Hubbard & Hertel, 2006).
During a lateral ankle sprain, the lateral ankle ligaments experience strain into the plastic region resulting in pathological laxity of the injured ankle joint (Hertel et al., 1999). Consequently, this leads to increased range of accessory movement (i.e. hypermobility) possible at the injured joint. Hypermobility of a joint increases the neutral zone of that joint, or the amount of accessory joint motion possible without ligament tensioning, further increasing the strain placed on the injured ligaments (Hubbard & Hertel, 2006). Additionally, hypermobility can cause joint instability when the ankle complex is put in susceptible positions during dynamic and functional activities, resulting in recurrent injury to the supporting structures that cross the ankle complex (Hertel, 2002). The increased mobility of the talus in the mortise may cause the talocrural joint axis of rotation to be deviated anteriorly or posteriorly in the frontal plane resulting in abnormal sagittal plane motion (i.e. talocrural dorsiflexion/plantar flexion; Hubbard & Hertel, 2006). It has been suggested that individuals with CAI have greater anterior and inferior displacement of the distal fibula, resulting in the ATFL resting in position with more slack. Hence, when the ankle complex moves into supination, the talus can complete a greater range of motion before tension is placed on the ATFL. This increases the vulnerability of the talocrural and subtalar joints while also increasing the susceptibility of recurrent episodes of ankle instability and/or lateral ankle sprain injuries (Hertel, 2002).

Although pathological laxity and hypermobility are often causes of mechanical instability, arthokinematic impairments at any of the joints of the ankle complex are also evident after an ankle sprain or in individuals with CAI leading to abnormal joint mechanics (Hertel, 2002; Hubbard & Hertel, 2006). Diminished joint range of motion of
the talocrural and subtalar joints is also considered to be a mechanical insufficiency that contributes to the recurrent ankle sprain paradigm (Hertel, 2002). Most commonly, diminished talocraul dorsiflexion range of motion is often observed after an acute lateral ankle sprain or in individuals with CAI, which may be attributed to a tight gastrocnemius-soleus complex (Hertel, 2002; Hertel et al., 1999). However, limited accessory movement at other joints in the ankle complex are likely to explain these impairments. In order for the talocrural joint to reach a closed-packed position, the talocrural joint must reach full dorsiflexion. For this to occur, the talus must glide posteriorly and externally rotate. However, if posterior glide and external rotation of the talus is restricted then the pattern of accessory movement and the joint axis of rotation is changed (Hertel, 2002; Hubbard & Hertel, 2006). As such, the talocrural joint axis of rotation becomes deviated anterior to the lateral malleolus, as it passes through the distal fibula, resulting in restricted talocrural dorsiflexion and subtalar eversion (i.e. pronation) while allowing greater talocrural plantar flexion and subtalar inversion (i.e. supination). These changes in accessory joint movement and the axis of rotation further increases the stress placed on the supporting structures of the ankle complex (Hertel, 2002; Hertel et al., 1999; Hubbard & Hertel, 2006).

Collectively, the mechanical insufficiencies can result in altered proprioceptive input from the ligamentous and musculotendinous mechanoreceptors of the ankle complex (Hubbard & Hertel, 2006). Abnormal joint mechanics increases the stress placed on the supporting structures (i.e. ligamentous and musculotendinous units) and the joint capsule, which may provide inaccurate proprioceptive information to the central nervous system. Inaccurate proprioceptive information consequently influences the activation
threshold of the gamma motor neuron system that negatively alters the neuromuscular firing patterns (Hertel, 2002; Hubbard & Hertel, 2006). Additionally, the adverse changes in musculotendinous stiffness may alter the proprioceptive feedback and the global neuromuscular firing patterns to recruit the proximal musculature earlier, rather than the distal musculature, to provide adequate stability on the affected limb (Hertel, 2002; Hubbard & Hertel, 2006; Sedory, McVey, Cross, Ingersoll, & Hertel, 2007).

**Summary**

In summary, a more complete pathological model has been developed by Hertel to expand upon the initial theories of ankle joint instability to encompass both functional and mechanical insufficiencies that contribute to the CAI paradigm (Hertel, 2002). Previous literature has shown that lateral ankle sprains can result in substantial sensorimotor and mechanical deficits that persist for several months, or even years, following injury and further increases the risk of recurrent lateral ankle sprains and ultimately the development of CAI (Hertel, 2000, 2008; Hertel et al., 1999; Hubbard & Hertel, 2006). This further emphasizes the need for researchers and clinicians to assess potential impairments in proprioception, neuromuscular control, and postural stability during functional and dynamic movement tasks to help develop rehabilitation programs aimed to improve clinical outcomes in individuals that develop lateral ankle instability. Implementing functional and dynamic movements into research and rehabilitation protocols will further assist researchers and clinicians to evaluate sensorimotor and mechanical insufficiencies concurrently and further expand the current scientific literature regarding the interactions between functional and mechanical instability.
Therefore, this project will examine potential differences in dynamic postural stability during a single leg squat and side-cut task in CAI and control participants.

**Ankle Inversion Perturbations**

The majority of ankle sprains, particularly those to the lateral ankle ligament complex, occur during open kinetic chain movements such as running, jump-landings and side-cut maneuvers (Dicus & Seegmiller, 2012; Doherty et al., 2014c; McKay et al., 2001). Although examinations of injury mechanisms during real-time incidents is the most direct way to study ankle sprain mechanics, this is not possible and unethical to conduct in laboratory studies. Therefore, researchers have designed and developed various methodological approaches to simulate the actual mechanisms of injury in controlled laboratory environments to further our understanding of the underlying biomechanical and neuromechanical mechanisms of lateral ankle sprain injuries (Ha et al., 2015). In this section, the commonly used laboratory devices that simulate the mechanism(s) of a lateral ankle sprain, methodological limitations, and the current scientific literature regarding ankle inversion perturbations in CAI cohorts will be reviewed and summarized.

**Tilt Platform/Trapdoor**

The most commonly used device in laboratory research to safely replicate the mechanism of a lateral ankle sprain is a tilt platform/trapdoor device. This device is constructed as a flat platform raised above the ground so that participants can stand in the bilateral stance position with full weight bearing on both limbs. Then, an investigator randomly triggers the platform, without the participants knowledge, to unexpectedly fall...
forcing the participants testing limb into subtalar inversion (Figure 10) (Chan, Fong, Yung, Fung, & Chan, 2008; Cordova et al., 2000; Denyer et al., 2013; Ebig, Lephart, Burdett, Miller, & Pincivero, 1997; Hopkins et al., 2007; Konradsen et al., 1997; Lynch, Eklund, Gottlieb, Renstrom, & Beynnon, 1996; Ricard et al., 2000a; Ricard et al., 2000b; Vaes et al., 2002). Given that many lateral ankle sprains occur during excessive subtalar inversion in combination with talocrural plantar flexion, previous studies implementing trapdoor devices have modified the design to incorporate a combination of subtalar inversion and talocrural plantar flexion (Eechaute, Vaes, Duquet, & Van Gheluwe, 2007, 2009; Lynch et al., 1996; Ricard et al., 2000a; Ricard et al., 2000b; Vaes et al., 2002). Furthermore, the use of the trapdoor has also been incorporated into walkways (Gruneberg et al., 2003; Hopkins et al., 2007; Midgley et al., 2007) and landing platforms (Gutierrez & Kaminski, 2010; Gutierrez et al., 2012) in which the trapdoor falls away when the participant steps/lands on the trapdoor forcing the subtalar joint into inversion, or a combination of subtalar inversion and talocrural plantar flexion.
Many studies have used the tilt platform/trapdoor device to examine the onset of reflexive muscle activation, or latency, of the peroneus longus and peroneus brevis to inversion perturbations in CAI populations (Donahue et al., 2014; Ebig et al., 1997; Eechaute et al., 2007, 2009; Hiller et al., 2011; Hopkins, Brown, Christensen, & Palmieri-Smith, 2009; Johnson & Johnson, 1993; Konradsen & Ravn, 1990; Lynch et al., 1996; Vaes et al., 2002; Vaes, Van Gheluwe, & Duquet, 2001). Latency has been previously defined as the time, measured in milliseconds (ms), between the initiation of a joint perturbation and the first rise in muscle activity above a pre-determined threshold (Konradsen & Ravn, 1990; Konradsen et al., 1997). Researchers have used thresholds ranging from 2 to 10 standard deviations above baseline muscle activity to determine the latency of the peroneus longus and peroneus brevis to unexpected inversion perturbations (Hopkins et al., 2009; Hopkins et al., 2007; Knight & Weimar, 2011b, 2012b; Lynch et al., 1996; Midgley et al., 2007). Although the thresholds used to determine peroneal latency in previous studies varies widely, latency provides a reliable assessment of the
reflexive muscle response when evaluating potential sensorimotor impairments to unexpected ankle inversion perturbations in individuals with CAI (Hertel, 2002, 2008).

Initial studies utilizing a trapdoor to examine peroneal latency in CAI cohorts were conducted by Konradsen and Ravn (Konradsen & Ravn, 1990, 1991). The authors investigated differences in the latency of the peroneus longus and peroneus brevis during inversion perturbations of 30° while standing on a trapdoor device between individuals with and without functional ankle instability. Muscle activity of the peroneus longus and peroneus brevis was determined using surface electromyography (EMG), and the time the trapdoor tilt was initiated to the first recording of the peroneals by the EMG system was designated as latency. The authors reported that the functionally unstable group demonstrated significantly longer latency in the peroneus longus and peroneus brevis in comparison to healthy controls. This led the authors to conclude that partial deafferentation, as initially suggested by Freeman and colleagues (Freeman, 1965a, 1965b; Freeman et al., 1965; Freeman & Wyke, 1967), of the lateral ankle ligaments resulted in proprioceptive deficits that negatively influenced the latency of the lateral ankle musculature during an inversion perturbation of 30° in the functionally unstable group (Konradsen & Ravn, 1990, 1991).

Another study using a trapdoor device utilized a perturbation consisting of subtalar inversion and talocrural plantar flexion to investigate the potential differences in the latency of the peroneus longus between healthy and CAI participants during a simulated lateral ankle sprain (Ebig et al., 1997). In this study, participants were instructed to stand on the platform in the bilateral stance with their weight evenly distributed on both limbs. The trapdoor device was then triggered by an investigator and
the platform unexpectedly fell beneath the participants forcing their ankle into subtalar inversion and talocrural plantar flexion. Muscle activity of the peroneus longus was collected using surface EMG and the latency was determined as the time in ms from the initiation of the perturbation to the onset of muscle activity of the peroneus longus. The primary investigator visually inspected the root mean square EMG signal of the peroneus longus to determine the onset of muscle activity above baseline to determine latency. Although this study reported no significant differences in the latency of the peroneus longus between CAI and control groups, it is possible that the lack of significant differences may be attributed to the subjective method employed by the investigators to determining the latency of the peroneus longus to subtalar inversion and talocrural plantar flexion stress (Ebig et al., 1997).

Other studies using a trapdoor device in which participants stand on a platform in full weight bearing and the platform unexpectedly falls forcing the ankle complex into subtalar inversion, or a combination of subtalar inversion and talocrural plantar flexion, have reported significant delays in the latency of the peroneal musculature in individuals affected by CAI (Lofvenberg, Karrholm, Sundelin, & Ahlgren, 1995; Vaes et al., 2001). However, other studies utilizing this device and methodology have not reported significant differences (Fernandes, Allison, & Hopper, 2000; Johnson & Johnson, 1993; Vaes et al., 2002). The initial studies utilizing trapdoor devices to investigate neuromuscular responses to ankle joint perturbations has led researchers to incorporate the trapdoor design into walkways (Donahue et al., 2014; Eechaute et al., 2007, 2009; Hopkins et al., 2009) and landing platforms (Gutierrez & Kaminski, 2010; Gutierrez et
al., 2012) to further examine lateral ankle sprain mechanics during open kinetic chain movements.

Gutierrez and Kaminski designed a supinating device that rotated 25° in the frontal plane upon landing to examine kinematic and neuromuscular parameters of a drop landing between ankle sprain coper, CAI, and matched control groups (Gutierrez & Kaminski, 2010). The authors designed this device so that participants could perform drop landings without the knowledge of if the landing platform would supinate or not upon initial contact. In this study, participants completed bilateral drop landings onto a platform with the supinating device embedded in the platform. Participants stood 30 cm superior and posterior to the landing area and were instructed to land in the bilateral stance with the testing limb contacting the supinating device and subsequently perform a maximal vertical jump. A total of ten trials were completed by the participants in which three trials were selected randomly to initiate the supination device. The authors reported ankle kinematic data from 200 ms pre-initial contact to 200 ms post-initial contact and surface EMG responses from the tibialis anterior and peroneus longus. However, due to the small sample size and very low statistical power, the authors only reported the descriptive statistics of the kinematic data and muscle activity responses (Gutierrez & Kaminski, 2010). Although the authors collapsed the means for kinematic data across groups, apparent differences were noted in talocrural plantar flexion, subtalar inversion and internal rotation indicating that the device safely simulated the mechanism of a lateral ankle sprain. Furthermore, an examination of the preparatory (200 ms pre-initial contact) and reactive (200 ms post-initial contact) muscle activity responses indicated that individuals in the control group appeared to land with a greater activation of the
peroneus longus during both preparatory and reactive time points compared to the ankle sprain copers and CAI participants. This preliminary data from the use of this device might indicate that individuals with an ankle sprain history or CAI may demonstrate altered neuromuscular control strategies during landing that impairs dynamic stabilization of the ankle complex when landing (Gutierrez & Kaminski, 2010).

A subsequent study was conducted by Gutierrez and colleagues to further expand upon their preliminary data using the supination device (Gutierrez & Kaminski, 2010; Gutierrez et al., 2012). The purpose of this study was to examine neuromuscular responses of the peroneus longus and tibialis anterior during bilateral drop landings from a height of 30 cm onto a supinating device, which unexpectedly rotated 25° in the front plane when the testing limb contacted the device upon landing. Muscle activity from 200 ms pre-initial contact (preparatory) to 200 ms post-initial contact (reactive) was analyzed during the drop-landings from a height of 30 cm in individuals with a history of a lateral ankle sprain but no residual effects (i.e. copers), CAI, and healthy matched controls. The authors reported that the CAI group demonstrated a significantly greater amount of preparatory and reactive peroneus longus activation in comparison to ankle sprain copers and healthy controls. While significant reductions in preparatory and reactive activation of the ankle musculature has been shown in CAI participants during drop-landings compared to healthy controls (Brown, Ross, Mynark, & Guskiewicz, 2004; Caulfield et al., 2004; Monaghan et al., 2006), the authors concluded that individuals affected by CAI may alter their motor control strategy to increase activation of the lateral ankle musculature to provide adequate dynamic stabilization to the ankle complex when there is knowledge of a potentially injurious situation when landing (Gutierrez et al., 2012).
**Outer Sole with Fulcrum**

While it has rarely been utilized in the scientific literature, an outer sole with a fulcrum has been used to create forced subtalar inversion upon landing in the unilateral stance (Figure 11) (Knight & Weimar, 2011a, 2011b, 2012a, 2012b, 2013; Simpson et al., 2017; Ubell, Boylan, Ashton-Miller, & Wojtys, 2003). This device is constructed so that a fulcrum is placed along the medial border of the outer sole, which ensures a laterally deviated subtalar joint axis of rotation in relation to the vertical ground reaction force vector, to create a dynamic inversion perturbation during ground contact (Knight & Weimar, 2012a; Ubell et al., 2003). Additionally, this allows researchers to assess biomechanical and neuromechanical parameters of ankle stability during dynamic forced subtalar inversion when landing in the unilateral stance, which is a commonly reported mechanism of injury in many sports (Doherty et al., 2016b).

*Figure 11.* Outer sole with fulcrum method (Simpson et al., 2017).

Ubell et al. (2003) was the first to use the fulcrum device during a dynamic landing task in which participants were instructed to prevent subtalar inversion upon landing in the unilateral stance. The authors constructed detachable outer soles, which...
were made of aquaplast, to fit and attach to the plantar aspect of a low-top athletic shoe. A 6 mm wide fulcrum, which was 27 mm in height, was placed 20 mm medial to the midline along the length of the outer sole to create a dynamic inversion perturbation of 24° upon landing from a 60 cm forward jump off the contralateral limb. In addition to the outer sole with a fulcrum, an outer sole with a flat bottom was also constructed to prevent the participants from anticipating the inversion perturbation upon landing (Ubell et al., 2003). This study examined the influence of three commonly used prophylactic ankle supports (i.e. soft, semi-rigid, and rigid) on success rates to prevent dynamic forced subtalar inversion upon landing in healthy male participants. The main findings from the study were that the rigid and semi-rigid prophylactic ankle supports yielded the highest success rates of preventing forced subtalar inversion of 46% and 52%, respectively, in comparison to no brace (18%) and soft brace conditions (34%; Ubell et al., 2003).

While the outer sole with fulcrum used in this study was novel, the authors did not examine any biomechanical or neuromuscular parameters during the dynamic inversion perturbation (Ubell et al., 2003). Knight and Weimar (2012a) modified the initial outer sole with fulcrum design to have a fulcrum that was 30 mm in height, which created a dynamic inversion perturbation of 25° upon landing from a step-down task. A series of studies were conducted by the authors using this modified outer sole with fulcrum (Knight & Weimar, 2011a, 2011b, 2012b, 2013). The purpose of these studies was to investigate the influence of limb dominance and ankle taping on temporal and neuromuscular variables during a dynamic inversion perturbation of 25° upon landing in individuals with and without a history of an ankle sprain. In these studies, participants had an outer sole with a fulcrum or an outer sole with a flat bottom attached to the bottom
of their shoe in a randomized fashion prior to stepping down from a height of 27 cm. This was done by the authors in attempt to prevent any anticipatory landing mechanics from the participants to the outer sole with fulcrum (Knight & Weimar, 2011a, 2011b, 2012b, 2013).

One study by Knight and Weimar (2011b) examined the peroneus longus and peroneus brevis latency using a 5 standard deviation threshold, as well as time to maximum inversion, during an unexpected inversion perturbation of 25° in participants with a history of a lateral ankle sprain, high ankle sprain, and no history of an ankle sprain. The authors reported that there were no significant differences between groups in latency of the peroneus longus and peroneus brevis, as well as no significant differences in time to complete the inversion perturbation (Knight & Weimar, 2011b). However, another study conducted by the authors using the outer sole with fulcrum method examined the impact of ankle taping on the latency of the peroneus longus using a 10 standard deviation threshold in individuals with and without a history of a lateral ankle sprain (Knight & Weimar, 2012b). Although the authors reported no significant injury group by ankle support (ankle tape vs. no ankle tape) interaction or main effect for injury group, significant reductions in peroneus longus latency across groups was observed when completing the dynamic inversion perturbation in an ankle taped condition. This led the authors to conclude that regardless of having a lateral ankle sprain injury history or lack thereof, applying adhesive tape to the ankle could improve proprioceptive input resulting in a reduction in the latency of the primary evertor of the ankle complex (Knight & Weimar, 2012b).
An additional study conducted by Knight and Weimar examined the effects of a limb dominance, previous lateral ankle sprain injury, and ankle taping on temporal variables during a simulated lateral ankle sprain (Knight & Weimar, 2012a). This study also utilized the outer sole with fulcrum to create a dynamic inversion perturbation of 25° upon landing from a height of 27 cm to measure time to maximum inversion and mean inversion speed, as well as the reliability and validity of these temporal measurements. Although there were no significant differences in time to maximum inversion and mean inversion speed across injury group, leg, or ankle support, this study demonstrated that the outer sole with fulcrum device demonstrated good reliability and construct validity for the temporal variables measured, further supporting the use of this device in the laboratory to replicate the mechanism of injury to study lateral ankle sprain mechanics (Knight & Weimar, 2012a).

While other studies have utilized this device to simulate the mechanism of a lateral ankle sprain to investigate the impact of limb dominance (Knight & Weimar, 2011a, 2013), fatigue and footwear (Simpson et al., 2017) in healthy adult populations, it appears that no empirical studies have been conducted using this device in CAI cohorts. Given that many lateral ankle sprains occur in open kinetic chain movements, such as landing in the unilateral stance from a jump, this device provides a suitable alternative to examine the underlying biomechanical and neuromechanical mechanisms and landing mechanics that could potentially be associated with recurrent lateral ankle sprains in CAI populations. Utilizing this device may possibly advance the current scientific knowledge of researchers and clinicians interested in mitigating recurrent lateral ankle sprains in populations with ankle pathology, specifically those affected by CAI.
**Tilted Surface**

An additional method that has received increasing attention in the literature recently is drop landings on a tilted surface (Ha et al., 2015). Much like the outer sole with fulcrum, this method allows for unexpected subtalar inversion, or a combination of subtalar inversion and talocrural plantar flexion, upon landing from a jump or step-down task to safely replicate the mechanism of a lateral ankle sprain (Dicus & Seegmiller, 2012; Fu et al., 2014; Sato et al., 2017). In brief, participants are instructed to stand on a platform that is raised above the landing surface and step or jump down and land on a flat or inverted platform (Figure 12). Inverted platforms used in the literature typically vary from 15° to 30° of inversion (Fu et al., 2014; Sato et al., 2017; Theodorakos et al., 2016), while other platform designs have combined both subtalar inversion and plantar flexion to safely replicate the actual mechanism of a lateral ankle sprain (Bhaskaran et al., 2015; Fu et al., 2014).

*Figure 12.* Tilted surface method.
The literature regarding drop landings on a tilted surface appear to be limited in CAI populations (Levin et al., 2015; Li et al., 2018). A recent study conducted by Li et al. (2018) investigated the differences in ankle and knee muscle activation between female individuals with CAI and healthy matched controls during bilateral drop landings on a tilted surface. This study analyzed muscle activity from the tibialis anterior, gastrocnemius lateralis, peroneus longus, biceps femoris, rectus femoris and vastus lateralis. Muscle activity from these muscles was analyzed during the preparatory phase of landing, which was defined as 50 ms prior to initial contact, and during the first 100 ms after initial ground contact when landing from the jump. Participants completed bilateral drop landings from a height of 30 cm with the testing limb contacting the inverted surface, which was rotated 25° in the frontal plane, and the contralateral limb contacting a flat platform placed beside the inverted surface. It was reported by the authors that during the preparatory phase of the drop landing significantly less peroneus longus but, significantly greater gastrocnemius lateralis muscle activity was present in the CAI group when compared to control subjects (Li et al., 2018). An additional finding during the preparatory phase of the drop landing was that the co-contraction index was significantly greater in the frontal plane in the CAI group when compared to controls. In regards to the landing phase, CAI participants had a significantly greater amount of tibialis anterior, rectus femoris, and vastus lateralis activation in comparison to the healthy controls. The authors concluded that the decrease in peroneus longus activation during the preparatory phase of landing on the inverted surface may increase the risk of the ankle giving way, further supporting the notion of altered feed-forward motor control in individuals with CAI. Furthermore, increased tibialis anterior activation during landing
likely contributed to the altered muscle activation of the more proximal muscles, such as the rectus femoris and vastus lateralis, which may have implications for atypical knee joint loading and biomechanics in female individuals affected by CAI (Li et al., 2018).

Another study examining neuromuscular control strategies during landing on an inverted surface in CAI subjects was conducted by Levin and colleagues (Levin et al., 2015). In this study, the authors examined muscle activity during bilateral drop landings from the tibialis anterior, peroneus longus, gastrocnemius medialis, and gluteus medius from 200 ms pre-initial contact to 300 ms post-initial contact. The bilateral drop landing task consisted of participants standing on a platform that was raised 20 cm above a flat and tilted surface of 25°. During the drop landing, participants were required to land with the testing limb on the tilted surface and the contralateral limb on the flat surface. Participants completed a series of 40 trials under the following conditions: 10 trials had a 0% chance to invert the testing limb; 20 trials had a 50% chance to invert the testing limb (i.e. 10 flat and 10 inverted trials); and 10 trials with 100% chance to invert the testing limb. In this study, participants were made aware of the drop landing conditions, but did not have knowledge as to when the platform would be inverted. Although no significant differences between groups for the testing limb side were reported, the main finding in this study was that individuals with CAI demonstrated significantly increased preparatory peroneus longus and gastrocnemius medialis muscle activity on the contralateral limb prior to contacting the flat landing surface during the 50% and 100% chance of inversion landing conditions (Levin et al., 2015). In addition, during the post-initial contact phase of all test conditions (i.e. 0%, 50%, and 100% chance of inversion) the CAI group demonstrated significantly less activity in the peroneus longus and gastrocnemius
medialis, as well as significant reductions in activity of the gluteus medius on the affected limb. The authors suggested that increased preparatory muscle activity in the contralateral limb of the CAI participants, especially when there is potential for an ankle inversion perturbation, was a protective landing strategy. More specifically, this protective strategy was adopted and intended to shift reliance of attenuating the biomechanical loads during ground contact to the non-affected limb, which was suggested to further protect the affected limb completing a bilateral landing on an inverted surface (Levin et al., 2015). These findings indicate central adaptations to neuromuscular landing strategies may become altered in CAI subjects when there is knowledge of a potential destabilizing perturbation (Levin et al., 2015). However, there is very minimal scientific evidence that supports these findings and that has further explored the anticipated landings in CAI cohorts.

**Anticipation to Inversion Perturbations**

Over the years, ankle sprain mechanics have been extensively studied using a wide variety of methodologies. However, replicating the rapid and unexpected nature of an actual lateral ankle sprain injury using laboratory simulations is difficult and has previously been cited as a major limitation when studying ankle sprain mechanics (Dicus & Seegmiller, 2012). Anticipation to inversion perturbations can confound biomechanical data and prohibit researchers in clinicians from accurately assessing the underlying mechanisms associated with ankle inversion injuries (Dicus & Seegmiller, 2012; Gutierrez et al., 2012; Ha et al., 2015; Hertel, 2008). Previous studies that have attempted to control for anticipatory responses to inversion perturbations during drop landings have reported significant changes in preparatory and reactive muscle activation, spatial, and
temporal variables of ankle stability (Dicus & Seegmiller, 2012; Gruneberg et al., 2003; Gutierrez & Kaminski, 2010; Gutierrez et al., 2012; Levin et al., 2015). Findings from these studies supports the notion that a cognitive awareness to potential ankle joint perturbations could alter motor control strategies that results in increased dynamic joint stabilization. As such, methodologies that examine anticipatory motor control strategies to ankle inversion perturbations will provide researchers and clinicians the opportunity to further evaluate landing mechanics that may be associated with recurrent lateral ankle sprains (Dicus & Seegmiller, 2012; Gruneberg et al., 2003; Gutierrez et al., 2012; Levin et al., 2015).

Dicus and Seegmiller (2012) examined biomechanical and neuromuscular parameters during unanticipated and anticipated unilateral drop landings on a tilted surface in healthy collegiate male and female participants. Although no differences between male and female participants were reported, significant reductions in peroneus longus latency during the anticipated landing condition was reported. Additionally, significant reductions in spatial and temporal values of ankle inversion velocity, ankle inversion angle, and peak vertical ground reaction force were also evident during the anticipated landing condition. The findings from this study indicates that anticipation to inversion perturbations is one main factor that can alter biomechanical outcomes when studying lateral ankle sprain mechanics (Dicus & Seegmiller, 2012).

While anticipation to inversion perturbations during open kinetic chain movements has resulted in significant differences in biomechanical and neuromechanical outcomes in healthy participants (Dicus & Seegmiller, 2012; Gruneberg et al., 2003; Nieuwenhuijzen & Duysens, 2007), limited literature exists concerning the anticipatory
landing strategies in individuals affected by CAI (Gutierrez et al., 2012; Levin et al., 2015). The findings from Levin and colleagues indicate that individuals with CAI demonstrate an altered motor control strategy, which resulted in reduced muscle activity on the affected limb but greater muscle activity on the contralateral limb, with the knowledge of a potential inversion perturbation during a bilateral drop landing (Levin et al., 2015). However, another study examining bilateral drop landings onto a supinating device reported that individuals with CAI demonstrated an increased preparatory muscle activity in the peroneus longus (Gutierrez et al., 2012), which opposes previous findings (Levin et al., 2015). It is possible that the methodological differences utilized in each study may explain the differences in results. However, it appears based on the limited literature available regarding anticipatory responses to ankle inversion perturbations in CAI cohorts that an altered neuromuscular control strategy may be adopted to further protect the injured limb from a potentially injurious situation when executing a drop landing (Dicus & Seegmiller, 2012; Gutierrez et al., 2012; Levin et al., 2015).

**Methodological Limitations**

The primary methodological limitation, regardless of device and/or methodological approach, is that researchers and clinicians are limited to investigating ankle sprain mechanics using controlled laboratory simulations (Ha et al., 2015). Although the most direct way to examine ankle sprain mechanics is to analyze the injury mechanisms during real-time incidents, these studies not possible to conduct. With this limitation in mind, research has led to the design and development of experimental methodologies in which biomechanical data can be extrapolated to dynamic movements
that initiate the actual mechanism(s) of a lateral ankle sprain (Dicus & Seegmiller, 2012; Gutierrez & Kaminski, 2010; Knight & Weimar, 2012a). Furthermore, this has advanced the scientific knowledge of researchers and clinicians regarding the underlying mechanisms that contribute to recurrent lateral ankle sprains (Hertel, 2008).

Another methodological limitation, particularly in studies that utilize a trapdoor device, is that a lateral ankle sprain typically does not occur in a closed kinetic chain when the floor unexpectedly falls away beneath an individual standing in a static bilateral stance (Dicus & Seegmiller, 2012; Ha et al., 2015; Hopkins et al., 2007; Knight & Weimar, 2012a). Although the development of these devices was novel and provided valuable information regarding ankle sprain mechanics, these devices are limited in scope because they do not allow for the examination of open kinetic chain movements, such as landing from a jump, nor can the biomechanical and neuromuscular data be extrapolated to such movements (Dicus & Seegmiller, 2012; Gruneberg et al., 2003). As such, these devices have been implemented into walkways (Gruneberg et al., 2003; Hopkins et al., 2007; Midgley et al., 2007) and landing platforms (Gutierrez & Kaminski, 2010; Gutierrez et al., 2012) to further expand upon initial design of the trapdoor to examine open kinetic chain movements. However, Gutierrez and colleagues reported that by using a trapdoor device in a landing platform that initiation of the inversion perturbation did not occur until 30-50 ms post-landing (Gutierrez & Kaminski, 2010; Gutierrez et al., 2012).

Although the authors’ device did result in ankle supination post-landing, the main limitation to the use of this device is that lateral ankle sprains, even during open kinetic chain movements, do not occur when the floor unexpectedly falls away beneath an individual. Furthermore, the authors conceded that a force platform could not be
incorporated into the design of this device (Gutierrez & Kaminski, 2010). Unfortunately, a kinetic analysis, which is crucial when studying ankle sprain mechanics, cannot be conducted using this device and severely limits the application of this device in controlled laboratory research.

Finally, as discussed previously, replicating the rapid and unexpected nature of an actual lateral ankle sprain injury using laboratory simulators is difficult and consistently cited as a major limitation (Dicus & Seegmiller, 2012). Anticipation to inversion perturbations can confound biomechanical data and prohibit researchers in clinicians from accurately assessing the underlying mechanisms associated with ankle inversion injuries (Dicus & Seegmiller, 2012; Gutierrez et al., 2012; Ha et al., 2015; Hertel, 2008). Thus, researchers and clinicians are presented with a considerable challenge to create empirical methodologies that create unexpected perturbations and control for anticipation these perturbations. If experimental methodologies can be developed that control for and examine anticipatory responses to inversion perturbations, researchers and clinicians will be able to accurately assess landing mechanics that initiate the actual mechanism of injury and further expand upon the high rates of recurrent lateral ankle sprains (Dicus & Seegmiller, 2012; Doherty et al., 2016b; Hertel, 2002, 2008).

**Summary**

Previous literature provides evidence that impairments in proprioception and neuromuscular control in CAI populations have resulted in prolonged peroneal latency and altered neuromuscular control during inversion perturbations (Donahue et al., 2014; Gutierrez et al., 2012; Hertel, 2008; Hiller et al., 2011; Konradsen & Ravn, 1990, 1991; Levin et al., 2015; Li et al., 2018; Lofvenberg et al., 1995; Vaes et al., 2001). Although
limited literature exists regarding drop landings on tilted surfaces and the influence of anticipation to ankle inversion perturbations in CAI populations, it appears that when individuals have the knowledge of a potential destabilizing perturbation that a protective motor control strategy is adopted to further protect the limb from subsequent injury (Dicus & Seegmiller, 2012; Gruneberg et al., 2003; Gutierrez et al., 2012; Levin et al., 2015). The findings by previous researchers investigating anticipated and unanticipated landings on tilted surfaces (Dicus & Seegmiller, 2012; Gutierrez et al., 2012; Levin et al., 2015) have assisted in the development of the experimental methodology that will be employed as part of this dissertation project. While much is still unknown about alterations in neuromuscular control in anticipation to inversion perturbations in CAI populations, especially during unilateral landings, part of this dissertation project will be to further investigate neuromuscular control during unexpected and expected unilateral landings on a tilted surface that simulates the mechanism of a lateral ankle sprain. This will be conducted in hopes to further the current scientific knowledge regarding anticipatory landing mechanisms that individuals with CAI adopt to further reduce their risk of recurrent injury.

**Dynamic Postural Stability**

Postural stability during unilateral jump-landings have been utilized to assess the sensorimotor impairments that are associated with CAI (Brown et al., 2004; Gribble & Robinson, 2010; Gribble & Robinson, 2009; Ross & Guskiewicz, 2004; Ross et al., 2005; Wikstrom et al., 2007; Wikstrom et al., 2010c; Wright et al., 2016). Quantifying postural stability during dynamic tasks such as a jump-landing has been extensively studied to further elucidate the postural stability deficits that manifest from functional and
mechanical insufficiencies in CAI populations. A variety of methods have been utilized in previous research to quantify postural stability in individuals with lower extremity injuries, particularly lateral ankle sprains (Ross & Guskiewicz, 2003; Wikstrom, Tillman, Smith, & Borsa, 2005). Time to stabilization (TTS) and the Dynamic Postural Stability Index (DPSI) are commonly used methods to quantify postural stability during dynamic movements and to screen individuals with CAI for potential deficits in lower extremity movement mechanics that could potentially result in recurrent injuries to the lower extremity (Ross & Guskiewicz, 2003; Wikstrom et al., 2005). Therefore, the purpose of this section will be to: (1) review investigations that have assessed dynamic postural stability using TTS in CAI populations, (2) review investigations that have assessed dynamic postural stability using DPSI in CAI populations, and (3) to discuss how methods used to quantify dynamic postural stability can be applied to functional exercises, such as the single leg squat, that are commonly used in physical therapy and rehabilitation programs.

**Time to Stabilization**

A commonly utilized method to examine dynamic postural stability during jump-landing tasks is by calculating a TTS (Ross & Guskiewicz, 2003). Time to stabilization is used to evaluate the amount of time, which is measured in seconds (s), it takes an individual to stabilize and dissipate ground reaction forces following a jump-landing in the unilateral stance on the affected limb. Unilateral anterior stop jump and drop landings have been used to assess TTS between CAI and healthy controls (Brown et al., 2004; Gribble & Robinson, 2010; Gribble & Robinson, 2009; Ross & Guskiewicz, 2003; Ross & Guskiewicz, 2004; Ross et al., 2005; Wright et al., 2016). Participants are instructed to
land in the unilateral stance on the affected limb from an anterior stop jump on a force platform and remain as still as possible while maintaining their balance for 20 s. The anterior/posterior and medial/lateral components of the ground reaction force are used to calculate a TTS in each direction (Ross & Guskiewicz, 2003). Each component of the ground reaction force is then analyzed in two separate time windows of 10-15 s and 15-20 s to determine the smallest absolute ground reaction force, which is then selected as the optimal range-variation value. The optimal range-variation value is then superimposed over the rectified ground reaction forces and an unbounded third-order polynomial is fitted to the anterior/posterior and medial/lateral components of the ground reaction force. Each component of the TTS is then determined by the point at which the unbounded third-order polynomial intersects with the optimal range-variation line on the force-time graph (Figure 13; Ross & Guskiewicz, 2003).

*Figure 13.* Time to stabilization (TTS) calculation from the force-time graph (Ross & Guskiewicz, 2003).
Several studies have implemented this method to examine potential dynamic postural stability deficits in CAI populations (Brown et al., 2004; Gribble & Robinson, 2010; Gribble & Robinson, 2009; Ross & Guskiewicz, 2004; Ross et al., 2005; Wright et al., 2016). Ross and colleagues first examined TTS during a unilateral anterior stop jump task in individuals with and without CAI in two separate studies (Ross & Guskiewicz, 2004; Ross et al., 2005). The unilateral anterior stop jump task used in both studies consisted of a 0.7 m jump in the anterior direction, which required participants to touch a target placed at 50% of their maximal vertical jump height, and land in the unilateral stance with their affected limb on a force platform and balance for 20 s. The authors reported that individuals in the CAI group demonstrated significantly longer TTS in both the anterior/posterior and medial/lateral directions, indicating deficits in dynamic postural stability (Ross & Guskiewicz, 2004; Ross et al., 2005). Another study that examined TTS during a unilateral anterior stop jump task reported that individuals with CAI had significantly longer TTS in the anterior/posterior direction, but no between group differences were noted for medial/lateral TTS (Brown et al., 2004). While Brown et al. (2004) did not find differences in medial/lateral TTS, consistent reports of deficits in anterior/posterior TTS suggests an inability for individuals with CAI to control accelerations of the center of mass in the sagittal plane when landing into a unilateral stabilized stance (Brown et al., 2004; Ross & Guskiewicz, 2004; Ross et al., 2005). Although lower extremity kinematics were not collected in these studies, it was speculated that differences in landing movement strategies between the groups examined may have also been a causative factor of the increase TTS in the anterior/posterior direction (Ross et al., 2005).
To further expand upon the speculation by Ross and colleagues (Ross & Guskiewicz, 2004; Ross et al., 2005) that altered lower extremity kinematics were linked to prolonged TTS, other studies examining TTS during jump-landings have examined ankle, knee and/or hip kinematic patterns to further elucidate findings from initial studies examining dynamic postural stability in individuals affected by CAI (Gribble & Robinson, 2010; Gribble & Robinson, 2009; Wright et al., 2016). A study conducted by Gribble and Robinson (2009) examined the differences in ankle, knee, and hip kinematics in addition to medial/lateral and anterior/posterior TTS between individuals with and without CAI during an anterior stop jump task. The authors reported sagittal plane ankle, knee, and hip angles at initial ground contact for both the affected and unaffected limb of the CAI group and the matched limbs of the control group. No differences in ankle or hip sagittal plane angles at initial ground contact were reported for limb or group. However, the CAI group demonstrated significantly greater knee extension at initial ground contact on both the affected limb and unaffected limb in comparison to controls. Consequently, significantly longer TTS in the anterior/posterior direction was also observed for the CAI group, but only on the affected limb in comparison to controls (Gribble & Robinson, 2009). It was concluded by the authors that greater knee extension during initial ground contact demonstrated by the CAI group could have resulted in a higher center of mass when landing, leading to a longer time to dissipate and control anterior/posterior ground reaction forces and ultimately reductions in dynamic postural stability (Gribble & Robinson, 2009).

Another study conducted by Gribble and Robinson (2010) further expanded upon their initial findings by examining ankle, knee, and hip kinematics 100 ms prior to ground
contact, peak and time to peak ankle, knee and hip angles during an anterior stop jump task between CAI and matched control groups (Gribble & Robinson, 2010). In addition to lower extremity kinematics, a resultant vector TTS was calculated by taking the square root of the sum of the squared anterior/posterior and medial/lateral TTS values, respectively. In this study, the CAI group demonstrated a significantly greater value of the resultant vector TTS indicating deficits in dynamic postural stability. Regarding kinematics, no significant differences were reported for the ankle and hip 100 ms prior to initial contact, peak or time to peak ankle and hip angles. Although no significant differences in ankle and hip kinematics were observed, significantly greater knee extension 100 ms prior to initial contact was noted in the CAI group (Gribble & Robinson, 2010). These findings in combination with the results from Gribble and Robinson (2009) would suggest that the kinematic alterations in the proximal segments prior to ground contact could potentially be a causative factor to the reductions in dynamic postural stability on the affected limb in individuals with CAI (Gribble & Robinson, 2010; Gribble & Robinson, 2009).

It is worth nothing that a recent study conducted by Wright et al. (2016) examined anterior/posterior and medial/lateral TTS, in addition to ankle kinematics at initial ground contact, during a unilateral drop landing from a height of 40 cm in CAI, ankle sprain coper, and control groups (Wright et al., 2016). While previous studies examining anterior stop jump tasks have not reported any significant differences in ankle kinematics or medial/lateral TTS (Gribble & Robinson, 2010; Gribble & Robinson, 2009), this study reported that individuals with CAI demonstrated significantly greater ankle dorsiflexion at initial ground contact and significantly longer medial/lateral TTS when compared to
ankle sprain copers and healthy matched controls (Wright et al., 2016). Although it does appear based on these studies that significant impairments in dynamic postural stability are evident in CAI cohorts using the TTS method, the specific kinematic adaptations resulting in such impairments are likely linked to the requirements of the jump-landing task utilized across studies (Brown et al., 2004; Gribble & Robinson, 2010; Gribble & Robinson, 2009; Wright et al., 2016). Therefore, it is likely the differences in findings regarding lower extremity kinematics and TTS between studies could be attributed to the nature of the jump-landing task used to examine dynamic postural stability (Brown et al., 2004; Gribble & Robinson, 2010; Gribble & Robinson, 2009; Wright et al., 2016).

**Dynamic Postural Stability Index**

Another commonly used method to quantify postural stability during dynamic tasks is the DPSI method (Wikstrom et al., 2005). This index was created due to the limitations of the TTS method that has been used in previous studies to quantify dynamic postural stability. One major limitation to the TTS method is that it only accounts for forces in two directions, anterior/posterior and medial/lateral, but objectively assessing forces in three directions may provide valuable insight to directional postural stability deficits. Additionally, determining differences between healthy and injured groups is difficult because the baseline measures allow for unequal group comparisons that may make it difficult to detect meaningful differences in postural stability (Wikstrom, Tillman, Schenker, & Borsa, 2008; Wikstrom et al., 2005). Given these mentioned limitations, Wikstrom and colleagues developed the DPSI method that assesses the mean square deviation that around a zero point, rather than assessing the standard deviation around a group mean (Wikstrom et al., 2005). These mean square deviations are
calculated from each component of the ground reaction force, which are standardized to participants’ body weight, to examine fluctuations in the medial/lateral (MLSI), anterior/posterior (APSI), and vertical (VSI) directions. A composite score (DPSI) of the MLSI, APSI, and VSI is also calculated to assess the resultant changes from each of the directions (Equations 1-4; Wikstrom et al., 2005). Hence, greater values of MLSI, APSI, VSI, and DPSI indicate decreased postural stability in that direction, respectively.

\[
MLSI = \sqrt{\frac{\sum (0 - GRFx(BW))^2}{\text{number of data points}}} \tag{1}
\]

\[
APSI = \sqrt{\frac{\sum (0 - GRFy(BW))^2}{\text{number of data points}}} \tag{2}
\]

\[
VSI = \sqrt{\frac{\sum (1 - GRFz(BW))^2}{\text{number of data points}}} \tag{3}
\]

\[
DPSI = \sqrt{\frac{\text{MLSI} + \text{APSI} + \text{VSI}}{\text{number of data points}}} \tag{4}
\]

A study conducted by Wikstrom and colleagues examined dynamic postural stability using the DPSI method during an anterior jump-landing task in individuals with and without CAI (Wikstrom et al., 2007). The jump-landing task consisted of jumping in the anterior direction 0.7 m while touching a target placed at 50% of the participants’ maximal vertical jump height and landing with the affected limb on a force platform and maintaining balance as still as possible for 10 s. The authors calculated MLSI, APSI, VSI, and a composite DPSI score during the unilateral jump-landing. While MLSI was not found to be significantly different between groups, individuals with CAI demonstrated significantly greater APSI, VSI, and DPSI scores compared when compared to healthy matched controls (Wikstrom et al., 2007). An additional study conducted by the authors examined the differences in dynamic postural stability using the DPSI method between ankle sprain copers, CAI, and healthy matched controls using the same anterior jump-landing task (Wikstrom et al., 2010c). The main findings from this
study were that both the ankle sprain copers and CAI individuals demonstrated significantly greater APSI and DPSI scores in comparison to controls, which supported the previous findings (Wikstrom et al., 2007; Wikstrom et al., 2010c). In addition, the authors also reported that individuals with CAI demonstrated a greater MSLI score when compared to ankle sprain copers.

Previous research has also suggested that jump-landing direction can influence postural stability scores using the DPSI method (Wikstrom et al., 2008). In this study, the authors examined dynamic postural stability during jump-landings in the anterior, diagonal, and lateral directions in healthy subjects. Results from this investigation showed that MLSI and VSI scores were significantly influenced by the jump direction. Specifically, the lateral and diagonal jump-landing tasks significantly increased the MLSI and VSI scores, while the anterior jump-landing task also produced a significantly greater VSI score compared to the other directions (Wikstrom et al., 2008). The findings from this study indicated that jump-landing direction does have an influence DPSI measures in healthy populations, which could also influence on DPSI measures in individuals a history of lower extremity injury. Further expanding upon these findings, a study was conducted by Brown et al. (2010) examining the influence of jump-landing direction on dynamic postural stability using the DPSI method between CAI and healthy matched controls (Brown, Bowser, & Orellana, 2010). Jump-landings were completed in the anterior, medial, and lateral directions. It was found that individuals with CAI demonstrated significantly greater VSI and DPSI scores in the anterior and lateral jump-landing directions. However, no differences were found in MLSI, APSI, VSI, or DPSI between groups for jump-landings in the medial direction (Brown et al., 2010).
There is evidence of dynamic postural stability deficits as measured by TTS and DPSI among individuals with CAI (Brown et al., 2004; Brown et al., 2010; Gribble & Robinson, 2010; Gribble & Robinson, 2009; Ross & Guskiewicz, 2004; Ross et al., 2005; Wikstrom et al., 2007; Wikstrom et al., 2010c; Wright et al., 2016). A point worth discussing is that it appears that the type of jump-landing task can influence dynamic postural stability, especially in CAI participants. While researchers have attributed deficits in dynamic postural stability during unilateral jump-landings in individuals with CAI to altered motor control strategies and sensorimotor impairments, it seems logical to postulate that the differences in findings across studies is likely attributed to the jump-landing protocols (Brown et al., 2010; Wikstrom et al., 2008). A unilateral anterior stop jump task requires an individual to propel their center of mass in the anterior direction, land in the unilateral stance on the affected limb, and stabilize for a given period of time (Ross & Guskiewicz, 2003; Wikstrom et al., 2005). Therefore, a greater reliance is placed on the individual to control the acceleration of the center of mass within the limits of stability predominantly in the anterior/posterior direction, rather than the medial/lateral direction. In contrast, a drop landing requires an individual to control the acceleration of the center of mass within the limits of stability predominantly in the medial/lateral and vertical directions.

Studies quantifying dynamic postural stability using TTS have reported that individuals with CAI demonstrate significant increases in anterior/posterior TTS while no differences were reported in medial/lateral TTS (Gribble & Robinson, 2010; Gribble & Robinson, 2009). However, Wright et al. (2016) did not report differences in anterior/posterior TTS but did report differences in medial/lateral TTS between CAI and
control groups (Wright et al., 2016). The main difference between these studies quantifying dynamic postural stability using TTS is the jump-landing protocol used. Most studies have utilized an anterior jump-landing task, while only one study has utilized a drop landing (Wright et al., 2016). These two dynamic tasks place different demands on the motor control system and given the potential sensorimotor and mechanical constraints that are present in individuals affected by CAI, differences in jump-landing protocols may elicit different movement adaptations that could explain the differences in results between studies (Gribble & Robinson, 2010; Gribble & Robinson, 2009; Wright et al., 2016).

Regarding studies which examine dynamic postural stability using the DPSI method, all investigations have examined dynamic postural stability during an anterior jump-landing task (Brown et al., 2010; Wikstrom et al., 2007; Wikstrom et al., 2010c). These studies have consistently reported greater APSI, VSI, and DPSI scores in CAI participants compared to controls. However, the study conducted by Brown et al. (2010) did not report the same findings for a lateral or medial jump-landing task (Brown et al., 2010). Many researchers have speculated that centrally mediated changes in neuromuscular control can manifests as alterations in the positioning of the more proximal segments during ground contact, resulting in significant decrements in dynamic postural stability (Brown et al., 2010; Gribble & Robinson, 2010; Gribble & Robinson, 2009; Wikstrom et al., 2007; Wikstrom et al., 2010c; Wright et al., 2016). However, only a limited number of investigations have examined the association between lower extremity kinematics and dynamic postural stability, making it difficult to conclude that deficits in dynamic postural stability during jump-landing tasks are directly linked to
alterations in lower extremity kinematic patterns (Gribble & Robinson, 2010; Gribble & Robinson, 2009; Wright et al., 2016).

**Functional Exercises**

Several methods of assessing proprioceptive, neuromuscular, and strength deficits have been implemented in CAI populations (Hertel, 2008; Hiller et al., 2011). Functional tests such as unilateral static balance, the SEBT, and the Y Balance Test™ have been commonly used to detect deficits in dynamic balance in individuals affected by CAI (McKeon & Hertel, 2008a; Olmsted et al., 2002; Plisky et al., 2009; Wikstrom et al., 2010a). These functional tests require the combination of somatosensory, visual, and vestibular afferent information combined with adequate efferent responses to control the center of mass within the limits of stability to maintain balance (Hertel, 2008). Researchers and clinicians have used a variety of instrumented and non-instrumented methods during functional exercises to evaluate the sensorimotor impairments associated with CAI (Hiller et al., 2011; McKeon & Hertel, 2008b).

Unilateral static balance has been extensively studied in CAI populations (Arnold et al., 2009; McKeon & Hertel, 2008b, 2008c). However, there have been inconsistent results regarding the use of traditional center of pressure (COP) excursion measures to detect deficits in unilateral static balance (Hiller et al., 2011; McKeon & Hertel, 2008b). Additional measures of time to boundary (TTB), which calculates the time it would take the instantaneous COP velocity to reach the anterior/posterior or medial/lateral limits of stability given it stays on that respective trajectory, have been previously used to identified deficits in unilateral postural stability more consistently (Hertel & Olmsted-Kramer, 2007; Hertel, Olmsted-Kramer, & Challis, 2006b; McKeon & Hertel, 2008a).
Studies that have quantified unilateral static balance using TTB have reported that individuals with CAI demonstrate a significantly reduced TTB (Hertel & Olmsted-Kramer, 2007; McKeon & Hertel, 2008a). Researchers have suggested that the constraints of CAI placed on the sensorimotor system results in a global reorganization of postural control strategies in the unilateral stance (Hertel, 2008; McKeon & Hertel, 2008a). Consequently, this potentially impairs the ability to effectively respond to external perturbations while maintaining the center of mass within the limits of stability (Hertel et al., 2006b).

While commonly utilized as an exercise in physical therapy and rehabilitation programs to mitigate sensorimotor impairments following a lateral ankle sprain (Donovan & Hertel, 2012), the SEBT and Y Balance Test™ are also commonly used methods to assess impairments in dynamic balance, lower extremity movement patterns and predict lower extremity injury potential (Gribble, Hertel, & Plisky, 2012; Olmsted et al., 2002; Plisky, Rauh, Kaminski, & Underwood, 2006). These clinical tests also allow researchers and clinicians to examine joint range of motion, strength, proprioception, and neuromuscular control during a functional movement to detect any deficits related to CAI (Gribble et al., 2012). In brief, the SEBT requires an individual to stand in the unilateral stance on the testing limb, reach with their contralateral limb in eight different directions as far as possible, touch a marked line, and return to the stance limb without losing their balance while reach distance is recorded (Olmsted et al., 2002). In a more simplified version, the Y Balance Test™ requires the same sequence of tasks, but only requires participants to reach in three different directions instead of eight (Plisky et al., 2009). Both the SEBT and Y Balance Test™ have been identified to be reliable and valid.
clinical screening tools to identify the impairments related to CAI (Gribble et al., 2012; Hale, Hertel, & Olmsted-Kramer, 2007; Olmsted et al., 2002).

The impact of CAI on reach distance during the SEBT has been extensively studied over the years in several different conditions (Gribble et al., 2012). Consistent reports of significant reach deficits during the SEBT in individuals with CAI in comparison to uninjured controls have been reported (Akbari, Karimi, Farahini, & Faghihzadeh, 2006; Gribble, Hertel, Denegar, & Buckley, 2004; Hale et al., 2007; Hertel, Braham, Hale, & Olmsted-Kramer, 2006a; Olmsted et al., 2002). A study conducted by Olmsted and colleagues (2004) was the first to report deficits in total reach distance during the SEBT, which was calculated as the sum of the distance in all eight directions, between individuals with and without CAI. The authors reported that participants with CAI performed significantly worse on their affected limb in comparison to their uninjured limb, as well as compared to the total reach distance of the matched limb of the control group (Olmsted et al., 2002). Several studies have reported significant reach deficits in the anterior, medial, posterior, lateral, posteromedial, and posterolateral directions on the injured limb when compared to the non-injured limb of CAI participants (Akbari et al., 2006; Gribble et al., 2004; Gribble et al., 2012), while also reporting significant performance deficits on the SEBT in comparison to healthy matched controls (Hertel et al., 2006a; Nakagawa & Hoffman, 2004).

It appears based on the evidence regarding performance on the SEBT that individuals with CAI demonstrate significant reductions in reach distance, indicating dynamic stability deficits (Gribble et al., 2012). Although these deficits may be attributed to the sensorimotor impairments related to CAI (Hertel, 2008), some researchers have
suggested that reduced lower extremity joint range of motion may also influence reach distance on the SEBT (Gribble et al., 2004; Gribble et al., 2012; Hoch, Staton, & McKeon, 2011; Hubbard & Hertel, 2006). More specifically, reductions in ankle dorsiflexion range of motion have been attributed to reach deficits on the SEBT, most notably in the anterior direction (Hoch et al., 2011). Additionally, reductions in ankle sagittal plane range of motion when reaching in the anterior direction has also been shown to alter proximal segment sagittal plane range of motion at the knee and hip (Gribble, Hertel, & Denegar, 2007; Gribble et al., 2004; Gribble et al., 2012). This has been supported by Gribble and colleagues who found that individuals with CAI demonstrated significantly less knee and hip flexion than healthy matched controls during the SEBT (Gribble et al., 2004). An additional study quantifying knee and hip kinematics during the SEBT has also reported that reductions in knee and hip sagittal plane range of motion significantly reduced reach distances, particularly in the anterior direction, in individuals with CAI (Gribble et al., 2007). Although studies have not consistently shown deficits in ankle dorsiflexion range of motion while completing the SEBT, alterations in knee and hip kinematics exhibited in previous studies is likely a plausible factor that contributes to diminished dynamic postural stability in individuals with CAI (Doherty et al., 2016c; Gribble & Robinson, 2010; Gribble et al., 2007; Gribble & Robinson, 2009; Wikstrom et al., 2007; Wikstrom et al., 2010c).

Although the SEBT has been used to detect dynamic postural stability deficits in CAI populations, the single leg squat is also another functional assessment that has received limited attention in CAI populations (Grindstaff et al., 2017). Traditionally, the single leg squat has been utilized as an exercise commonly implemented in physical
therapy and rehabilitation programs, as well as a clinical measure to examine the quality of lower extremity movement and predict lower extremity injury potential (Dolak et al., 2011; Earl et al., 2007). Furthermore, this task requires adequate lower extremity strength, stability, and neuromuscular control and poor performance on this task would identify deficits in dynamic postural stability (Claiborne et al., 2006).

Recently, only one research study investigating the differences in performance on the single leg squat in individuals with CAI has been conducted (Grindstaff et al., 2017). The objective of this study was to determine the differences in ankle dorsiflexion range of motion between three movement quality groups of individuals with unilateral CAI. Ankle dorsiflexion range of motion was determined using the weight-bearing lunge test and participants were placed into good, moderate, or poor movement quality groups based on their performance on the single leg squat. Each participant was video recorded in the frontal plane and an investigator reviewed performance on the single leg squat to score the participants. Points were awarded to participants if they: (1) removed their hands from their hips, (2) exhibited pelvis rotation and/or elevation, (3) had trunk lean, (4) displayed dynamic knee valgus, which was determined if the tibial tuberosity deviated beyond the second metatarsal, and (5) had an inability to maintain a unilateral stance for the duration of the task (Grindstaff et al., 2017). The authors reported that an additional point was awarded if the tibial tuberosity exceeded the medial border of the testing limb, resulting in a total of 6 possible points. Individuals were placed into the good category if they scored 0-1 points, moderate if they scored 2-3 points, and poor if they scored 4 or more points. The authors reported that the poor movement quality group demonstrated significantly reduced ankle dorsiflexion range of motion when compared to the good
movement quality group, but not the moderate movement quality group (Grindstaff et al., 2017). It was concluded by the authors that poor performance on the single leg squat was linked to reductions in ankle dorsiflexion range of motion. However, given the lack of differences between the poor and moderate movement quality groups, the authors also speculated that altered lower extremity movement patterns were also a likely causative factor to the poor performance on the single leg squat (Grindstaff et al., 2017).

Summary

In summary, dynamic postural stability deficits are present during dynamic movement tasks in individuals affected by CAI (Brown et al., 2004; Brown et al., 2010; Gribble & Robinson, 2010; Gribble & Robinson, 2009; Hertel & Olmsted-Kramer, 2007; Ross & Guskiewicz, 2004; Ross et al., 2005; Wikstrom et al., 2007; Wikstrom et al., 2010c; Wright et al., 2016). While other functional assessments are commonly used been to detect sensorimotor, strength, and postural stability impairments in individuals with CAI (McKeon & Hertel, 2008a; Olmsted et al., 2002; Plisky et al., 2009; Wikstrom et al., 2010a), there has been limited use of the single leg squat exercise in CAI populations (Beazell et al., 2012; Grindstaff et al., 2017). The findings by Grindstaff et al. (2017) provide initial insight into identifying potential dynamic postural stability deficits in individuals with CAI using the single leg squat exercise, but a comprehensive biomechanical analysis is warranted to expand upon these initial findings. Examining biomechanical parameters during a single leg squat will provide further aid to researchers and clinicians regarding movement adaptations associated with deficits in dynamic postural stability. Furthermore, this would provide empirical data that would further optimize physical therapy and rehabilitation programs to improve patient outcomes and
potentially mitigate the amount of recurrent lateral ankle sprain injuries. Therefore, another part of this dissertation project will be to quantify dynamic postural stability using the DPSI method and examine lower extremity kinematics during a single leg squat exercise to determine the differences between individuals with and without CAI.

**Dynamic Movement Adaptations**

Open kinetic chain movements require a high-level of sensorimotor function to execute tasks effectively and provide rapid joint stabilization to prevent lower extremity injury (Hertel, 2008). The sensorimotor and mechanical constraints related to CAI have been suggested by many researchers to alter feed-forward and feedback mechanisms of motor control, resulting in biomechanical movement adaptations during jump-landings and side-cut maneuvers (Caulfield et al., 2004; Caulfield & Garrett, 2002; Doherty et al., 2016c; Koshino et al., 2016; Koshino et al., 2014; Monaghan et al., 2006). A biomechanical and neuromechanical assessment of these jump-landings and side-cut maneuvers has been warranted by researchers and clinicians because these dynamic movements have a high risk of lower extremity injury (Doherty et al., 2016b; McKay et al., 2001). Individuals with CAI have demonstrated alterations in neuromuscular control and lower extremity movement adaptations during dynamic tasks (Brown, Padua, Marshall, & Guskiewicz, 2008; Caulfield et al., 2004; Monaghan et al., 2006), which could potentially explain the high rate of recurrent lateral ankle sprains in individuals with CAI (Doherty et al., 2016b; Hiller et al., 2011). While lateral ankle sprains typically occur during ground contact in the unilateral stance when performing a jump-landing or rapid change of direction maneuver (i.e. side-cut), this section will investigate and
summarize the literature regarding motor control strategies in individuals with CAI during unilateral jump-landing and side-cut tasks.

**Unilateral Landings**

Landing from a jump in the unilateral stance imposes large and rapid impulse loads to the ankle complex (Caulfield & Garrett, 2004). This requires substantial feed-forward and feedback neuromuscular control to provide dynamic joint stabilization and attenuate biomechanical loads during ground contact (Caulfield & Garrett, 2002, 2004; Doherty et al., 2016c; Monaghan et al., 2006). The notion individuals that are affected by CAI have centrally mediated and/or supraspinal level changes that result in alterations in neuromuscular control and kinematic movement adaptations has been investigated using a variety of biomechanical measures (Brown et al., 2004; Caulfield et al., 2004; Caulfield & Garrett, 2002; Doherty et al., 2016c; Gribble & Robinson, 2009; Hertel, 2008; Monaghan et al., 2006; Wright et al., 2016). Caufield and Garrett (2002) conducted one of the first studies that investigated ankle and knee sagittal plane kinematics in individuals with and without CAI during a unilateral landing task. In this seminal study, participants completed drop landings on the affected limb from a height of 40 cm while ankle and knee sagittal plane kinematics from 100 ms pre-initial contact to 200 ms post-initial contact were analyzed. The main findings from this study were that the CAI group demonstrated significantly greater ankle dorsiflexion from 10 ms pre-initial contact to 20 ms post-initial contact, as well as significantly greater knee flexion 20 ms pre-initial contact to 60 ms post-initial contact when compared to the matched limb of the controls (Caulfield & Garrett, 2002). The authors suggested that a combination of an altered feed-forward motor program, as regulated by the gamma motoneuron system, and
proprioceptive deficits were likely the cause of the preparatory adjustment which altered ankle and knee sagittal plane kinematics (Caulfield & Garrett, 2002).

To further expand upon these initial findings (Caulfield & Garrett, 2002), a study was conducted by Delahunt et al. (2006) investigating lower extremity kinematics during a unilateral drop landing from a height of 35 cm in individuals with and without CAI (Monaghan et al., 2006). This study examined differences in ankle, knee, and hip kinematics in the sagittal, frontal, and transverse planes during a time window of 200 ms pre-initial contact to 200 ms post-contact. Although the authors did not report any significant differences in knee kinematics between groups, significant differences were found at the ankle. More specifically, individuals with CAI demonstrated significantly greater ankle inversion 200 to 95 ms pre-initial contact, significantly less ankle dorsiflexion 90 to 200 ms post-contact and reductions in sagittal plane ankle joint angular velocity 50 to 125 ms post-contact (Monaghan et al., 2006). Although the findings from the Delahunt et al. (2006) study were different than greater ankle dorsiflexion before and after ground contact reported by Caufield and Garrett (2002), these findings suggest that individuals with CAI may exhibit altered ankle joint positioning during landing, indicated by greater ankle inversion prior to ground contact and plantar flexion during ground contact, that could potentially lead to recurrent injury to the unstable ankle when exposed to unanticipated perturbations during ground contact (Monaghan et al., 2006).

Other studies examining ankle kinematics during unilateral landings have not supported the findings by Delahunt and colleagues (Monaghan et al., 2006). Although some studies have reported no differences in ankle sagittal plane kinematics (Brown et al., 2012; De Ridder, Willems, Vanrenterghem, Robinson, & Roosen, 2015; Doherty et
al., 2016c; Gribble & Robinson, 2010; Gribble & Robinson, 2009), several studies have reported that individuals with CAI exhibit significantly greater ankle dorsiflexion prior to and during ground contact during unilateral landings (Brown et al., 2008; Caulfield & Garrett, 2002; Kipp & Palmieri-Smith, 2012; Wright et al., 2016). Researchers have suggested that greater ankle dorsiflexion exhibited during landing tasks in individuals with CAI is a movement adaptation exhibited to further protect the lateral ankle ligaments (Brown et al., 2012; Brown et al., 2008; Caulfield & Garrett, 2002; Wright et al., 2016). When the ankle complex moves into dorsiflexion via posterior glide of the talus in the mortise, the talocruial joint is positioned in a more compact and stable position and the lateral ankle ligaments are less likely to be stretched (Hertel, 2002; Hubbard & Hertel, 2006). A tendency towards greater ankle dorsiflexion in individuals with CAI is likely a subconscious adaptation in an attempt to reduce ground reaction forces when landing while instantaneously protecting the lateral ankle ligaments from recurrent damage (Caulfield & Garrett, 2002, 2004).

The constraints of CAI resulting in altered ankle sagittal plane kinematics during jump-landings have also been shown to directly influence the positioning of more proximal segments in the kinetic chain (Brown et al., 2012; Brown et al., 2008; Caulfield & Garrett, 2002; Doherty et al., 2016c; Gribble & Robinson, 2010; Gribble & Robinson, 2009). Many studies examining unilateral jump-landings in CAI populations have reported altered knee kinematics (Brown et al., 2012; Caulfield & Garrett, 2002; Gribble & Robinson, 2010; Gribble & Robinson, 2009), while other studies have reported altered hip kinematics (Brown et al., 2012; Doherty et al., 2016c; Monaghan et al., 2006). The investigations conducted by Gribble and Robinson did not report any differences in ankle
or hip sagittal plane kinematics during an anterior jump-landing task in individuals with and without CAI (Gribble & Robinson, 2010; Gribble & Robinson, 2009). However, the authors did report significantly greater knee extension in individuals with CAI prior to and during initial ground contact when landing in the unilateral stance (Gribble & Robinson, 2010; Gribble & Robinson, 2009). Conversely, other studies reporting knee and hip kinematics have shown individuals with CAI demonstrate greater knee and hip flexion when landing in the unilateral stance (Brown et al., 2012; Caulfield & Garrett, 2002; Doherty et al., 2016c). It is possible that the knee and hip kinematic differences observed across these studies may be attributed to the differences in the jump-landing task. For example, participants in the Gribble and Robinson studies completed a unilateral anterior jump-landing in which they were instructed to “stick” the landing and subsequently maintain their balance for 5 s after ground contact (Gribble & Robinson, 2010; Gribble & Robinson, 2009). Other studies reporting greater hip and knee flexion when landing analyzed lower extremity kinematics during unilateral drop landings (Caulfield & Garrett, 2002; Doherty et al., 2016c) and jump-landings in multiple directions (Brown et al., 2012). Although the available literature does not provide a consensus of maladaptive movement adaptations during jump-landings in individuals affected by CAI, findings from previous studies examining lower extremity kinematics would suggest that proximal segment adaptations that arise due to the constraints of CAI could be linked to the demands of the jump-landing task.

While much emphasis in the literature has been placed on the kinematic adaptations that result from the constraints of CAI, the resultant movement adaptations have been suggested to alter the kinetic patterns during ground contact. A study by
Caufield and Garrett (2004) reported that individuals with CAI produced significantly greater peak vertical ground reaction forces during a unilateral drop landing from a height of 40 cm at two discrete time points of 24 to 35 ms and 85 to 150 ms post-initial contact, respectively (Caulfield & Garrett, 2004). In addition to greater peak vertical ground reaction forces, the CAI group reached peak lateral and anterior ground reaction forces quicker when compared to controls (Caulfield & Garrett, 2004). Although some studies have not reported differences in patterns of the ground reaction force during unilateral jump-landings (Brown et al., 2008; Doherty et al., 2016c; Kipp & Palmieri-Smith, 2012), Delahunt et al. (2006) also reported that individuals with CAI produced a greater rate and magnitude of the vertical ground reaction force, as well as greater peak lateral and posterior ground reaction forces in comparison to controls during a unilateral jump-landing (Monaghan et al., 2006). Previous research has suggested that these alterations in the vertical and lateral ground reaction force patterns in individuals with CAI during a unilateral landing could potentially produce large joint moments that results in the ankle giving way and/or excessive supination of the ankle complex leading to a recurrent lateral ankle ligament injury (Caulfield & Garrett, 2004; Monaghan et al., 2006).

Although damage to the lateral ankle ligaments has been suggested to disrupt the sensory mechanoreceptors located in the ankle ligaments resulting in proprioceptive and neuromuscular control defects (Freeman, 1965a, 1965b; Freeman et al., 1965; Freeman & Wyke, 1967), only a few studies have investigated muscle activation during unilateral landings in individuals with CAI (Brown et al., 2004; Caulfield et al., 2004; Monaghan et al., 2006). Caufield et al. (2004) investigated muscle activity from the peroneus longus, soleus, and tibialis anterior in individuals with and without CAI during two jump-landing
tasks (Caulfield et al., 2004). The two jump-landing tasks consisted of a drop jump from a height of 40 cm and a single leg 100 cm anterior jump and maintenance of balance for 3 s after initial contact. Muscle activity during both jump-landing tasks were analyzed during a time window of 150 ms pre-to 150 ms post-initial contact. Although no differences in peroneus longus, soleus, or tibialis anterior activity was found during the 150 ms post-initial contact, the CAI group demonstrated significantly less peroneus longus activity 150 ms pre-initial ground contact (Caulfield et al., 2004). Another study also reported no differences between CAI and controls in peroneus longus, tibialis anterior, soleus, or rectus femoris muscle activity 200 ms post-initial contact during a unilateral drop landing, but did report significant reductions in peroneus longus activity during the 200 ms pre-initial contact (Monaghan et al., 2006). Findings from these studies indicate feed-forward motor control strategies are altered in individuals with CAI and the reductions in preparatory peroneus longus activity, which is necessary to provide dynamic joint stabilization to help prevent a lateral ankle sprain. Furthermore, these reductions in ankle muscle activity may further increase the risk of the ankle complex giving way when initial ground contact is unexpected, such as landing on another individuals’ foot, forcing the ankle into excessive inversion resulting in repetitive lateral ankle sprain injuries (Brown et al., 2004; Caulfield et al., 2004; Monaghan et al., 2006).

**Side-Cutting**

Change of direction movements, such as lateral side-cutting, are also commonly executed dynamic sports movements that can also result in a lateral ankle sprain (McKay et al., 2001). These movements require an individual to rapidly change direction against a support limb in which greater medial-lateral ground reaction forces can be imposed on
the ankle complex of the stance limb than jump-landings (Dayakidis & Boudolos, 2006; Huang, Lin, Kuo, & Liao, 2011). During these type movements, the medial border of the foot usually contacts the ground first resulting in a large lever arm for the ground reaction force relative to the subtalar joint axis of rotation (Fuller, 1999). Hence, greater supination moments could be produced that unexpectedly force the ankle complex into excessive inversion resulting in damage to the lateral ankle ligaments (Suda & Sacco, 2011). Although previous literature has primarily examined movement adaptations in individuals with CAI during unilateral jump-landings, lateral side-cutting movements have a high potential for a lateral ankle sprain and may also detect altered movement adaptations related to CAI (Koshino et al., 2016; McKay et al., 2001). However, these types of movements appear to be less studied in CAI populations (Dayakidis & Boudolos, 2006; Huang et al., 2011; Koshino et al., 2016; Koshino et al., 2014; Suda & Sacco, 2011).

Dayakidis and Boudolos (2006) conducted an initial investigation that examined the ground reaction force patterns in individuals with and without CAI during two types of cutting movements (Dayakidis & Boudolos, 2006). The cutting movements consisted of a side shuffle, which required participants to shuffle 90° laterally to the left and right, and a 45° forward v-cut. During the v-cut movement, participants were required to run forward 7 m and contact the force platform with their testing limb and subsequently perform a 45° cut to the contralateral side. The magnitude and time to peak vertical and medial-lateral ground reaction forces were reported during the stance phase of both cutting movements. Although no between group differences in the magnitude or time to peak ground reaction forces were found for the side shuffling task, individuals with CAI
demonstrated a quicker time to peak vertical ground reaction force and produced a greater magnitude of the vertical ground reaction force on their affected limb when compared to their uninjured limb (Dayakidis & Boudolos, 2006). However, there were no between group or limb differences for time to peak or magnitude of the medial-lateral ground reaction force during the v-cut movement. The authors postulated that the altered vertical ground reaction force pattern could increase the risk of a lateral ankle sprain, but shifting impact forces from medial-lateral to the vertical direction could be a protective strategy to improve impact force attenuation to make the ankle complex more stable and resistant to excessive inversion forces (Dayakidis & Boudolos, 2006).

Another study examined foot plantar pressure and center of pressure excursions during a lateral shuffling movement in individuals with and without CAI (Huang et al., 2011). The lateral shuffling movement utilized in this study consisted of moving laterally 90° left to right while contacting a force platform. The main findings of this study were that the individuals with CAI demonstrated significantly greater peak plantar pressures at the first through fourth metatarsal areas, as well as significantly greater lateral excursions of the center of pressure from 11% to 60% of the stance phase during the lateral shuffling movement (Huang et al., 2011). In addition, it was found that individuals with CAI demonstrated a delay in shifting the center of pressure back towards the medial aspect of the foot during the stance phase. The center of pressure is the centroid of the ground reaction force acting on the plantar aspect of the foot and a laterally deviated center of pressure during the early and mid-stance phases indicates an increased lever arm relative to the subtalar joint axis of rotation that could produce greater inversion moments of the ankle from the ground reaction force in individuals with CAI during a lateral shuffling
movement (Fuller, 1999; Huang et al., 2011). Furthermore, the tendency of the center of pressure to deviate laterally might suggest that the ankle complex could have been in a more inverted position, which would further increase the propensity of the ankle giving way resulting in lateral ankle ligament damage (Fuller, 1999; Huang et al., 2011).

Although initial studies provided initial insight to the altered biomechanical adaptations that occur in individuals with CAI that may increase their risk of recurrent injury during dynamic change of direction asks (Dayakidis & Boudolos, 2006; Huang et al., 2011), the lack of ankle kinematic and muscle activity data limits the interpretation of these initial findings. More recently, a few studies have assessed lower extremity kinematics and muscle activity during side-cut movements in individuals with CAI (Koshino et al., 2016; Koshino et al., 2014; Suda & Sacco, 2011). Significant reductions in preparatory and reactive peroneus longus activity (Suda & Sacco, 2011), as well as greater EMG activity of the gastrocnemius has been found in a group of CAI subjects during a side-cut movement (Koshino et al., 2016; Suda & Sacco, 2011). The combination of reduced peroneus longus and increased gastrocnemius muscle activation prior to ground contact in individuals with CAI could result in the ankle complex being in a vulnerable position of greater plantar flexion and inversion, a kinematic adaption which has been observed in individuals with CAI (Koshino et al., 2016; Monaghan et al., 2006).

In the studies that have reported kinematics, it appears that individuals with CAI demonstrate a more proximal movement strategy to execute a side-cut task (Koshino et al., 2016; Koshino et al., 2014). While researchers have speculated greater ankle inversion prior to anticipated or unanticipated ground contact could result in a lateral ankle sprain, this notion has only been supported during discrete time points during
dynamic tasks (Koshino et al., 2016; Monaghan et al., 2006). One study reported that ankle inversion was significantly greater in individuals with CAI from 200 ms to 165 ms prior to ground contact (Koshino et al., 2016), while another study reported there were no significant differences between groups for ankle kinematics during a side-cut task (Koshino et al., 2014). However, the aforementioned investigations reported that individuals with CAI exhibited greater sagittal plane knee and hip flexion during the stance phase (Koshino et al., 2016; Koshino et al., 2014). This altered pattern of movement in the more proximal segments, especially during a side-cut task, could be a protective movement strategy to further protect the affected ankle. More specifically, transferring reliance to the more proximal segments to dissipate ground reaction forces would result in greater sagittal plane knee and hip flexion in order to mitigate the impact loads imposed to the affected ankle during ground contact. Furthermore, this proximal movement adaptation could also be adopted in attempt to lower the center of mass to gain dynamic stability of the affected limb when performing a dynamic change of direction task (Koshino et al., 2016; Koshino et al., 2014).

**Conclusion**

Lateral ankle sprains are the most common musculoskeletal injury, with reports that up to 40% of individuals will develop CAI following injury. The functional and mechanical impairments related to CAI have been shown to negatively impact postural stability and dynamic movement mechanics, which could further increase the risk of repetitive injuries to the lateral ankle ligaments. As such, an investigation of the biomechanical movement adaptations that arise from the impairments of CAI during
functional exercises and dynamic movements that generally initiate the mechanism of a lateral ankle sprain injury are warranted.

It appears based on the available literature that there is a gap examining postural stability during a single leg squat and the altered biomechanical movement patterns during a side-cut task. Moreover, much emphasis has been placed on exploring the underlying biomechanical and neuromechanical factors during inversion perturbations, but previous research has not examined motor control strategies during anticipated and unanticipated landings on an inverted surface in CAI populations. The findings from this study will attempt to address the current gaps in the CAI literature and provide scientific evidence regarding the movement adaptations associated with CAI.
CHAPTER III
CENTER OF PRESSURE EXCURSIONS IN INDIVIDUALS WITH CHRONIC ANKLE INSTABILITY DURING A SINGLE LEG SQUAT

Abstract

Background

Postural control deficits in individuals with chronic ankle instability (CAI) are well documented. However, traditional center of pressure (COP) and time-to-boundary (TTB) measures of postural control have not been used to quantify deficits in postural control during a single leg squat in individuals with and without CAI. Research question: This study aimed to compare postural control between individuals with self-reported CAI and healthy controls during a single leg squat using traditional COP and TTB measures of postural control.

Methods

Thirty participants (CAI = 15, Controls = 15) completed a total of five single leg squats on a force platform from a height of 25 cm on both limbs. The COP trace recorded from the force platform was used to compute traditional COP and TTB measures in the medial/lateral (ML) and anterior/posterior (AP) directions.
Results

A 2 (group) x 2 (limb) mixed model ANOVA revealed the CAI group exhibited significantly lower TTB ML absolute minimum on their affected limb compared to the matched limb of the control group ($p = 0.002$). On average, individuals with CAI demonstrated significantly lower TTB ML mean of minima ($p = 0.004$) and TTB SD of minima in both ML ($p < 0.001$) and AP ($p = 0.002$) directions. However, no significant interactions or main effects found for any of the eight traditional COP measures were observed ($p > 0.05$).

Significance

While traditional COP measures did not reveal any differences in postural control, TTB measures of postural control revealed individuals with CAI exhibited increased postural instability on both limbs during the single leg squat. This suggests a constrained sensorimotor system resulting in postural control impairments during a functional task, which could be linked to recurrent episodes of the ankle giving way in individuals with CAI.

Introduction

Lateral ankle sprains (LAS) are a common orthopedic injury sustained in athletics and the general population (Doherty et al., 2014c). While some individuals return to high-level activity without any residual impairments, high rates of recurrent injury (van Rijn et al., 2008) and a continuum of residual symptoms that persist for months following an initial LAS are commonly reported (Hertel, 2008). Chronic ankle instability (CAI), which is defined as repetitive episodes of the ankle give way leading to recurrent LAS injuries
(Hertel, 2002), commonly occurs after a LAS (Tanen et al., 2014). Prior studies have documented that unilateral static postural control deficits occur following an acute LAS (Doherty et al., 2014a; Wikstrom, Naik, Lodha, & Cauraugh, 2010b) and in individuals with CAI (Arnold et al., 2009; Hertel & Olmsted-Kramer, 2007; McKeon & Hertel, 2008b). Therefore, postural control assessments are used to evaluate sensorimotor function following an acute LAS and identify individuals at risk to develop CAI.

Traditional center of pressure (COP) excursions, which indicate the rate and magnitude of postural sway, are a common method of assessing postural control (Palmieri, Ingersoll, Stone, & Krause, 2002). Although some studies have revealed differences in postural control using traditional COP measures in CAI cohorts, there are studies have opposed these findings. Researchers have suggested traditional COP measures may not adequately detect postural control deficits or changes in postural control strategies in individuals that are affected by CAI (Hertel & Olmsted-Kramer, 2007; Hertel et al., 2006b; McKeon & Hertel, 2008b; Wikstrom et al., 2010a). Time-to-boundary (TTB) is a spatiotemporal analysis that estimates the time it would take the COP to reach the limits of the base of support (i.e. border of the foot) if the COP trajectory were to continue with its instantaneous directional velocity (Hertel et al., 2006b). Therefore, a lower TTB indicates an individual has less time to execute a postural correction in order to preserve the COP within the boundaries of the base of support while maintaining an upright posture (Hertel et al., 2006b; Wikstrom et al., 2010a). TTB measures of postural control have been shown to be poorly correlated with traditional COP measures (Hertel et al., 2006b), suggesting that TTB may capture additional aspects of postural control that are not identified using traditional COP measures.
measures (Hertel & Olmsted-Kramer, 2007; McKeon & Hertel, 2008a; Pope et al., 2011; Wikstrom et al., 2010a).

Although deficits in static postural control have been identified more consistently in individuals with CAI using TTB measures (Hertel & Olmsted-Kramer, 2007; McKeon & Hertel, 2008a; Pope et al., 2011; Wikstrom et al., 2010a), this spatiotemporal analysis has been underutilized when identifying static and dynamic postural control impairments in individuals with CAI. Despite the limited use in the CAI literature (Beazell et al., 2012; Grindstaff et al., 2017), the single leg squat is a functional assessment commonly implemented in rehabilitation programs to screen for movement patterns that may predict future lower extremity injury (Claiborne et al., 2006; Dolak et al., 2011). Utilizing traditional COP and TTB measures of postural control would further elucidate deficits in dynamic postural control that may be associated with recurrent LAS injury in individuals with CAI. Therefore, the objective of this study was to assess postural control using traditional COP and TTB measures during a single leg squat in individuals with and without self-reported CAI. It was hypothesized that individuals with self-reported CAI would demonstrate greater COP and reduced TTB measures compared to the control group.

Methods

Participants

Individuals with self-reported CAI (n = 15) and healthy matched controls (n = 15) based on gender, age and limb dominance with no self-reported history of musculoskeletal injuries were recruited from a sample of convenience on a university campus (Table 1). Participants were placed into the CAI group if they met all of the
following criteria: self-reported a history of 2 or more LAS with 1 of those LAS occurring within the previous 12 months, sustained a LAS that required non-weight bearing activity or immobilization for ≥24 hours, a history of the affected ankle “giving way”, and scored 27 or less the Cumberland Ankle Instability Tool (CAIT; Gribble et al., 2014). Exclusion criteria included a history of surgery or fracture to either lower extremity, any acute musculoskeletal injury to the lower extremity within the previous 3 months, or a diagnosed musculoskeletal or neurological disorder (Gribble et al., 2014). Prior to the initiation of data collection, all participants were required to read and sign an informed consent document that outlined study procedures and associated risks. Additionally, participants were asked to complete the CAIT questionnaire and subjectively report their total number of LAS occurrences. Ethical approval for all study procedures was granted from the Institutional Review Board at the authors’ university prior to completion of data collection procedures.

Procedures

Participants first completed a familiarization session, which provided them with an explanation of testing procedures and the opportunity to practice the single leg squat task as many times as desired. The same investigator provided the instructions for completing the single leg squat during each participant’s familiarization session. After completion of the familiarization session, a single testing session was completed less than a week later.

The single leg squat task was completed in the barefoot condition on a custom-built platform with an AMTI AccuGait force platform (Watertown, MA, USA) embedded and raised 25 cm above the ground to collect kinetic data at 100 Hz during the single leg
squat using the MotionMonitor software (Chicago, IL, USA) (Figure 14). To maintain consistency between participants during the single leg squat task, participants were instructed to place their testing foot on the force platform, keep their hands on their hips and eyes facing forward, and place their contralateral limb anterolateral to the testing limb. Participants were then instructed to maintain full weight bearing on the testing limb, descend the contralateral limb 25 cm and make contact on a second force platform placed beneath them, without shifting 25% of their weight onto the contralateral limb, and subsequently ascend back the standing position. No specific instructions were given to the participants regarding the rate at which they could descend/ascend during the single leg squat.

Each participant completed 5 successful trials, which was used in the statistical analysis, on each limb (10 total trials) with 30 s rest between trials. The testing order (affected or unaffected limb) was counterbalanced between participants. Failed attempts were marked and trials were repeated if participants if any of the following occurred: failure to maintain balance on the testing limb, removal of either hand from the participants hips, failure to record a vertical ground reaction force of at least 20 N with the contralateral limb, the contralateral limb touched the testing limb, or if the participants shifted more than 25% of their weight to their contralateral limb, which was verified by the second force platform they were required to touch with the contralateral limb.
Data Analysis

Center of pressure

The COP trace that was recorded from the force platform was exported to Excel (Redmond, WA, USA) and eight traditional COP measures were computed. Mean COP velocity and root-mean-square (RMS) excursions (equations 5 and 6) of the COP were calculated in the medial/lateral (ML) and anterior/posterior (AP) directions. Additionally, the range of the COP excursions (maximum minus minimum COP positions) and percent of the available range used (range divided by foot width or length) were calculated in the ML and AP directions.

\[
\text{Mean COP Velocity} = \left( \frac{1}{n} \right) \sum_{i=0}^{n} |COP_i - COP_{i-1}| \tag{5}
\]

\[
\text{RMS Excursions} = \sqrt{\left( \frac{1}{n} \right) \sum_{i=0}^{n} (COP_i - COP_{avg})^2} \tag{6}
\]

Time-to-boundary

TTB measures were also calculated based on previously published guidelines (Hertel et al., 2006b). Each participant’s foot length and width were measured using the Arch Height Index Measurement System (Cranbury, NJ, USA), which was used to model each participants foot as a rectangle to determine their boundaries of the base of support. The COP data was separated into ML and AP components and then the COP position and velocity were determined for each individual data point. Instantaneous COP positions were then used to calculate the distance to the ML and AP border of the foot, respectively. This distance was then divided by the corresponding directional velocity to calculate TTB in the ML and AP directions. This measure estimates the time in seconds it would take the COP at each data point to reach the boundaries of the base of support if it
continued to deviate with an unchanged trajectory and velocity. Hence, a lower TTB means the COP is approaching the boundaries of the base of support at a faster rate (Hertel et al., 2006b). These calculations were completed for each trial in each respective direction and a typical TTB series contains peaks (maxima) and valleys (minima). Each TTB minima represents the lowest point in time prior to a change in the direction of the COP, where the COP is closest in time to the boundaries of the base of support and potential points of postural instability. The first and second signal derivatives were computed to identify the TTB minima for each trial (Hertel et al., 2006b). TTB measures that were calculated and reported were the absolute, mean, and standard deviation (SD) of the TTB minima in the ML and AP directions.

**Statistical Analysis**

All data is reported as mean ± SD. Independent samples t-tests were computed to compare anthropometric measures and CAIT scores between CAI and control groups. To compare COP and TTB measures, a series of 2 (group) x 2 (limb) mixed model analyses of variance (ANOVA) with repeated measures on the limb variable. Tukey’s post hoc correction tests were computed when significant interactions were observed. Cohen’s D effect sizes (ES) were computed for all dependent measures (Cohen, 1992). All statistical analyses were computed using SPSS Statistics (Armonk, NY, USA) and statistical significance was considered when \( p < 0.05 \).

**Results**

Table 1 displays anthropometrics and scores on the CAIT questionnaire. Results from the independent samples t-test revealed no significant differences between groups in
age, height, mass, foot length or foot width ($p > 0.05$). Significantly lower scores on the CAIT were reported for the CAI group in comparison to the control group ($p < 0.001$), while the CAI group subjectively reported a significantly greater amount of LAS occurrences than the control group (Table 1).

The COP and TTB data are presented in Tables 2 and 3. No significant interactions, group or limb main effects were identified for any of the eight traditional COP measures ($p > 0.05$; ES = 0.01-0.55). For TTB measures, a significant interaction was observed for TTB ML absolute minimum ($p = 0.002$), with the CAI group demonstrating a significantly faster TTB ML absolute minimum in on the affected limb when compared to the matched limb of the control group ($p < 0.001$; ES = 3.00). Significant group main effects were also observed for TTB ML mean of minima ($p = 0.004$; ES = 0.87), TTB ML SD of minima ($p < 0.001$; ES = 1.13) and TTB AP SD of minima ($p = 0.002$; ES = 0.94). The CAI group demonstrated significantly less TTB ML mean of minima and TTB SD of minima in both the ML and AP directions (Table 3). No other significant interactions or main effects for TTB measures were observed.

**Discussion**

This study was conducted to determine if the postural control impairments previously reported during a unilateral static stance in individuals with CAI (Arnold et al., 2009; Hertel & Olmsted-Kramer, 2007; McKeon & Hertel, 2008a; Wikstrom et al., 2010a) would also be exhibited during a single leg squat as quantified by traditional COP and TTB measures of postural control. To our knowledge, this was the first study to quantify postural control using both traditional COP and TTB measures during a single leg squat in individuals with and without CAI. The main findings in the present study were
that the CAI group exhibited significantly lower TTB measures of postural control during
the single leg squat when compared to healthy controls. Contrary to our hypothesis that
the CAI group would demonstrate greater traditional COP measures of postural control,
no significant differences between CAI and control groups were observed, and therefore,
we were only able to partially confirm our initial hypotheses.

Recent investigations have shown that CAI alters postural control resulting in
reduced postural sway to compensate for ankle stability deficits when performing
functional movements (dos Santos, Gorges, & Rios, 2014; Rios, Gorges, & dos Santos,
2015). However, these findings were not supported in the current investigation as no
significant interactions or main effects were found for any of the eight traditional COP
measures reported (Table 2). Although we did not report lower extremity kinematics or
muscle activity, we speculate the CAI group likely utilized a more proximal joint and
muscular recruitment postural control strategy to compensate for the localized
sensorimotor deficits. Individuals with CAI have been shown to exhibit proximal joint
movement and muscular recruitment strategies during functional and dynamic sagittal
plane movements to compensate for impaired ankle joint stability (Caulfield & Garrett,
2002; Doherty et al., 2016a, 2016c; Kim, Son, Seeley, & Hopkins, 2017). Therefore, this
compensatory movement strategy, in addition to reports of reductions in postural sway as
a result of utilizing a proximal joint and muscular recruitment strategy (Rios et al., 2015),
provide a plausible explanation for the lack of between group differences in traditional
COP measures of postural control.

Despite the lack of significant differences for traditional COP measures,
significantly lower TTB measures in the CAI group were observed during the single leg
squat (Table 3). Previous literature has not consistently identified postural control deficits in CAI cohorts using traditional COP measures (dos Santos et al., 2014; Hertel & Olmsted-Kramer, 2007; Rios et al., 2015; Wikstrom et al., 2010a), however, studies including a spatiotemporal analysis of TTB have identified deficits in postural control more consistently (Hertel & Olmsted-Kramer, 2007; McKeon & Hertel, 2008a; Pope et al., 2011; Wikstrom et al., 2010a). These findings support prior studies that have suggested TTB measures of postural control may identify postural control deficits more effectively than traditional COP measures in individuals with CAI (Hertel & Olmsted-Kramer, 2007; Hertel et al., 2006b; McKeon & Hertel, 2008a; Pope et al., 2011; Wikstrom et al., 2010a). TTB measures of postural control consider the magnitude of COP excursions in relation to the boundaries of the base of support which yields potential points of postural instability, rather than traditional COP measures of postural control in which only the average rate and magnitude of all COP excursions are considered. Hence, the significantly lower TTB ML absolute minimum and TB ML mean of minima observed in the CAI group denotes postural equilibrium was maintained with the COP closer in time to the ML limits of stability during the single leg squat, which indicates greater ML postural instability. Furthermore, these findings suggest TTB measures of postural control may also be used to evaluate sensorimotor function and detect postural control deficits in individuals with CAI more effectively than traditional COP measures of postural control during functional movements.

An additional finding in this study was a significant reduction in the standard deviation of the TTB minima in both the ML and AP directions on both limbs in the CAI group (Table 3), which has also been reported in the literature during unilateral postural
control assessments (Hertel & Olmsted-Kramer, 2007; McKeon & Hertel, 2008a). Previous research has postulated that a decrease in variability of TTB measures of postural control indicates the magnitude of constraints imposed on the sensorimotor system (Hertel & Olmsted-Kramer, 2007; Hertel et al., 2006b; McKeon & Hertel, 2008a; Wikstrom et al., 2010a). Consequently, damaged sensory afferents that manifest as a result of chronic ankle joint injury can compromise the available somatosensory feedback and diminishes the ability of the postural control system to effectively produce efficient postural corrections to maintain postural equilibrium (Doherty et al., 2014a; Hertel & Olmsted-Kramer, 2007; McKeon & Hertel, 2008a). Therefore, the reductions in the standard deviation of TTB minima in both the ML and AP directions likely reflects that individuals with CAI produce postural control and movement strategies that are less variable and efficient, which arise from constraints on the sensorimotor system, when performing a single leg squat.

Furthermore, with the exception of a significant interaction for TTB ML absolute minimum, significant group main effects for three out of the six reported TTB measures were observed with large effect sizes (ES = 0.87-1.13; Table 3). That is, the CAI group on average exhibited significantly lower TTB measures of postural control during the single leg squat on both limbs. Recent literature has supported the hypothesis that an acute LAS compromises sensorimotor function resulting in a maladaptive reorganization of centrally mediated motor control strategies that impairs static and dynamic postural control on both the injured and non-injured limbs (Bastien et al., 2014; Doherty et al., 2014a; Doherty et al., 2015e; Wikstrom et al., 2010b). Although studies that assess longitudinal bilateral postural control impairments following an acute LAS are limited,
static and dynamic postural control deficits on the injured and non-injured limbs 6 months following an acute LAS (Doherty et al., 2015a) and in individuals with CAI (Doherty et al., 2016a; Hertel & Olmsted-Kramer, 2007) have been reported. In combination with the current results, these findings might indicate long-term alterations in centrally mediated postural control and movement strategies can manifest long after an initial LAS occurs, which highlights a potential underlying mechanism associated with recurrent LAS and the development of CAI. These findings could have clinical implications for developing effective rehabilitation and training programs to improve sensorimotor impairments that occur following a LAS and reduce the propensity of recurrent LAS in CAI populations.

This study did have limitations that should be considered. First, only COP measures of postural control were reported. Lower extremity kinematic and muscular activity data would further elucidate postural control strategies in individuals with CAI during the single leg squat and could further substantiate the clinical implications of our findings. Second, selection criteria of individuals with CAI was determined from subjective responses from the CAIT questionnaire and not confirmed by a physician or any quantitative clinical test. Although we followed the strict guidelines for CAI selection criteria provided by the International Ankle Consortium (Gribble et al., 2014), it is possible that participants being unfamiliar with the CAIT questionnaire may have subjectively provided incorrect responses regarding their LAS history and/or subjective feelings of ankle instability. Finally, only CAI and healthy matched control groups were compared. Not all individuals that suffer an acute LAS develop CAI, and thus, are deemed as ankle sprain copers. Future studies should consider an ankle sprain coper
group when examining postural control to determine differences between these three groups.

**Conclusion**

This study found that individuals with CAI exhibited deficits in TTB measures of postural control on both limbs during the single leg squat compared to controls. These findings indicate constraints on the sensorimotor systems as a result of chronic ankle joint injury alters centrally mediated spatiotemporal postural control strategies during functional movements, which may also highlight an underlying mechanism linked to the development of CAI. Moreover, TTB measures appear to also identify postural control deficits during functional movements, as opposed to traditional COP measures, and should be evaluated in subsequent studies that quantify postural control in individuals with and without CAI.

Table 1

*Participant Characteristics and Cumberland Ankle Instability Tool Scores*

<table>
<thead>
<tr>
<th>Variable</th>
<th>CAI (n = 15)</th>
<th>CON (n = 15)</th>
<th>p-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (y)</td>
<td>21.3 ± 1.6</td>
<td>21.5 ± 1.5</td>
<td>0.730</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>171.0 ± 11.2</td>
<td>169.9 ± 10.6</td>
<td>0.788</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>73.4 ± 15.2</td>
<td>75.5 ± 13.0</td>
<td>0.698</td>
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<tr>
<td>CAIT Score</td>
<td>18.9 ± 3.7</td>
<td>29.7 ± 0.6</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Total Ankle Sprains</td>
<td>6.0 ± 3.2</td>
<td>0.0 ± 0.0</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Foot Length (cm)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Dominant</td>
<td>25.7 ± 2.0</td>
<td>25.2 ± 1.9</td>
<td>0.492</td>
</tr>
<tr>
<td>Non-Dominant</td>
<td>25.6 ± 2.0</td>
<td>25.3 ± 2.0</td>
<td>0.612</td>
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<tr>
<td>Foot Width (cm)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Dominant</td>
<td>10.4 ± 0.9</td>
<td>10.3 ± 0.7</td>
<td>0.674</td>
</tr>
<tr>
<td>Non-Dominant</td>
<td>10.3 ± 0.8</td>
<td>10.3 ± 0.7</td>
<td>0.891</td>
</tr>
</tbody>
</table>

All data are reported as mean and standard deviation. CAIT = Cumberland Ankle Instability Tool; CAI = chronic ankle instability group; CON = control group.
Table 2

*Center of Pressure Measures During the Single Leg Squat*

<table>
<thead>
<tr>
<th>Variable</th>
<th>CAI ((n = 15))</th>
<th>Control ((n = 15))</th>
<th>Group</th>
<th>Limb</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>COP RMS ML (cm)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>affected limb</td>
<td>0.82 ± 0.18</td>
<td>0.75 ± 0.16</td>
<td>0.678 (0.10)</td>
<td>0.374 (0.21)</td>
</tr>
<tr>
<td>unaffected limb</td>
<td>0.82 ± 0.13</td>
<td>0.84 ± 0.29</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>COP RMS AP (cm)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>affected limb</td>
<td>1.85 ± 0.55</td>
<td>1.86 ± 0.74</td>
<td>0.798 (0.06)</td>
<td>0.361 (0.22)</td>
</tr>
<tr>
<td>unaffected limb</td>
<td>2.05 ± 0.65</td>
<td>1.95 ± 0.65</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>COP ML velocity (cm/s)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>affected limb</td>
<td>4.24 ± 0.90</td>
<td>4.02 ± 0.86</td>
<td>0.413 (0.17)</td>
<td>0.069 (0.55)</td>
</tr>
<tr>
<td>unaffected Limb</td>
<td>4.32 ± 0.52</td>
<td>4.89 ± 1.21</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>COP AP velocity (cm/s)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>affected limb</td>
<td>7.94 ± 1.59</td>
<td>7.69 ± 1.72</td>
<td>0.936 (0.21)</td>
<td>0.291 (0.25)</td>
</tr>
<tr>
<td>unaffected limb</td>
<td>8.16 ± 1.55</td>
<td>8.34 ± 1.97</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>COP ML range (cm)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>affected limb</td>
<td>3.21 ± 0.69</td>
<td>2.84 ± 0.58</td>
<td>0.445 (0.18)</td>
<td>0.231 (0.31)</td>
</tr>
<tr>
<td>unaffected limb</td>
<td>3.21 ± 0.53</td>
<td>3.30 ± 0.97</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>COP AP range (cm)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>affected limb</td>
<td>7.33 ± 2.21</td>
<td>6.71 ± 1.89</td>
<td>0.387 (0.28)</td>
<td>0.231 (0.26)</td>
</tr>
<tr>
<td>unaffected limb</td>
<td>7.81 ± 2.36</td>
<td>7.36 ± 1.92</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>ML ranged used (%)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>affected limb</td>
<td>30.84 ± 6.67</td>
<td>27.55 ± 4.94</td>
<td>0.356 (0.24)</td>
<td>0.124 (0.41)</td>
</tr>
<tr>
<td>unaffected limb</td>
<td>31.46 ± 4.53</td>
<td>31.84 ± 7.42</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>AP range used (%)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>affected limb</td>
<td>28.69 ± 8.89</td>
<td>26.85 ± 8.34</td>
<td>0.515 (0.20)</td>
<td>0.229 (0.28)</td>
</tr>
<tr>
<td>unaffected limb</td>
<td>30.86 ± 8.98</td>
<td>29.42 ± 8.25</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

All data are reported as mean and standard deviation. COP = center of pressure; RMS = root-mean-square; CAI = chronic ankle instability group; CON = control group; ES = Cohen’s D effect size.
Table 3

*Time-to-Boundary Measures During the Single Leg Squat.*

<table>
<thead>
<tr>
<th>Variable</th>
<th>CAI ((n = 15))</th>
<th>Control ((n = 15))</th>
<th>Group (p) value (ES)</th>
<th>Limb (p) value (ES)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TTB ML absolute minimum (s)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>affected limb</td>
<td>0.19 ± 0.04*</td>
<td>0.31 ± 0.07</td>
<td>0.004 (1.09)</td>
<td>0.005 (0.73)</td>
</tr>
<tr>
<td>unaffected limb</td>
<td>0.19 ± 0.05</td>
<td>0.22 ± 0.07</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TTB AP absolute minimum (s)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>affected limb</td>
<td>0.29 ± 0.10</td>
<td>0.36 ± 0.09</td>
<td>0.217 (0.33)</td>
<td>0.363 (0.19)</td>
</tr>
<tr>
<td>unaffected limb</td>
<td>0.30 ± 0.12</td>
<td>0.31 ± 0.12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TTB ML mean of minima (s)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>affected limb</td>
<td>0.79 ± 0.19</td>
<td>0.96 ± 0.14†</td>
<td>0.004 (0.87)</td>
<td>0.288 (0.24)</td>
</tr>
<tr>
<td>unaffected limb</td>
<td>0.77 ± 0.15</td>
<td>0.90 ± 0.21†</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TTB AP mean of minima (s)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>affected limb</td>
<td>1.04 ± 0.25</td>
<td>1.20 ± 0.29</td>
<td>0.251 (0.31)</td>
<td>0.585 (0.11)</td>
</tr>
<tr>
<td>unaffected limb</td>
<td>1.13 ± 0.26</td>
<td>1.18 ± 0.37</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TTB ML SD of minima (s)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>affected limb</td>
<td>0.85 ± 0.27</td>
<td>1.40 ± 0.45†</td>
<td>&lt;0.001 (1.13)</td>
<td>0.600 (0.09)</td>
</tr>
<tr>
<td>unaffected limb</td>
<td>0.94 ± 0.53</td>
<td>1.40 ± 0.43†</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TTB AP SD of minima (s)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>affected limb</td>
<td>0.93 ± 0.33</td>
<td>1.63 ± 0.43†</td>
<td>0.002 (0.94)</td>
<td>0.174 (0.29)</td>
</tr>
<tr>
<td>unaffected limb</td>
<td>1.33 ± 0.64</td>
<td>1.56 ± 0.55†</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

† denotes significantly different than CAI group \((p < 0.05)\); * denotes significantly different than the matched limb of the control group \((p < 0.05)\); All data are reported as mean and standard deviation. TTB = time-to-boundary; CAI = chronic ankle instability group; CON = control group; ES = Cohen’s D effect size.
Figure 14. Single leg squat task. Force platform set up for the single leg squat task. Participants kept the testing foot on the force platform, lowered the contralateral limb and touched the second force platform placed 25 cm beneath them (right) and then ascended back to the starting position (left) while keeping their hands on their hips for the entire trial.
CHAPTER IV
LOWER EXTREMITY JOINT KINETICS DURING A SIDE-CUT MANEUVER IN INDIVIDUALS WITH AND WITHOUT CHRONIC ANKLE INSTABILITY

Abstract

Individuals with chronic ankle instability (CAI) demonstrate altered lower extremity joint kinetics and stiffness during jump-landings. However, potential lower extremity joint kinetic compensations as a result of CAI during a side-cut task are unknown. This study examined lower extremity joint kinetics and sagittal plane joint stiffness in individuals with and without CAI during a side-cut task. Thirty participants (15 CAI, 15 Control) completed a side-cut task consisting of a 70 cm anterior hop forward, land and subsequently change direction 45° to the contralateral side. Net internal joint moments and sagittal plane ankle, knee, and hip joint stiffness were assessed during the stance phase of the side-cut task. Results revealed the CAI group demonstrated significantly greater ankle plantar flexion moment (3%-16% of stance phase) and significantly reduced ankle eversion moment (39%-81% of stance phase) and knee abduction moment (52%-75% of stance phase) in comparison to controls ($p = 0.009-0.049; d = 0.62-0.97$). Significantly greater hip joint stiffness was also observed for the CAI group compared to controls with a large effect size ($p = 0.029; d = 1.00$). Reductions in ankle eversion moment and increased hip joint stiffness observed in the CAI group indicates alterations in lower extremity joint kinetics compared to healthy controls. The
ankle and hip joint kinetic alterations may contribute to an increased risk of recurrent lateral ankle sprains in individuals with CAI, and thus, may assist clinicians in developing effective rehabilitation programs to improve movement patterns and mitigate the potential risk of recurrent injury.

Introduction

Lateral ankle ligament sprains are a common injury sustained in athletics (Fernandez et al., 2007; Hootman et al., 2007). This injury accounts for 7.3% of all reported injuries sustained in collegiate athletics with the highest incidence rates reported in basketball, soccer, and volleyball (Roos et al., 2017). Although a general misconception is that lateral ankle sprains are inconsequential injuries that typically heal quickly, a wide spectrum of sensorimotor (Hertel, 2000, 2008) and mechanical (Hertel et al., 1999; Hubbard & Hertel, 2006) deficits can manifest for several months, and sometimes years, following the initial injury. Chronic ankle instability (CAI), which is a common pathology that develops after acute lateral ankle ligament trauma, is characterized by subjective feelings of ankle joint instability or the ankle repetitively giving way during functional activity resulting in subsequent lateral ankle sprains (Delahunt et al., 2010; Hertel, 2002).

The lateral ankle sprain often occurs during dynamic open kinetic chain movements such as jump-landings (Terada & Gribble, 2015) or rapid center of mass accelerations (i.e. side-cutting or change of direction; Kristianslund, Bahr, & Krosshaug, 2011; Remus et al., 2018). Recent investigations provide evidence of altered movement strategies during jump-landings that manifest 2 weeks (Doherty et al., 2015b; Doherty et al., 2014b) and 6 months following a first time, acute lateral ankle sprain (Doherty et al.,
2015c), and in individuals that develop CAI (Caulfield & Garrett, 2002; Delahunt, Monaghan, & Caulfield, 2006; Doherty et al., 2016c). Most notably, individuals with CAI have been shown to utilize a hip dominant strategy to execute dynamic movements such as jump-landings and side-cut tasks (Doherty et al., 2016c; Kim et al., 2017; Koshino et al., 2014; Son, Kim, Seeley, & Hopkins, 2017). This movement strategy is an apparent compensation that arises from the constraints on the sensorimotor system that arise from CAI to reduce impact forces on the affected ankle, resulting in an intralimb redistribution of impact force attenuation from the distal to the proximal joints (Kim et al., 2017; Son et al., 2017). Therefore, damage to the lateral ankle ligaments can result in longitudinal alterations in movement dynamics during sports related movements, which may contribute to recurrent lateral ankle sprains, and ultimately, the development of CAI.

Lower extremity joint kinematics, neuromuscular control, and energetics alterations are well documented during jump-landings in individuals affected by CAI (Caulfield & Garrett, 2002, 2004; Delahunt et al., 2006; Doherty et al., 2016c; Son et al., 2017). Despite published case reports of lateral ankle sprains occurring during side-cut tasks (Kristianslund et al., 2011; Remus et al., 2018), movement dynamics in individuals with CAI during side-cut tasks has received little attention in the literature (Koshino et al., 2016; Koshino et al., 2014; Suda & Sacco, 2011). Furthermore, side-cutting has a high risk of a lateral ankle sprain because the center of pressure of the foot may continue to deviate laterally during ground contact. This would increase the moment arm of the subtalar joint and potentially produce inversion moments that cause rapid and excessive inversion resulting in lateral ankle ligament damage (Fong et al., 2009; Fuller, 1999). Therefore, assessing movement dynamics, particularly lower extremity joint kinetics, in
individuals with CAI is warranted to identify potential maladaptive movement strategies during sports related tasks that may be associated with an increased the risk of recurrent injury.

The objective of this study was to examine lower extremity joint kinetic patterns and joint stiffness during a side-cut task in individuals with and without CAI. Prior studies have found alterations in lower extremity joint kinetics and increased proximal joint stiffness in individuals with CAI when performing a single leg jump-landing (Doherty et al., 2016c; Kim et al., 2017; Son et al., 2017). As such, we hypothesized that individuals with CAI would exhibit altered lower extremity joint kinetic patterns and increased proximal joint stiffness compared to healthy controls when performing a side-cut task.

**Methods**

**Participants**

Sample size estimation using G-Power software (Düsseldorf, Germany) determined a total of 26 participants would be needed to achieve a desired power of 0.80, using a moderate effect size and alpha set at 0.05 (Cohen, 1992). Fifteen participants with self-reported CAI (7 male, 8 female; age: 21.3 ± 1.6 y; height: 171.0 ± 11.2 cm; mass: 73.4 ± 15.2 kg) and fifteen healthy matched controls (7 male, 8 female; age: 21.5 ± 1.5 y; height: 169.9 ± 10.6 cm; mass: 75.5 ± 13.0 kg) that were currently participating in competitive or recreational sports completed study procedures. Selection criteria for CAI participants was based on the recommendations from the International Ankle Consortium: (1) self-reported history of 2 or more lateral ankle sprains, with 1 of those
lateral ankle sprains occurring within the previous 12 months; (2) sustained a lateral ankle sprain that required non-weight bearing activity or immobilization for more than 24 hours; (3) self-reported history of the affected ankle “giving way”; (4) a Cumberland Ankle Instability Tool (CAIT) score of less than 27 (Gribble et al., 2014). Exclusion criteria for both groups included: (1) history of surgery or fracture to either lower extremity; (2) any musculoskeletal injury to the lower extremity within the last 3 months; (3) diagnosed with any musculoskeletal or neurological disorder. All participants were required to read and sign an informed consent document that identified risks and procedures of the study. Prior to the initiation of data collection, ethical approval was obtained for all study procedures from the Institutional Review board at the authors’ university.

Instrumentation

Twelve infra-red Bonita 10 cameras (Vicon, Oxford, UK) recording at 200 Hz were used to collect 3D lower extremity kinematic data. Retro-reflective marker sets (i.e. clusters), which were constructed out of orthoplast, were attached to the participants posterior pelvis, and bilaterally on the thighs, shanks, and feet using double sided tape. Nylon therapeutic wraps were place around the clusters to further minimize marker movement artifact during the side-cut task (described below). Additionally, ground reaction force data was also collected from a portable AMTI AccuGait force platform (Watertown, MA, USA) sampling at 1,000 Hz during the side-cut task. The kinematic and ground reaction force data was collected simultaneously and time synchronized using the MotionMonitor software (Innovative Sports Training, Inc., Chicago, IL, USA).
Experimental Procedures

Each participant first completed a familiarization session. During this session a CAIT questionnaire and an injury history survey was completed, which allowed participants to subjectively report their level of ankle instability and the total number of lateral ankle sprains they had sustained. Additionally, anthropometric data was also obtained and participants were provided with a detailed description of the testing procedures and a chance to practice the side-cut task as many times as desired to reduce any potential learning effects. The same investigator provided each participant with instructions for completing the side-cut task. After completion of the familiarization session, participants reported back to the laboratory within 72 hours to complete their one experimental testing session wearing a low-top athletic shoe of their choice.

Upon arrival to the laboratory for the single experimental testing session, participants completed a dynamic warm up protocol that consisted of body weight squats, skips, high-knees, jogging, exaggerated gait swings and lunges. After the dynamic warm up, the side-cut task was completed. The side-cut task implemented in this study was modified from previous investigations using a side-cut task in CAI cohorts (Koshino et al., 2016; Koshino et al., 2014). To complete the side-cut task, participants were positioned 0.70 cm away from the center of the force platform, which was positioned so that the top of the force platform was level with the ground, and instructed to stand on their non-testing limb with approximately 45° of knee and hip flexion. A verbal cue was given to the participant to perform an anterior jump and land with their testing limb on the force platform. After contacting the force platform with the testing limb, participants subsequently changed their direction 45° to the contralateral side and ran as quickly as
possible for 3 m. The 45° side-cut angle was marked on the ground to provide participants with a visual representation of the proper cutting angle and the required running distance. Participants practiced the side-cut task (5-10 trials) on the leg that was to be tested before any trials were recorded. The testing limb in the CAI group was determined from the CAIT questionnaire that participants subjectively reported as their affected ankle, while the testing limb of the control group was gender matched to a participant in the CAI group with a similar age, height, mass, and limb dominance. A total of 3 successful trials were recorded and used in the final analysis. Attempts were repeated if the participant’s entire foot did not contact the force platform or if any retro-reflective markers were lost during the side-cut task.

Data Processing and Analysis

Each participant’s lower extremity was constructed in the MotionMonitor software to determine the ankle, knee, and hip joint centers. The joint centers were defined in the software by placing a retro-reflective measurement sensor on prominent anatomical landmarks to estimate the foot, ankle, knee, and hip joint centers. Ankle joint centers were defined using the medial and lateral malleoli and the distal second phalanx, while knee joint centers were defined using the medial and lateral femoral condyles. Hip joint centers were calculated using the anterior superior iliac spine and the L5/S1 joint and the proximal segment served as the reference point in the software to create the foot, ankle, knee, and hip joints. The ankle and knee joint centers were calculated using the centroid method and the hip joint centers were calculated using the Davis method (Davis, Ounpuu, Tyburski, & Gage, 1991). The same investigator located the prominent anatomical landmarks for all participants’ segment constructions.
Ankle, knee, and hip kinematics were calculated using the Grood-Suntay angle orientation method (Grood & Suntay, 1983). Time synchronized lower extremity kinematic and ground reaction force data was filtered with a low-pass third-order Butterworth filter with a frequency of 15 Hz. Participants anthropometric data, as well as time synchronized kinematic and ground reaction force data, were used to compute net internal joint moments of the ankle, knee, and hip using an inverse dynamics approach in the MotionMonitor software. Net internal joint moments were analyzed in the sagittal, frontal, and transverse planes during the stance phase of the side-cut task and normalized to body mass for each subject. The stance phase was defined as the time interval when the vertical ground reaction force exceeded 15 N after initial contact until the vertical ground reaction force went below 15 N (i.e. toe off). Each participants stance phase was normalized to 100% from initial contact (0%) to toe off (100%) for the statistical analysis (Kim et al., 2017; Koshino et al., 2016; Son et al., 2017). Furthermore, sagittal plane ankle, knee, and hip joint stiffness was also computed as the change in net internal joint moment divided by the angular displacement between initial contact and peak dorsiflexion, knee and hip extension during the stance phase (Doherty et al., 2016c; Kim et al., 2017).

**Statistical Analysis**

All statistical analyses were performed using the statistical software package in Excel (Microsoft Corporation, Redmond, WA, USA). Descriptive and dependent variables are reported as mean ± standard deviation (SD). Independent samples t-tests were used to compare descriptive characteristics and CAIT scores between CAI and control groups. To compare stance-averaged ankle, knee, and hip net internal joint
moments during the side-cut task between CAI and control groups, independent samples
two tailed t-tests were computed for each discrete time point during the stance phase.
Cohen’s D effect size data was also calculated for all dependent variables as the
difference in means divided by the pooled SD and were evaluated as small (d < 0.40),
moderate (d = 0.40-0.80), and large (d > 0.80) effects (Cohen, 1992). Statistical
significance was considered when p < 0.05.

Results

Results from the independent samples t-test revealed that the CAI and control
groups were similar in age (p = 0.730), height (p = 0.788), and mass (p = 0.698). The
CAI group subjectively reported a significantly lower CAIT score than the control group
(CAI: 18.9 ± 3.7 vs. Control: 29.7 ± 0.6; p < 0.001) and on average 6.0 ± 3.2 total lateral
ankle sprains.

Sagittal, frontal, and transverse plane stance-averaged net internal joint moments
during the side-cut task are presented in Figures 15-23. Results showed that the CAI
group demonstrated a significantly greater ankle plantar flexion moment from 3%-16%
of the stance phase compared to controls (p = 0.011-0.050; d = 0.62-0.97). In the frontal
plane, the CAI group showed a significantly less ankle eversion moment from 39%-81%
of the stance phase (p = 0.009-0.049; d = 0.62-0.92) and significantly less knee abduction
moment from 52%-75% of the stance phase (p = 0.27-0.049; d = 0.63-0.75) compared to
the control group. There were no other statistical differences in sagittal, frontal, or
transverse plane net internal joint moments between groups during the side cut task.

Table 4 represents sagittal plane ankle, knee, and hip joint stiffness for each group
during the side-cut task. There were no significant differences between groups for sagittal
plane ankle ($p = 0.094; d = 0.50$) or knee joint ($p = 0.430; d = 0.05$) stiffness. Conversely, individuals with CAI demonstrated significantly greater hip joint stiffness compared to controls ($p = 0.029; d = 1.00$) with a mean difference of 0.12 Nm kg$^{-1}$ degrees$^{-1}$ between groups.

**Discussion**

This study assessed lower extremity joint kinetic patterns and sagittal plane joint stiffness during a side-cut task in individuals with and without CAI. The primary findings in the study were that individuals with CAI demonstrated an increased plantar flexion moment during the initial contact phase and reductions in ankle eversion and knee abduction moments during the mid- to late stance phases of the side-cut task. Although no group differences were observed for sagittal plane ankle or knee joint stiffness, the CAI group displayed an increase in sagittal plane joint stiffness during the side-cut task. These results supported our hypothesis that increased proximal joint stiffness would be observed in the CAI group, however, findings in lower extremity joint kinetic patterns only partially confirmed our initial hypothesis.

Increased ankle plantar flexion moment was found in the CAI group during the initial contact phase (3%-16%) of the side-cut task. The ankle plantar flexors (i.e. gastrocnemius-soleus muscle complex) provide sagittal plane joint stability through eccentric muscle actions during initial foot contact to dissipate high impulse loads. Prior investigations have reported increased gastrocnemius activation in CAI participants during the ground contact phase when performing a rapid change of direction task (Koshino et al., 2016; Suda & Sacco, 2011). Although muscle activity was not reported in this study, an increased plantar flexion moment may be attributed to increased activation
of the gastrocnemius-soleus muscle complex during the early stance phase of the side-cut task. The increased ankle plantar flexion moment would indicate that the CAI group may increase sagittal plane joint stabilization during initial foot contact in preparation to control impact forces prior to changing directions on the unstable ankle. These findings are in contrast to previous reports of significant reductions in ankle plantar flexion moment during the mid- to late stance phases of a land and jump 90° to the contralateral side in individuals with CAI compared to ankle sprain copers and controls (Kim et al., 2017; Son et al., 2017). The differences in side-cut movement tasks utilized in the literature are a plausible explain for the differences observed across these studies. Prior investigations have used single and double leg landings, and more recently, a single leg landing with a 90° jump to the contralateral side to examine joint energetic patterns in CAI cohorts during dynamic maneuvers that commonly initiate the mechanism of a lateral ankle sprain. Although these movements are predominately sagittal plane movements, tasks that utilize a multiplanar motion, such as the side-cut task performed in this study, may not necessary elicit the same sagittal plane ankle joint kinetic alterations previously demonstrated in CAI cohorts (Kim et al., 2017; Son et al., 2017; Terada, Pfile, Pietrosimone, & Gribble, 2013).

Conversely, we did observe a significantly reduced ankle eversion moment in the CAI group from 39%-81% of the stance phase with medium to large effect sizes (Figure 18). When performing a side-cut task, greater medio-lateral ground reaction forces, in addition to an increased inversion and internal rotation angle of the subtalar joint in preparation to rapidly change direction, can augment the inversion moment of the ankle complex during ground contact (Dayakidis & Boudolos, 2006; Koshino et al., 2017). The
peroneus longus and peroneus brevis, which are the primary ankle evertors of the subtalar joint, are responsible for providing dynamic frontal plane joint stabilization through eccentric muscle actions to assist with controlling the rate and magnitude of inversion displacement during ground contact (Hertel, 2002). Previous research has shown individuals affected by CAI exhibit significant reductions in neuromuscular control, particularly in the ankle evertors, during pre-landing and post-landing phases of jump-landings (Caulfield et al., 2004; Delahunt et al., 2006; Kunugi, Masunari, Yoshida, & Miyakawa, 2017; Son et al., 2017), and more recently side-cut tasks (Koshino et al., 2016; Suda & Sacco, 2011). The constraints on sensorimotor system that arise from repetitive lateral ankle ligament trauma provide a plausible explanation for the reduced ankle eversion moments observed in the CAI group from the mid- to late stance phase of the side-cut task. These findings, in combination with previous findings of reduced neuromuscular control during dynamic movements (Caulfield et al., 2004; Delahunt et al., 2006; Koshino et al., 2016; Kunugi et al., 2017; Son et al., 2017; Suda & Sacco, 2011), suggest alterations to centrally mediated motor control strategies that result in reduced frontal plane dynamic stabilization. Consequently, this may lead to the ankle being in a disadvantageous position to produce sufficient evertor torque to prevent excessive frontal plane movement when the lateral ankle is loaded during a side-cut or rapid change of direction maneuver, causing the ankle complex to give way into excessive inversion. However, further research is warranted to determine the potential link between ankle position and moments that may cause the ankle to give way during dynamic movements to further substantiate the clinical implication of this finding.
With regard to proximal segment joint kinetics, no significant differences were found between groups for knee or hip extensor moments (Figure 16 and 17). However, the CAI group exhibited increased sagittal plane hip joint stiffness compared to controls with a large effect size (Table 4). Joint stiffness considers the kinetic and kinematic parameters that provide an estimate of the applied forces that cause changes in movement patterns at each joint, respectively (Doherty et al., 2016c). The increased sagittal plane hip joint stiffness displayed by the CAI group denotes a hip dominant movement strategy when performing the side-cut task. This finding supports previous evidence of individuals utilizing a hip dominant strategy following a first time, acute lateral ankle sprain (Doherty et al., 2015b; Doherty et al., 2014b), 6 months following a first time, acute lateral ankle sprain (Doherty et al., 2015a; Doherty et al., 2015d), and in individuals that develop CAI when performing various dynamic movement tasks (Doherty et al., 2016c; Kim et al., 2017; Koshino et al., 2016; Koshino et al., 2014; Son et al., 2017). This indicates the sensorimotor impairments associated with lateral ankle ligament trauma and CAI results in the affected ankle potentially being unable to adequately withstand impact and rotational forces when performing dynamic maneuvers. Therefore, a compensatory intralimb load redistribution emerges to increase reliance on the proximal joints to attenuate impact forces to maintain overall body equilibrium and prevent excessive joint displacement on the affected ankle. It appears based on the current evidence that the use of a proximal joint dominant movement strategy can persist long after a first time lateral ankle sprain. Consequently, this erroneous movement pattern has been suggested to be a gateway to the development of chronic ankle joint instability and considered an
underlying factor that may contribute to recurrent lateral ankle sprains in individuals with CAI.

In conclusion, individuals with CAI demonstrated altered ankle joint kinetics and proximal joint stiffness in comparison to healthy controls when performing the side-cut task. The observed alterations in ankle moments and increased hip joint stiffness provides insight to potential changes in movement dynamics that emerge during a side-cut task due to the constraints of CAI. These apparent movement strategies may contribute to recurrent lateral ankle sprains in individuals with CAI. Although these findings may be useful to assist researchers and clinicians in developing effective rehabilitation programs to improve movement patterns and mitigate the potential risk of recurrent injury, research is still limited regarding movement dynamics during side-cut and rapid change of direction tasks in individuals with CAI. Further examination of movement strategies during these tasks to support the clinical implications of our findings is warranted.

Although this study revealed differences between groups during the side-cut task, there were a few limitations that should be considered. First, muscle activity data was not reported which may limit the interpretation of our findings. Examining neuromuscular control during the side-cut task would further elucidate the differences we observed in joint kinetics and joint stiffness between groups. Second, we were unable to compute frontal or transverse plane joint stiffness because it was difficult to accurately quantify these parameters due to lower moments and joint displacement displayed by the participants. Finally, the side-cut task utilized in this study was simulated and participants knew which direction they would be changing. Additional research is warranted that implements protocols that investigate the differences between anticipated and
unanticipated change of direction tasks in individuals with CAI. This would further emphasize the clinical implications of CAI and identify movement strategies that contribute to an increased risk of the ankle giving way during side-cut or rapid change of direction movements.

Table 4

*Sagittal Plane Joint Stiffness During the Side-Cut Task*

<table>
<thead>
<tr>
<th>Joint</th>
<th>CAI Mean ± SD</th>
<th>Control Mean ± SD</th>
<th>p Value</th>
<th>Mean Difference</th>
<th>95% CI of the Difference</th>
<th>Effect Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ankle</td>
<td>-0.06 ± 0.01</td>
<td>-0.08 ± 0.04</td>
<td>0.094</td>
<td>0.02</td>
<td>-0.01 - 0.04</td>
<td>0.50</td>
</tr>
<tr>
<td>Knee</td>
<td>-0.16 ± 0.16</td>
<td>-0.17 ± 0.20</td>
<td>0.430</td>
<td>0.01</td>
<td>-0.12 - 0.15</td>
<td>0.05</td>
</tr>
<tr>
<td>Hip</td>
<td>-0.25 ± 0.15</td>
<td>-0.14 ± 0.09†</td>
<td>0.029</td>
<td>0.12</td>
<td>-0.24 - 0.01</td>
<td>1.00</td>
</tr>
</tbody>
</table>

† indicates significantly different than CAI group (p < 0.05). All data are reported as mean and standard deviation. CAI = chronic ankle instability group.

*Figure 15.* Sagittal plane net internal joint moment of the ankle. CAI = chronic ankle instability group; CON = control group. All data are reported as mean and standard deviation. Boxed area indicates statistical significance (p < 0.05).
Figure 16. Sagittal plane net internal joint moment of the knee. CAI = chronic ankle instability group; CON = control group. All data are reported as mean and standard deviation.

Figure 17. Sagittal plane net internal joint moment of the hip. CAI = chronic ankle instability group; CON = control group. All data are reported as mean and standard deviation.
Figure 18. Frontal plane net internal joint moment of the ankle. CAI = chronic ankle instability group; CON = control group. All data are reported as mean and standard deviation. Boxed area indicates statistical significance ($p < 0.05$).

Figure 19. Frontal plane net internal joint moment of the knee. CAI = chronic ankle instability group; CON = control group. All data are reported as mean and standard deviation. Boxed area indicates statistical significance ($p < 0.05$).
Figure 20. Frontal plane net internal joint moment of the hip. CAI = chronic ankle instability group; CON = control group. All data are reported as mean and standard deviation.

Figure 21. Transverse plane net internal joint moment of the ankle. CAI = chronic ankle instability group; CON = control group. All data are reported as mean and standard deviation.
**Figure 22.** Transverse plane net internal joint moment of the knee. CAI = chronic ankle instability group; CON = control group. All data are reported as mean and standard deviation.

**Figure 23.** Transverse plane net internal joint moment of the hip. CAI = chronic ankle instability group; CON = control group. All data are reported as mean and standard deviation.
CHAPTER V
ANKLE KINEMATICS AND NEUROMUSCULAR CONTROL IN INDIVIDUALS WITH CHRONIC ANKLE INSTABILITY: A COMPARISON OF UNEXPECTED AND EXPECTED ANKLE INVERSION PERTURBATIONS

Abstract

Background

Chronic ankle instability (CAI) is a common pathology that develops following a lateral ankle sprain. Although neuromuscular control during inversion perturbations in CAI cohorts has been extensively investigated, literature regarding potential anticipatory mechanisms to inversion perturbations in individuals with CAI is limited. This study assessed ankle kinematics and neuromuscular control in individuals with and without CAI during unexpected (UE) and expected (EXP) inversion perturbations.

Methods

Individuals with CAI (n = 15) and healthy matched controls (n = 15) performed UE and EXP single leg landings on a tilted surface rotated 20° in the frontal plane to simulate the mechanism of a lateral ankle sprain. Ankle inversion angle at initial contact (IC), time to maximum inversion angle, maximum inversion angle and velocity, and muscle activity from the tibialis anterior (TA), medial gastrocnemius (MG), peroneus longus (PL) and peroneus brevis (PB) 200 milliseconds pre-IC and post-IC was analyzed. Latency of the PL and PB and co-contraction index (CCI) were also assessed.
Findings

CAI exhibited significantly less time to maximum inversion angle, greater maximum inversion angle, and a longer PL latency compared to controls during both landing conditions \((p < 0.05)\). For landing condition, significantly greater maximum inversion angle, less inversion angle at IC, longer PB latency, less TA activity, and frontal plane CCI was found during the UE landing \((p < 0.01)\).

Interpretation

Individuals with CAI displayed prolonged PL latency and reduced ability to control frontal plane ankle movement compared to controls. However, similar motor control strategies were observed for both groups when there was knowledge of the inversion perturbation.

Introduction

Chronic ankle instability (CAI), which commonly develops following a first time acute lateral ankle sprain, is a condition characterized by repetitive bouts of ankle instability causing the ankle to give way leading to recurrent lateral ankle sprains (Delahunt et al., 2010; Hertel, 2002). Damage to the mechanoreceptors located within the lateral ankle ligaments, and potentially the muscle spindles, has been suggested to negatively alter sensorimotor function (Freeman, 1965a; Hertel, 2008; Munn, Sullivan, & Schneiders, 2010). As a consequence, reductions in neuromuscular control of the lateral ankle musculature, such as the peroneus longus and peroneus brevis, has been shown to be one causative factor contributing to recurrent lateral ankle sprains in individuals that develop CAI (Hopkins et al., 2009; Sierra-Guzmán, Jiménez, & Abián-Vicén, 2018).
Extensive research has been conducted over the years using a variety of methodologies and devices that replicate the mechanism of a lateral ankle sprain to assess neuromuscular control to sudden inversion in individuals with a history of a lateral ankle sprain and CAI (Ha et al., 2015). While these studies provide valuable insight to the underlying pathology that contributes to recurrent lateral ankle sprains and the development of chronic ankle joint instability, only a few studies have controlled for anticipatory responses to inversion perturbations in CAI cohorts (Gutierrez et al., 2012; Levin et al., 2015). Increased preparatory and reactive neuromuscular control of the lateral ankle musculature and altered ankle joint kinematics has been shown in anticipation to inversion perturbations, indicating significant alterations to movement dynamics arise when there is knowledge of a potentially destabilizing perturbation (Dicus & Seegmiller, 2012; Gehring, Wissler, Lohrer, Nauck, & Gollhofer, 2014; Gruneberg et al., 2003). Therefore, anticipatory responses to inversion perturbations can confound biomechanical data and prohibits an accurate assessment of real time injury mechanisms and potential sensorimotor deficits arise from the constraints of CAI.

Individuals with CAI have been shown to exhibit alterations in preparatory and reactive neuromuscular control during single leg jump-landings (Caulfield et al., 2004; Delahunt et al., 2006; Kunugi et al., 2017; Li et al., 2018). Specifically, reports of significant reductions in preparatory peroneus longus and peroneus brevis muscle activity on the affected ankle in individuals with CAI has been reported when landing from a jump on one foot (Caulfield et al., 2004; Delahunt et al., 2006; Kunugi et al., 2017). These reductions in preparatory ankle evertor neuromuscular control have also corresponded with increased subtalar inversion angles and ankle frontal plane variability.
during the preparatory phase of a jump-landings (Delahunt et al., 2006; Kipp & Palmieri-Smith, 2012). This provides evidence that CAI alters centrally mediated motor control strategies, resulting from a constrained sensorimotor system, causing reduced ankle neuromuscular control in preparation for initial ground contact. Consequently, the maladaptive ankle movement dynamics may coincide with reduced dynamic ankle joint stabilization and an increased risk of aberrant ankle positioning when initial ground contact is unexpected.

Although recent investigations highlight potential anticipatory motor control alterations to inversion perturbations in individuals affected by CAI during bilateral jump-landings (Gutierrez et al., 2012; Levin et al., 2015), it is difficult to extrapolate results from these studies to a single leg landing that generally initiates the mechanism of a lateral ankle sprain (Terada & Gribble, 2015). Therefore, this investigation aimed to assess ankle kinematics and neuromuscular control in individuals with and without CAI during unexpected and expected single leg landings on an inverted surface that safely replicates the mechanism of a lateral ankle sprain. Given findings from previous studies investigating unexpected and expected bilateral landings on a tilted surface in CAI cohorts (Gutierrez et al., 2012; Levin et al., 2015), we hypothesized the CAI group would demonstrate reduced neuromuscular control and altered ankle kinematics compared to healthy controls during unexpected and expected unilateral landings on the tilted surface.

**Methods**

**Participants**

Fifteen individuals with CAI (n = 15) and 15 healthy matched controls (n = 15) based on age, mass, gender with no history of any musculoskeletal injuries to the lower
extremity completed study procedures. Individuals were placed in the CAI group if they had: (i) history of at least two lateral ankle sprains with one of those lateral ankle sprains occurring within the previous 12 months; (ii) sustained a lateral ankle sprain that required non-weight bearing activity and/or immobilization for ≥24 hours; (iii) experienced the affected ankle “giving way” or “feelings of instability”; (iv) a score of 27 or less Cumberland Ankle Instability Tool (CAIT; Gribble et al., 2014). Exclusion criteria included a history of surgery or fracture to either lower extremity, any acute musculoskeletal injury to the lower extremity within the previous 3 months, or a diagnosed musculoskeletal and/or neurological disease/disorder. All participants read and signed an informed consent document outlining potential risks and procedures of the study. Prior to the initiation of data collection, ethical approval for the study was obtained from the Institutional Review Board at the authors’ university.

**Instrumentation**

Flat and inverted platforms were constructed to allow a force platform (AMTI AccuGait, Watertown, MA, USA) sampling at 1,000 Hz to be embedded on the top of each platform. The inversion platform was rotated 20° in the frontal plane to produce an ankle inversion perturbation of upon landing from a height of 30 cm in the unilateral stance. Both the flat and inverted platforms were constructed to maintain a consistent step-down height of 30 cm from the center of the force platform and grip tape was applied to the top of the force platform to prevent the participants’ foot from slipping during the step-down task. The platform design was derived from recently published studies using unilateral landings on an inverted surface (Sato et al., 2017; Theodorakos et al., 2016) and an inversion perturbation of 20° was chosen for participant safety,
especially those with CAI, as lateral ankle sprains can occur when the subtalar joint exceeds 30° of inversion (Terada & Gribble, 2015).

Ankle kinematic data was collected at 100 Hz using a 3-dimensional motion capture system equipped with 12 infra-red Bonita 10 cameras (Vicon, Oxford, UK). Retro-reflective marker clusters were attached to the participant’s posterior pelvis and bilaterally on the thigh, shank, and dorsal foot using double sided tape and nylon therapeutic wraps to further reduce marker movement artifact.

A wireless surface electromyography (EMG) system (Noraxon, Scottsdale, AZ, USA) sampling at 1,500 Hz was used to collect muscle activity during the step-down task. Surface electrodes were placed with an inter-electrode distance of less than 2 cm over the most prominent part of the muscle belly of the tibialis anterior (TA), medial gastrocnemius (MG), peroneus longus (PL), and peroneus brevis (PB). Prior to electrode placement, each site was shaved, abraded, and thoroughly cleaned with isopropyl alcohol. The electrode placement sites were verified via manual muscle testing (Kernozek, Durall, Friske, & Mussallem, 2008; Knight & Weimar, 2011b).

**Procedures**

Participants first completed a familiarization session, which provided each participant with detailed information regarding study procedures. In addition, participants completed the CAIT questionnaire and were permitted to practice the step-down task onto the flat surface as many times as desired during this session. Although participants were made aware, both verbally and in the written consent document, that an inversion platform would be used without their knowledge during their testing session, participants
were restricted from visually seeing the inverted platform during this session to further reduce anticipation to the inversion perturbation.

Less than a week later, participants returned to the laboratory in a low top athletic shoe of their choice to complete their one day of testing session. Each testing session began with participants performing practice step-down trials (5-10 trials) onto the flat platform to establish a normal step-down pattern. The step-down task consisted of participants standing on the non-testing limb with their testing limb relaxed over the edge of a box that was raised 30 cm above the center of the force platform embedded on the flat platform. Participants were instructed to step forward and land on the platform with their testing limb only and subsequently take another 30 cm step down and land on the ground with their non-testing limb. This task is very similar to walking down a flight of stairs. During all step-down conditions, participants were reminded to keep their eyes facing forward and were required to wear dribbling goggles (Spalding, Bowling Green, KY, USA) to create visual obstruction of the participants’ feet and the landing surface. Participants then completed a total of five normal step-down trials onto the flat surface that were recorded with 30 s rest periods between each step-down trial. Following completion of the five normal step-down trials, participants were faced away from the testing space, and they listened to music being played on noise cancelling headphones for 60 s to take away the knowledge of the subsequent landing on either the flat or inverted surface.

Participants then completed a maximum of 10 more trials of the step-down task onto the flat surface with a 60 s breaks between trials while facing away from the testing space and listening to music being played on noise-cancellation headphones. However,
the inverted platform was switched with the flat platform without the participants’
knowledge on a random trial, which was randomized using Excel (Microsoft
Corporation, Redmond, WA, USA), and was considered the unexpected (UE) inversion
perturbation. Immediately following the UE trial, each participant subjectively reported
on a scale of 1-10 if they were expecting the inverted platform during the UE trial. To
further reduce anticipation to the UE inversion perturbation, trial numbers 1 and 10 were
excluded. Following the UE trial, the inverted platform was re-adjusted and participants
were given a 60 s break before completing the step-down task onto the inverted platform
again. However, this time the investigator gave participants the verbal instruction that
they will be “landing on the inverted platform” and treated as the expected (EXP)
inversion perturbation.

Data Processing and Analysis

All kinematic, muscle activity and force platform data was collected
simultaneously and time synchronized at 1,000 Hz using the MotionMonitor software
(Innovative Sports Training Inc., Chicago, IL, USA). Ankle kinematics were calculated
in the MotionMonitor software using the Grood-Suntay angle orientation method (Grood
& Suntay, 1983). Foot and ankle joint centers were defined in the software by placing the
measurement sensor on the lateral and medial malleoli and the distal second phalanx.
Knee joint centers were defined by placing the measurement sensor on the medial and
lateral femoral condyles, while hip joint centers were defined by placing the
measurement sensor on the anterior superior iliac spine and the L5/S1 joint (Gribble &
Robinson, 2010; Gribble & Robinson, 2009). Ankle and knee joint centers were
calculated using the centroid method, while hip joint centers were calculated using the Davis Method (Davis et al., 1991) in the MotionMonitor software.

The raw ankle kinematic data was filtered with a low-pass third-order Butterworth filter with a cutoff frequency of 15 Hz. The distal shank served as the frame of reference for all discrete ankle kinematic variables. Maximum inversion velocity, maximum ankle inversion angle, inversion angle at IC and time to maximum inversion angle were computed for UE and EXP trials. Maximum inversion velocity (°/s) and maximum inversion angle (°) was defined as the maximum inversion velocity and angle during the post-IC period, while time to maximum inversion angle in milliseconds (ms) was defined as the total time to complete the inversion perturbation during the post-IC period.

Raw EMG signals for each trial were amplified by a gain of 1,000, filtered using a third-order Butterworth filter with a cutoff frequency of 15-500 Hz, and full wave rectified in the MotionMonitor software prior to being exported for analysis. The average muscle activity during the 200 ms pre-initial contact (IC) and 200 ms post-IC was normalized to each participant's maximum 100 ms average of a 3 s maximum voluntary isometric contraction (MVIC) for each muscle. Pre-IC was identified as the 200 ms before IC (when the vertical ground reaction force exceeded 15 N), while post-IC was identified as the first 200 ms after IC. This 400 ms time window was selected to be analyzed as lateral ankle sprains occur within the first 200 ms of initial ground contact (Kristianslund et al., 2011; Terada & Gribble, 2015). Co-contraction index (CCI) was also calculated for pre-IC and post-IC from in the sagittal and frontal plane using equation 7 (Suda, Amorim, & Sacco Ide, 2009). Muscle pairs for sagittal plane CCI were
the TA and MG, while muscle pairs for frontal plane CCI were the combined average of the PL and PB and the TA.

\[
\text{Co-Contraction Index (CCI)} = \frac{EMG_{\text{Minimum}}}{(EMG_{\text{Minimum}} + EMG_{\text{Maximum}})/2}
\]  

(7)

Latency of the PL and PB was also calculated from the rectified EMG signal as the time in ms from when the vertical component of the ground reaction force exceeded 15 N, which coincided with the initiation of the inversion perturbation, to the point where muscle activity exceeded 5 standard deviations (SD) above the 200 ms pre-IC averaged muscle activity. While previous studies have used 2 SD (Hopkins et al., 2007; Midgley et al., 2007) and 10 SD (Knight & Weimar, 2011a, 2012b) thresholds, 2 SD may be too sensitive and 10 SD may be too high of a threshold to determine the onset of muscle activity. Therefore, we analyzed PL and PB latency using a 5 SD threshold to be consistent with previous literature examining latency during dynamic inversion perturbations (Knight & Weimar, 2011a, 2011b).

**Statistical Analysis**

Descriptive and dependent measures were calculated as mean ± SD. Independent samples two tailed \( t \)-tests were computed to compare CAIT scores and descriptive data between CAI and control groups. Ankle kinematic and EMG measures were analyzed using a series of 2 (condition) x 2 (group) mixed model analysis of variance (ANOVA) with condition (UE vs. EXP) serving as the repeated measure. Tukey’s post hoc tests were performed when significant interactions were found. Cohen’s D effect size data were also computed for all kinematic and EMG variables. Statistical analyses were
performed using a statistical software package (SPSS Statistics, Armonk, NY, USA). The level of statistical significance was set at 0.05.

**Results**

Descriptive and CAIT scores from the participants is presented in Table 5. Participants’ age, height, and mass were not statistically different between groups ($p > 0.05$). Individuals with CAI reported significantly lower CAIT scores ($p < 0.001$) and a significantly greater total number of lateral ankle sprain occurrences ($p < 0.001$).

Table 6 displays the ankle kinematic data from the UE and EXP trials. No significant condition by group interactions were found any of the ankle kinematic variables ($p > 0.05$). Significant group main effects were observed for time to maximum inversion and maximum inversion angle. The CAI group demonstrated significantly less time to maximum inversion ($p = 0.041; d = 0.53$) and a significantly greater maximum inversion angle ($p = 0.010; d = 0.80$). There was also a significant condition main effects for inversion angle at IC and maximum inversion angle, with significant reductions in maximum inversion angle ($p < 0.001; d = 0.95$) and significantly greater inversion angle at IC ($p = 0.003; d = 0.73$) during the EXP trial when compared to the UE trial. No other significant interactions or main effects were noted.

Tables 7-9 display muscle activity data from the UE and EXP trials. Results revealed no significant condition by group interactions for latency of the PL and PB, or for any of the pre-IC and post-IC muscle activity variables ($p > 0.05$). A significant group main effect for PL latency was observed, with the CAI group exhibiting significantly longer PL latency compared to the control group ($p < 0.001; d = 1.20$). Significant condition main effects were also observed for PL and PB latency, with significantly
reduced PL ($p = 0.004; d = 0.90$) and PB ($p = 0.011; d = 0.66$) latency during EXP when compared to UE (Table 3). Regarding post-IC muscle activity, significant condition main effects were found for TA and frontal plane CCI. Significantly greater TA activity ($p = 0.009; d = 0.40$) and frontal plane CCI ($p < 0.001; d = 0.97$) were found during the EXP trial in comparison to the UE trial. There were no other significant interactions or main effects for pre-IC or post-IC EMG variables.

**Discussion**

The primary objective of this study was to assess ankle kinematics and neuromuscular control in individuals with and without CAI during unexpected and expected inversion perturbations. The main findings in this study were that the CAI group exhibited reduced time to maximum inversion, greater maximum inversion angle and prolonged PL latency compared to controls. With respect to landing condition, the UE trial produced a greater maximum inversion angle, less inversion angle at IC, less TA muscle activity and frontal plane CCI 200 ms post-IC, and prolonged PB latency. This was the first study to our knowledge that examined ankle kinematics and neuromuscular control during unexpected and expected inversion perturbations when landing on one foot between CAI and healthy controls.

**Influence of Chronic Ankle Instability**

On average, significant reductions in time to maximum inversion and significantly greater maximum inversion angles were found in the CAI group in comparison to controls with medium to large effect sizes (Table 6). Spatial and temporal ankle kinematic parameters provide a means of assessing the ability of the primary ankle
evertors, particularly the PL and PB, to provide dynamic frontal plane stabilization through eccentric muscle actions that assist with controlling ankle inversion moments during sudden inversion (Knight & Weimar, 2012a). Previous studies have not reported any differences in time to maximum inversion between individuals with and without CAI (Eechaute, Vaes, Duquet, & Van Gheluwe, 2009; Vaes, Duquet, & Van Gheluwe, 2002). However, differences in methodological approaches implemented across these studies are a plausible explanation for the conflicting results. These studies utilized a trapdoor device, which produces sudden inversion of the subtalar joint by the platform unexpectedly falling away from beneath the participant while standing in a bilateral static position. The scope of this methodological approach is limited given that lateral ankle sprains do not occur when the floor falls away in a closed kinetic chain (Hopkins et al., 2007; Knight & Weimar, 2012a), and may not provide a reliable and valid assessment of the ability of the peroneal musculature to control frontal plane movement of the subtalar joint during a dynamic inversion perturbation. Given that a single leg landing on a tilted surface was utilized in the current study to closely mimic the mechanism of a lateral ankle sprain, increased maximum inversion angle and faster time to maximum inversion implies a reduced ability to prevent excessive frontal plane movement during an inversion perturbation when landing on one foot in individuals with CAI.

In addition, we also observed that individuals with CAI had a significantly longer latency of the PL with a large effect size (Table 7). It has been suggested that damage to the sensory receptors located within the lateral ankle ligaments can result in an inability of the gamma motoneuron system to adjust the sensitivity of the muscle spindles, making them less sensitive to any unexpected or rapid lengthening of the
peroneal musculature (Hertel, 2008). Consequently, this disruption in the gamma motoneuron loop would lead to reductions alpha motor unit activation and a longer reaction time to aberrant ankle positioning (Hertel, 2002; Hiller et al., 2011). Although there are reports of no differences in latency of the peroneal musculature between CAI and controls (Eechaute et al., 2009; Munn et al., 2010; Vaes et al., 2002), longer latency of the peroneal musculature has been reported in individuals with CAI (Donahue, Docherty, & Riley, 2014; Hopkins et al., 2009; Sierra-Guzmán et al., 2018; Vaes, Van Gheluwe, & Duquet, 2001). It should also be considered that the EMG processing techniques utilized across studies to determine the latency of the peroneal musculature during inversion perturbations varies widely, which is a likely explanation for the lack of consistent findings. In the present study, we chose a threshold of 5 SD above the 200 ms muscle activity prior to be consistent with previous studies examine peroneal latency during a single leg landing (Knight & Weimar, 2011a, 2011b). Therefore, our findings indicate that damage to the afferent receptors located within the lateral ankle ligaments, and potentially the lateral ankle musculature, alters spinal level motor control resulting in reduced sensitivity of the muscle spindles, and consequently, delayed reaction time of the PL to potentially injurious perturbations.

**Influence of Landing Condition**

An additional objective of this investigation was to assess potential anticipatory motor control strategies to ankle inversion perturbations when landing on one foot. When participants were expecting the inversion perturbation, significantly greater ankle inversion angle at IC and significant reductions in maximum ankle inversion angle with medium to large effects (Table 6; $d = 0.73-0.95$) were observed. That is, participants in
both groups displayed similar discrete ankle kinematics during the EXP landing condition. These findings are consistent with previous literature that has reported that knowledge of an inversion perturbation can alter post-landing discrete ankle kinematic parameters (Dicus & Seegmiller, 2012; Gehring et al., 2014). Dicus and Seegmiller (2012) were the first to examine ankle kinematics to unexpected and expected single leg landings onto a tilted surface in a group of healthy subjects and reported significant reductions in maximum ankle inversion angles when the inversion perturbation was expected. Similarly, Gehring et al. used a trapdoor in a walkway to also examine the influence of anticipation and found reductions in maximum ankle inversion angle with expectation to the ankle inversion perturbation (Gehring et al., 2014). Although these studies did not include an ankle sprain coper or CAI group comparison, the main effects for landing condition suggests similar anticipatory motor control strategies may be utilized between CAI and control groups to increase frontal plane stabilization in attempt to reduce the magnitude of frontal plane ankle displacement when there is knowledge of a destabilizing perturbation.

In addition, we also observe significant increases in TA muscle activity and frontal plane CCI with moderate to large effects (Table 9; $d = 0.40-0.97$) across both groups during the post-IC period during the EXP landing condition. Although some studies have reported reductions and in preparatory and reactive muscle activity on the affected ankle in individuals with CAI during jump- landings (Caulfield et al., 2004; Delahunt et al., 2006; Kunugi et al., 2017), other studies have found no differences (Brown, Ross, Mynark, & Guskiewicz, 2004; Levin et al., 2015) or increased muscle activity on the affected ankle (Gutierrez et al., 2012). It has been suggested that CAI may
not influence reflexive activation of the ankle musculature, but rather, alter spinal or supraspinal level feedforward motor control strategies (Hertel, 2008). While there is some evidence that does support this hypothesis, there are limited investigations that investigate the potential anticipatory motor control strategies to inversion perturbations during landing in individuals with CAI (Gutierrez et al., 2012; Levin et al., 2015). The increased TA muscle activity we observed during the EXP landing condition across both groups is likely a protective motor control strategy that arises in following foot contact in anticipation to an inversion perturbation to place the talocrural joint in a more tightly packed position to protect the lateral ankle ligaments from excessive frontal plane displacement. Likewise, the increase in TA muscle activity also resulted in increased frontal plane muscular co-contraction during the EXP trial, which coincided with reductions in maximum ankle inversion angle observed during the EXP landing. Therefore, these findings provide some evidence that a similar anticipatory motor control strategy may be elicited in individuals with and without CAI when there is knowledge of a potentially injurious perturbation.

**Limitations**

While we did observe differences in ankle kinematics and neuromuscular control between groups and landing conditions, there were limitations that should be mentioned. First, to ensure participant safety, especially for those with CAI, only an inversion perturbation of 20° was used to simulate the mechanism of a lateral ankle sprain. This resulted in inversion velocities that were below the velocities observed during injury scenarios. Second, only discrete ankle kinematic parameters were reported limiting the analysis of our current findings. Examining lower extremity kinematic patterns prior to
and during ground contact during unexpected inversion perturbations would further elucidate the feedforward and feedback motor control strategies that may be associated with recurrent lateral ankle sprains in CAI. Finally, only participants with and without CAI were included in the current study. Given that many individuals that sustain an acute lateral ankle sprain return to high-level activity without any residual impairments, investigating a group of ankle sprain copers in future research would further substantiate our findings.

**Conclusion**

The findings from the study indicate alterations to ankle kinematics and neuromuscular control, as evidence by prolonged PL latency, in individuals with CAI. However, when there was knowledge of the inversion perturbation, similar motor control strategies were elicited across both groups. Additional research is needed to further examine the potential protective and anticipatory motor control strategies in individuals with CAI to destabilizing perturbations. This data would further highlight the clinical applications of our findings and assist clinicians and researchers in developing effective perturbation training programs intended to mitigate the risk of recurrent injuries in individuals affected by CAI.
Table 5

Descriptive and Cumberland Ankle Instability Tool Data

<table>
<thead>
<tr>
<th>Variable</th>
<th>CAI (n = 15)</th>
<th>CON (n = 15)</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (y)</td>
<td>21.3 ± 1.6</td>
<td>21.5 ± 1.5</td>
<td>0.730</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.71 ± 0.11</td>
<td>1.70 ± 0.11</td>
<td>0.788</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>73.4 ± 15.2</td>
<td>75.5 ± 13.0</td>
<td>0.698</td>
</tr>
<tr>
<td>CAIT Score</td>
<td>18.9 ± 3.7</td>
<td>29.7 ± 0.6</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Total No. of Ankle Sprains</td>
<td>6.0 ± 3.2</td>
<td>0.0 ± 0.0</td>
<td>&lt; 0.001</td>
</tr>
</tbody>
</table>

CAI = chronic ankle instability group; CON = control group; CAIT = Cumberland Ankle Instability Tool; All data is reported as mean and standard deviation.

Table 6

Ankle Kinematic Data During the Ankle Inversion Perturbations

<table>
<thead>
<tr>
<th>Variable</th>
<th>Condition</th>
<th>p Value (d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time to Maximum Inversion (ms)</td>
<td>Unexpected</td>
<td>Expected</td>
</tr>
<tr>
<td>CAI</td>
<td>61.33 ± 19.91</td>
<td>56.36 ± 23.11</td>
</tr>
<tr>
<td>Control</td>
<td>68.87 ± 17.50</td>
<td>69.73 ± 18.77</td>
</tr>
<tr>
<td>Inversion Angle at IC (°)</td>
<td>Unexpected</td>
<td>Expected</td>
</tr>
<tr>
<td>CAI</td>
<td>11.35 ± 4.25</td>
<td>15.19 ± 5.17</td>
</tr>
<tr>
<td>Control</td>
<td>9.95 ± 5.44</td>
<td>13.66 ± 5.77</td>
</tr>
<tr>
<td>Maximum Inversion Angle (°)</td>
<td>Unexpected</td>
<td>Expected</td>
</tr>
<tr>
<td>CAI</td>
<td>21.39 ± 2.94</td>
<td>18.48 ± 3.86</td>
</tr>
<tr>
<td>Control</td>
<td>18.98 ± 2.90</td>
<td>15.93 ± 2.89</td>
</tr>
<tr>
<td>Maximum Inversion Velocity (°/s)</td>
<td>Unexpected</td>
<td>Expected</td>
</tr>
<tr>
<td>CAI</td>
<td>183.95 ± 70.67</td>
<td>186.86 ± 63.42</td>
</tr>
<tr>
<td>Control</td>
<td>167.25 ± 35.70</td>
<td>165.65 ± 67.99</td>
</tr>
</tbody>
</table>

† indicates statistically different than CAI group (p < 0.05); # indicates significantly different than the expected condition (p < 0.05). CAI = chronic ankle instability group; CON = control group; d = Cohen’s D effect size. All data are reported as mean and standard deviation.
Table 7

*Criteria for onset of muscle activity was determined as 5 standard deviations above average muscle activity 200 ms before initial contact. † indicates significantly different than CAI group (p < 0.05). # indicates significantly different than expected landing condition (p < 0.05). CAI = chronic ankle instability group; CON = control group; d = Cohen’s D effect size. All data are reported as mean and standard deviation.

Latency of the Peroneus Longus and Peroneus Brevis During the Ankle Inversion Perturbations

<table>
<thead>
<tr>
<th>Variable</th>
<th>Condition</th>
<th>p Value (d)</th>
<th>Group</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Unexpected</td>
<td>Expected</td>
<td></td>
</tr>
<tr>
<td><strong>Peroneus Longus Latency (ms)</strong>*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CAI</td>
<td>70.08 ± 20.25†</td>
<td>50.05 ± 16.08</td>
<td>0.004 (0.90) &lt; 0.001 (1.20)</td>
</tr>
<tr>
<td>Control</td>
<td>46.36 ± 12.89‡</td>
<td>37.87 ± 14.22†</td>
<td></td>
</tr>
<tr>
<td><strong>Peroneus Brevis Latency (ms)</strong>*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CAI</td>
<td>53.56 ± 13.77#</td>
<td>48.67 ± 16.71</td>
<td>0.011 (0.66) 0.208 (0.35)</td>
</tr>
<tr>
<td>Control</td>
<td>53.23 ± 16.00#</td>
<td>38.07 ± 14.83</td>
<td></td>
</tr>
</tbody>
</table>
Table 8

*Normalized Pre-Landing Muscle Activity Data During the Ankle Inversion Perturbations*

<table>
<thead>
<tr>
<th>Variable</th>
<th>Condition</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Unexpected</td>
<td>Expected</td>
</tr>
<tr>
<td><strong>Tibialis Anterior</strong></td>
<td>CAI</td>
<td>3.74 ± 2.67</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>3.86 ± 3.05</td>
</tr>
<tr>
<td><strong>Medial Gastrocnemius</strong></td>
<td>CAI</td>
<td>3.06 ± 2.67</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>2.65 ± 2.81</td>
</tr>
<tr>
<td><strong>Peroneus Longus</strong></td>
<td>CAI</td>
<td>4.43 ± 3.09</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>5.01 ± 3.92</td>
</tr>
<tr>
<td><strong>Peroneus Brevis</strong></td>
<td>CAI</td>
<td>3.80 ± 2.18</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>4.18 ± 3.16</td>
</tr>
<tr>
<td><strong>Sagittal Plane CCI</strong></td>
<td>CAI</td>
<td>0.53 ± 0.25</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>0.48 ± 0.23</td>
</tr>
<tr>
<td><strong>Frontal Plane CCI</strong></td>
<td>CAI</td>
<td>0.66 ± 0.22</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>0.66 ± 0.23</td>
</tr>
</tbody>
</table>

Muscle activity 200 ms pre-landing during the ankle inversion perturbations (%MVIC). CAI = chronic ankle instability group; CON = control group; CCI = co-contraction index; $d = $Cohen’s D effect size; MVIC = maximum voluntary isometric contraction.
Table 9

Normalized Post-Landing Muscle Activity During the Ankle Inversion Perturbations

<table>
<thead>
<tr>
<th>Variable</th>
<th>Condition</th>
<th>p Value (d)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Unexpected</td>
<td>Expected</td>
</tr>
<tr>
<td><strong>Tibialis Anterior</strong></td>
<td>CAI</td>
<td>2.96 ± 1.88*</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>2.72 ± 1.09*</td>
</tr>
<tr>
<td><strong>Medial Gastrocnemius</strong></td>
<td>CAI</td>
<td>8.02 ± 5.50</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>5.00 ± 4.82</td>
</tr>
<tr>
<td><strong>Peroneus Longus</strong></td>
<td>CAI</td>
<td>5.42 ± 3.17</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>5.32 ± 3.75</td>
</tr>
<tr>
<td><strong>Peroneus Brevis</strong></td>
<td>CAI</td>
<td>7.01 ± 2.63</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>6.81 ± 5.44</td>
</tr>
<tr>
<td><strong>Sagittal Plane CCI</strong></td>
<td>CAI</td>
<td>0.57 ± 0.25</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>0.58 ± 0.23</td>
</tr>
<tr>
<td><strong>Frontal Plane CCI</strong></td>
<td>CAI</td>
<td>0.58 ± 0.21*</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>0.60 ± 0.23*</td>
</tr>
</tbody>
</table>

* indicates significantly different than expected trial (p < 0.05). Muscle activity 200 ms post-landing during the ankle inversion perturbations (%MVIC). CAI = chronic ankle instability group; CON = control group; CCI = co-contraction index; d = Cohen’s D effect size; MVIC = maximum voluntary isometric contraction.
CHAPTER VI
CONCLUSIONS

While lateral ankle sprains are often viewed by the general population as an injury with no long-lasting consequences, the sensorimotor and mechanical constraints that arise from an acute lateral ankle sprain can negatively impact postural control, dynamic movement mechanics, and neuromuscular control to inversion perturbations. The findings from this investigation provides evidence that individuals affected by CAI demonstrate significant impairments in postural control during a single leg squat, altered movement strategies during a side-cut task, and neuromuscular control deficits during an inversion perturbation when compared to healthy controls. However, similar anticipatory motor control strategies were elicited in CAI and healthy controls when inversion perturbations were expected. Results from this study will benefit researchers and clinicians in developing appropriate rehabilitation protocols that are intended to restore the sensorimotor deficits that persist following a lateral ankle sprain injury and to mitigate the risk of recurrent injury and the development of CAI.

This single leg squat task revealed that individuals with CAI displayed postural control deficits in comparison to healthy controls. Although no significant differences were observed in the eight traditional COP measures calculated, significant reductions in TTB measures were noted on both limbs in the CAI group. These findings would suggest that TTB measures of postural control, which have been underutilized in postural control
assessments in CAI cohorts, may be more effective at detecting postural control impairments than traditional COP based measures. Additionally, these findings indicate significant constraints on the sensorimotor system that arise from chronic ankle joint instability resulting in centrally mediated spatiotemporal postural control alterations during functional movements. These deficits in postural control during a functional movement further highlights a potential underlying mechanism to the development of chronic ankle joint instability, which may contribute to the recurrent episodes of the ankle giving way frequently experienced during functional and dynamic movements in individuals affected by CAI.

During the stance phase of the side-cut task, individuals with CAI displayed altered ankle joint kinetics and increased hip joint stiffness. These findings would indicate the potential changes in movement dynamics that arise due to the sensorimotor and mechanical constraints. In order to reduce the demands on the more distal segments, such as the affected ankle, during a dynamic movement task, participants with CAI adopted a more proximal joint movement strategy. This movement strategy has been well-documented across the literature in a variety of functional and dynamic tasks and has been shown to manifest following a first time, acute lateral ankle sprain and well into chronicity. Consequently, this hip dominant strategy is often considered a maladaptive movement pattern that is invariably considered to contribute to recurrent lateral ankle sprains in CAI populations. While findings from the side-cut task identify differences in movement dynamics in individuals with and without CAI, a gap remains in the literature regarding movement strategies during side-cut and rapid change of direction tasks, which
often initiate the mechanism of a lateral ankle sprain, and further examining of these
movements in CAI cohorts is warranted.

Despite extensive literature examining neuromuscular control and lower extremity
kinematics in individuals with CAI during inversion perturbations, few investigations
have considered the anticipatory motor control strategies to inversion perturbations.
Results from the unexpected and expected landings on the inverted surface provide
evidence that neuromuscular control impairments do manifest in individuals with CAI.
Researchers have suggested that spinal, or supra-spinal, level feedforward alterations to
motor control strategies occur from the neuromuscular and mechanical constraints of
CAI. While there is certainly evidence to support this theory, the results from this
investigation indicate that individuals with CAI displayed similar feedforward and
feedback motor control strategies during both unexpected and expected landing
conditions.

**Limitations**

The primary limitation to this study was that dynamic movements that generally
initiate the mechanism of a lateral ankle sprain, such as a single leg landing on one foot
or a side-cut task used in this study, were only simulations. Various intrinsic and extrinsic
human/environmental factors that are commonly present during real time injury scenarios
were absent during these tasks, and therefore, may limit the interpretation of the current
findings. Second, there is still a possibility that individuals were anticipating the
unexpected inversion perturbation. Although we did implement a protocol that has been
shown to discriminate between unexpected and expected perturbations and constantly
reminded participants to use a normal step-down pattern, participants having the
knowledge that a destabilizing perturbation was going to occur at some point during their step-down trials could have confounded the results. Finally, only CAI and control groups were tested and compared. Many individuals that sustain a lateral ankle sprain return to high-level activity without any residual impairments or complaints of instability and are deemed ankle sprain copers. Given that lateral ankle sprains are the most common musculoskeletal injury, examining differences between groups CAI, ankle sprain copers, and control groups may provide a more clinically relevant comparison.

**Future Research**

In order to further substantiate the findings of the current study, future research should examine other functional tasks commonly implemented in rehabilitation programs to quantify postural control using both traditional COP and TTB measures to detect deficits in postural control and those at risk to develop CAI following a lateral ankle sprain. Future studies should also consider implementing protocols that investigate the differences between anticipated and unanticipated change of direction tasks. This would further emphasize the potential movement strategies that cause the ankle to give way during side-cut or rapid change of direction movements. Finally, research should continue to investigate the anticipatory motor control mechanisms to various destabilizing perturbations in individuals with CAI. This would further assist researchers and clinicians in developing rehabilitation and perturbation training protocols that are intended to mitigate recurrent injuries and restore the sensorimotor impairments that manifest following a lateral ankle sprain.
REFERENCES


doi:10.1016/j.gaitpost.2013.11.016

doi:10.1007/s00167-016-4059-4


doi:https://doi.org/10.1016/j.jbiomech.2018.05.015


APPENDIX A

INSTITUTIONAL REVIEW BOARD APPROVAL AND
INFORMED CONSENT DOCUMENT
Title of Research Study: Functional and Dynamic Task Performance in Individuals with and without Chronic Ankle Instability

Study Site: Human Performance Laboratory, Center for Advanced Vehicular Systems Neuromechanics Laboratory, Department of Kinesiology, McCarthy Gym 117

Researchers: Jeffrey Simpson and Dr. Adam Knight, Department of Kinesiology, Mississippi State University

Purpose

This study will look at how ankle instability changes one leg squat and change of direction performance. We will also look at a one leg landing on a flat and tilted surface. We want to see if people with ankle instability perform a one leg squat and change of direction task differently than people that do not have ankle instability. In addition, we want to see if people with and without ankle instability land differently when they know what surface they will be landing on.

Procedures

If you do this study, you will be asked to come to the Neuromechanics Laboratory, located in room 117 of McCarthy Gymnasium. To do this study, you must be 18-35 years old, and meet this criterion: no history of broken bones in your lower leg, surgery, and no diagnosed disease or disorder. Also, you must exercise every week (150 minutes or more of moderate or 75 minutes or more of vigorous physical activity per week). After coming to the Neuromechanics Laboratory, you will be asked to fill out the Cumberland Ankle Instability Tool (CAIT), physical activity and injury surveys. These surveys are given to know
participants’ ankle sprain history, ankle instability, pain, or any other disease or disorder. After filling out the surveys, you will be able to read and ask questions about this consent document and the study procedures. After signing the consent document, your height, weight, and foot arch height will be measured by the researchers, and then you will be allowed to practice each of the tasks that you will perform during the study. This visit should take about 30 minutes to complete.

The second day you will be asked to report to the Human Performance Laboratory located in room 1109 in the Center for Advanced Vehicular Systems. You will be asked to a t-shirt and athletic shorts and a pair of non-high top athletic shoes. Upon arriving at the Human Performance Laboratory, you will be prepared for testing. We will use EMG (electromyography) to measure the muscle activity of six muscles in your lower leg. We will put small, sticky pads over six different spots on your dominant leg, which is the leg you use to kick a ball with. To get a good EMG signal, we may have to shave, clean, and slightly rub the places where the sticky pads will be placed. This will be a small area on the front, back, and side of your lower leg. After the sticky pads are placed on each of these areas, you will be asked to push as hard as possible with your foot and leg against an immovable object in different directions to measure your maximum muscle activity. You will have to pull your foot up, push your foot down, and push your foot to each side and flex and extend your knee. You will be asked to do this in each direction for about 3 to 5 seconds.

After the sticky electrodes are placed on your lower leg and we have measured your maximum muscle activity, special marker sets (clusters) will be placed on your lower body. These will be placed over your clothing and some will be attached directly to your
skin. The markers will be placed on your lower back, both of your thighs, both of your shins, and the top of both of your feet. The markers will be secured to your body using a non-sticky athletic wrap. These markers are used to see your body movements with the special cameras that are in the lab. This will allow us to create a skeleton model of your body and measure your different movements during the study. Nobody will know who you are from your motion capture trials, it only displays a general model of the skeletal system and no identifying features. Once the sticky pads and markers are placed on you, the researchers will ask you to stand in the center of the room. A researcher will use a wand like device to point to different bony parts and your joints, such as your hip, knee, and ankle so the camera system will know where the specific body parts of your lower body are located. You will be asked to stand still for about one or two minutes. After we have set you up on the camera system, the next step in the study is to complete each performance task.

**One Leg Squat**

First, you will do a one leg squat. You will be asked to place your testing foot on the center of a force platform that is raised 10 inches from the ground on a flat platform. An investigator will give you a verbal cue and you will descend the non-testing foot 10 inches without shifting your weight onto the non-testing foot. During the descent, you will be required to touch a force platform with the heel of your non-testing foot that is positioned beneath you. After you contact the force platform placed beneath you, then you will ascend back to the standing position. During the single leg squat task, you will be asked to keep both hands on your hips and keep your eyes facing forward. You will be
asked to complete a total of 10 trials, 5 trials on the dominant leg and 5 trials on the non-dominant leg.

**Change of Direction Task**

Next, you will do a change of direction task. You will stand 70 cm from the center of a platform and asked to stand on your non-testing leg with your knee slightly bent. After a verbal cue from a researcher, you will jump forward and land on the platform with your testing foot and quickly change direction 45 degrees towards the non-testing leg and run 3 meters as fast as possible. This 45-degree angle will be marked on the ground with tape and you will be asked to follow these markings as best as possible. You will do a total of 6 trials, 3 trials on your dominant limb and 3 trials on your non-dominant limb.

**Step Down Task**

Last, you will do a step-down task. You will be asked to stand on a 24-inch-high box and wear a pair of sports glasses that do not let you see your feet. You will be asked to place the foot of your dominant leg out in front of the box, balancing on your non-dominant leg. When told, you will step off the box from a height of 12 inches, landing on the force platform with your dominant leg, and then you will take an additional 12-inch step down from the force platform onto the ground with your non-dominant leg. The task is like walking down two stairs. The force platform will be placed on either a flat surface or a surface that is tilted 20 degrees with respect to the ground. On each platform, the center of the force platform will be 12 inches above the ground and 12 inches below the top of the box you are standing on. You will perform a minimum number of 8 trials and a maximum number of 20 trials. The first 5 trials you will step down onto the force platform located on the flat surface. You will be given 1 minute of rest between each of
these 5 trials. After the first 5 trials, you will be given noise cancelling headphones to wear and will face away from the testing area. During trials 6 through 15, you will step down onto the force platform on the flat surface, but during 1 of the trials, you will step down onto the force platform on the surface that is tilted 20 degrees with respect to the ground. The placement of this step down onto the rotated surface will be random during trials 6-15 (unexpected landing) and spotters will be there to catch you if you lose your balance. You will be given 3 minutes of rest between trials 6-15. After performing the step-down trial onto the rotated surface, you will perform another step-down trial onto the rotated surface, but you will know that you are stepping down onto the rotated surface. After performing the second step down trial onto the rotated surface, you will perform 1 final step down task onto the force platform on the flat surface. The second day of the study will take about 90 minutes. The total time commitment for the entire study is about 120 minutes.

**Risks or Discomforts**

There is a risk that you might have an allergic reaction to the sticky glue found on the EMG pads, or a reaction to the rubbing and cleaning of the sticky pad sites. If you have a bad allergy, please let the researchers know. There is a small risk of injury during the one leg squat, change of direction, and step down task. The distance you are required to step down is small, but it is possible to sustain an injury such as an ankle sprain. Spotters will be present to assist you if you do lose your balance when stepping down or during the one leg squat. However, to further decrease the risk of injury you will be allowed to practice all the performance tasks before any data is collected.
Benefits

There are no direct benefits from participating in this study.

Confidentiality

Your data and information will only be handled by the researchers listed on this form. The signed consent documents will be stored in a file cabinet in a location that only the researchers listed on this form have access to. All data files will be stored on the password protected computer in the Human Performance Lab. A copy of the data may also be transferred and stored on a password protected University computer in the Neuromechanics Lab. All data will be given a code and the code sheet will be destroyed when data collection is completed.

Please note that these records will be held by a state entity and therefore are subject to disclosure if required by law. Research information may be shared with the MSU Institutional Review Board (IRB) and the Office for Human Research Protections (OHRP) and others who are responsible for ensuring compliance with laws and regulations related to research. The information from the research may be published for scientific purposes; however, your identity will not be given out.

Questions

If you have any questions about this research project or want to provide input, please feel free to contact Jeffrey Simpson or Adam Knight at 662-325-2963, or email us at jds1313@msstate.edu and/or ack24@msstate.edu.

For questions regarding your rights as a research participant or to request information, please feel free to contact the MSU Human Research Protection Program (HRPP) by
phone at 662-325-5220, e-mail at irb@research.msstate.edu, or visit our participant page on the website at http://orc.msstate.edu/humansubjects/participant/.

To report problems, concerns, or complaints pertaining to your involvement in this research study, you may do so anonymously by contacting the MSU Ethics Line at http://www.msstate.ethicspoint.com/.

**Research-related injuries**

MSU has not provided for any payment to you or for your treatment if you are harmed because of taking part in this study.

In addition to reporting an injury to Jeffrey Simpson or Adam Knight at 662-325-2963 and to the Research Compliance Office at 662-325-3994, you may be able to obtain limited compensation from the State of Mississippi if the injury was caused by the negligent act of a state employee where the damage is a result of an act for which payment may be made under §11-46-1, et seq. Mississippi Code Annotated 1972. To obtain a claim form, contact the University Police Department at MSU UNIVERSITY POLICE DEPARTMENT, Williams Building, Mississippi State, MS 39762, (662) 325-2121.

**Voluntary Participation**

Please understand that your participation is voluntary. Your refusal to participate will involve no penalty or loss of benefits to which you are otherwise entitled. You may discontinue your participation at any time without penalty or loss of benefits.

Additionally, the researchers reserve the right to terminate the subject’s participation in the study without the subject’s consent.
### Options for Participation

Please initial your choice for the options below:

- ___ The researchers may contact me again to participate in future research studies about ankle stability.

- ___ The researchers may NOT contact me again regarding future research.

---

Please take all the time you need to read through this document and decide whether you would like to participate in this research study.

If you agree to participate in this research study, please sign below. You will be given a copy of this form for your records.

________________________________________  __________
Participant Signature  Date

________________________________________  __________
Investigator Signature  Date
From: nrs54@msstate.edu
Sent Date: Wednesday, February 21, 2018 11:25:03 AM
To: ack24@msstate.edu, ajt188@msstate.edu, bam610@msstate.edu, 
ems664@msstate.edu, hc783@msstate.edu, hw557@msstate.edu, 
jd1313@msstate.edu, ly161@msstate.edu, mak525@msstate.edu, 
mrb710@msstate.edu, mw2049@msstate.edu, pes103@msstate.edu, 
rjb2@msstate.edu, rgb166@msstate.edu, rmr319@msstate.edu, smc798@msstate.edu, 
snk128@msstate.edu, tpl52@msstate.edu, zp147@msstate.edu, zrs48@msstate.edu
Cc: 
Bcc: 
Subject: Approval Notice for Study # IRB-18-023, Functional and dynamic task performance in 
individuals with chronic ankle instability.

Message:
Protocol ID: IRB-18-023
Principal Investigator: Adam Knight
Protocol Title: Functional and dynamic task performance in individuals with chronic ankle instability.
Review Type: EXPEDITED
Approval Date: February 21, 2018
Expiration Date: February 15, 2019

The above referenced study has been approved. To access your approval documents, log into 
myProtocol and click on the protocol number to open the approved study. Your official approval letter 
can be found under the Event History section. For non-exempt approved studies, all stamped 
documents (e.g., consent, recruitment) can be found in the Attachment section and are labeled 
accordingly.

If you have any questions that the HRPP can assist you in answering, please do not hesitate to 
contact us at irb@research.msstate.edu or 662.325.3994.
APPENDIX B

PHYSICAL ACTIVITY AND INJURY HISTORY QUESTIONNAIRE
Physical Activity and Injury Questionnaire

1. How many days per week do you typically engage in physical activity?
   0-1  2-3  4-5  5+

2. How many hours per week would you estimate you lift weights?
   ___________________

3. How many hours per week would you estimate you do high-intensity exercise?
   ______

4. How many hours per week would you estimate you do aerobic exercise?
   __________

5. Have you ever had any kind of surgery on your lower extremity?
   YES   NO

6. Have you ever been diagnosed with any neurological, musculoskeletal, and/or cardiopulmonary disease or disorders?
   YES   NO

7. Have you ever sustained a lateral ankle sprain?
   YES   NO
   If you answered YES, when was the last time you suffered a lateral ankle sprain?
   __________________________________________________________________

8. If you answered YES to question 7, was your ankle sprain diagnosed by a physician, athletic trainer, physical therapist, etc.?
   YES   NO

9. Did you have to wear any type of ankle brace/tape/walking boot OR limit your physical activity for more than 24 hours when you sprained your ankle?
   YES   NO
10. Have you ever felt like your ankle(s) were unstable during physical activity?
   YES  NO
   If you answered YES, what activities make your ankle(s) feel unstable?
   ________________________________________________________________

11. Have you ever sustained any other kind of injury to your lower extremities?
   YES  NO
   If you answered YES, please explain:
   ________________________________________________________________

12. How many total ankle sprains have you sustained, if any? _________________

13. Are you currently involved in playing recreational or competitive sports?
   YES  NO
   If yes, what sports?
   ________________________________________________________________

CAIT SCORE: _______________
APPENDIX C

CUMBERLAND ANKLE INSTABILITY TOOL
Figure C1. Cumberland Ankle Instability Tool (CAIT) questionnaire

(Hiller et al., 2006)
APPENDIX D

RECRUITMENT FLYER
Participants Needed!!!

Influence of chronic ankle instability on single leg squat, lateral side-cut, and landing performance

We are conducting a research project to investigate the potential impact of chronic ankle instability (i.e. history of ankle sprains) on single leg squat, lateral side-cut, and landing performance. We are looking for healthy male and female participants that meet these criteria:

➢ Males and females in the age range of 18 – 35 years
➢ No history of lower extremity fracture, lower extremity surgery, or any neurological/musculoskeletal/cardiovascular disorder or disease.
➢ Physical fitness level must meet the minimum recommended guidelines for adults to participate in the study. The minimum recommended guidelines are defined as ≥ 150 minutes per week of moderate intensity physical activity or ≥ 2 days per week of resistance training exercise.

In addition to the above criteria, individuals must also:
➢ Have no history of an ankle sprain OR have suffered an ankle sprain within the last 12 months
➢ Have no history of an injury to any other joint in the lower extremity (i.e. knee or hip) within the previous 3 months.

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APPENDIX E

RETRO-REFLECTIVE MARKER PLACEMENT
Figure E1. Retro-reflective marker placement on the participant

Retro-reflective marker sets (i.e. clusters) were placed on the posterior pelvis (right) and on both thighs, lower leg, and feet (left). Clusters were attached using double sided tape and nylon orthopedic wraps.
APPENDIX F

SURFACE ELECTROMYOGRAPHY PLACEMENT
Figure F1. Anterior view of the surface electromyography electrode placement on the participants

Figure F2. Sagittal view of the surface electromyography electrode placement on the participants
Figure F3. Posterior view of the surface electromyography electrode placement on the participants