

KINEMATIC PATTERNS ON THE STAR EXCURSION BALANCE TEST AND Y-  
BALANCE TEST AND POSTURAL STABILITY IN INDIVIDUALS WITH CHRONIC  
ANKLE INSTABILITY

by

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ABSTRACT

*Background:* The star excursion balance test (SEBT) and Y-balance test (YBT) are similar tests that have been commonly applied to assess dynamic postural stability deficits in the Chronic Ankle Instability (CAI) population. However, they could in fact require different task performance and/or movements to assess dynamic postural stability, as they use different measuring techniques and one uses a platform. The purposes of this study were to determine if there is a significant difference in performance in the kinematic patterns of CAI and control groups on the SEBT and the YBT, and to determine if there is a significant difference in dynamic postural control stability between the groups while performing the SEBT. *Methods:* 70 participants (35 in the CAI and 35 in the control group) performed in the Anterior (AN), Posteromedial (PM), and Posterolateral (PL) directions of the SEBT (on the single force plate) and the YBT. Also, the kinematics of hip, knee, and ankle joint in sagittal, frontal, and transverse planes were calculated and analyzed. Center of Pressure (COP) data with a sampling rate of

180Hz were collected while performing the SEBT. *Findings:* Compared with the control group, the CAI group achieved significantly shorter reach distance in the AN and PM reach directions on the SEBT. On the YBT, the CAI group had significantly shorter reach distance in the PM and PL directions compared with the control group. In the CAI group, participants had significantly greater reach distance in the PL direction on the YBT compared with the SEBT. Comparing performance on the SEBT and YBT within each group, significant differences in angular displacement and joint angle at the point of maximum reach at the hip, knee, and ankle in 3 planes were observed. The CAI group had significantly lower A-P  $COP_{SD}$  (cm) and  $COP_{A-95}$  (cm<sup>2</sup>) than the control group while performing the SEBT in the AN, PM, and PL reach directions. *Interpretation:* Clinicians and researchers should not apply these dynamic postural control tasks interchangeably or compare reach distances from one task to another. Also, clinicians may need to incorporate rehabilitation techniques to challenge COP control during dynamic balance tasks.

**INDEX WORDS:** functional performance tests, postural stability, joint angular kinematics

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## CHAPTER 1

### INTRODUCTION

Lateral ankle sprains are the most common single injury during sports participation and the most commonly observed type of ankle sprain.<sup>1,2</sup> Approximately 628,000 ankle injuries, including fractures and sprains, occur every year in the United States.<sup>3</sup> Such injuries are commonly treated in emergency rooms, accounting for about 20% of all injuries treated in emergency rooms in the United States.<sup>3</sup> Additionally, ankle sprains lead to significant lost time due to injury, delayed return to physical activity, and long-term disability in up to 60% of patients.<sup>1,4</sup>

The primary predisposing factor of incurring an ankle sprain is a history of having had prior ankle sprains.<sup>5</sup> Recurrent ankle sprain is a common problem. Eighty percent of individuals have experienced recurrent ankle sprain after the initial ankle sprain.<sup>1</sup> A previous study<sup>4</sup> found that 40% of individuals reported persistent symptoms of Chronic Ankle Instability (CAI) after they returned to full physical activity from the initial incident. Therefore, the initial ankle sprain may lead to recurrent ankle sprains, which may result in CAI. CAI can be defined by a repeated sensation of giving way, a feeling of ankle instability, and recurrent ankle sprains.<sup>6,7</sup>

Additionally, individuals with CAI typically report pain and functional deficits in ankle proprioception, cutaneous sensation, nerve-conduction velocity, neuromuscular response times, postural control, and strength.<sup>8-10</sup> Furthermore, 68–78% of individuals with CAI have experienced post-traumatic ankle osteoarthritis.<sup>11-13</sup> Identifying whether or not someone has CAI

and classifying the degree of CAI severity are of critical importance. However, determining the best way to identify those with CAI and quantify the degree of dysfunction is unclear and currently difficult. One possible solution is to use functional performance tests, which are dynamic physical measures to evaluate general lower body function. Functional performance tests are very useful because they combine multiple components, such as muscular strength, neuromuscular coordination, and joint stability, which could be affected by joint injury.<sup>14,15</sup> Docherty et al.<sup>14</sup> found that individuals with CAI tend to present with functional performance deficits. Specifically, dynamic postural control tests have been used to measure and/or identify functional performance deficits in individuals with CAI.<sup>16</sup>

The Star Excursion Balance Test (SEBT) is one of the most commonly used dynamic postural control tests in clinical and research settings.<sup>17</sup> The SEBT is an established outcome measure of dynamic postural stability that assesses a combination of range of motion, flexibility, and neuromuscular control, with test-retest intra-class correlation ranging from 0.89 to 0.93 and coefficients of variation ranging from 3.0% to 4.6%, thus indicating good measurement stability.<sup>18</sup> It is simple to use with tape or measuring tape on any flat floor surface.

The Y-Balance Test™ (YBT) (Functional Movement.com, Danville, VA) is a commercial product that has been developed to improve the efficiency of administration of the SEBT. The YBT only comprises 3 reach directions including the anterior (AN), posteromedial (PM), and posterolateral (PL) compared to the 8 directions of the SEBT.<sup>18</sup> The YBT kit consists of a raised platform and 3 reach arms attached to sliding measuring boxes. The advantage of the YBT is that it takes less time to complete. Plisky et al.<sup>18</sup> and Shaffer et al.<sup>19</sup> reported excellent inter-rater (0.99 – 1.00), intra-rater (0.85 – 0.91), test-retest reliability, and standard error measure (SEM) among multiple raters.

As a modified version of the SEBT, the YBT should produce similar results in the AN, PM, and PL reach directions, and both tests should require a similar movement strategy. These tests are often used interchangeably, but could in fact assess different performance abilities. Moreover, previous studies<sup>20,21</sup> found that participants reached farther in the AN reach direction on the SEBT than on the YBT and participants were characterized by a more flexed position of the hip joint at the point of maximum reach on the YBT than on the SEBT. These studies only evaluated reach distance and only in healthy populations. Also, a previous study<sup>21</sup> did not investigate the kinematic pattern in all 3 planes.

While the YBT and SEBT both measure reach distances of one single limb while in single limb stance, the techniques for the tests are different. The YBT requires the participant to stand on one limb on the elevated pedestal and use the toe of the other limb to slide an indicator down a calibrated pipe, thus partially weight-bearing or at least touching a surface with this reach limb. However, the SEBT requires the participant to stand on the floor on one leg, and then move the other foot out as far as possible to reach, without weight-bearing or touching the ground until the reach limb toe touches the ground at the maximum reach distance.

Various instrumented clinical postural control tests have been developed to identify those with CAI for the purpose of research and clinical assessment.<sup>16,22</sup> Instrumented clinical postural stability tests using a force plate (e.g., center-of-pressure velocity [COPV], center-of-pressure area [COPA], time to boundary [TTS], and dynamic postural stability index [DPSI]) have been validated and associated with self-reported ankle instability in individuals with CAI.<sup>16,22-24</sup> Although many previous studies have been conducted to measure postural stability performance on the force plate, to our knowledge, most of them measured postural-stability performance in static positions with eyes open and/or closed or in dynamic postural control while maintaining

their balance from a single leg landing. However, no studies have measured instrumented dynamic postural stability while performing the SEBT.

### Statement of problem

Despite consistent use of the SEBT to determine reach deficits both between and within healthy individuals and those with CAI, no previous study has measured performance using the YBT in individuals with CAI.<sup>25</sup> A comparison of any differences between reaching performance on the SEBT and the YBT in the CAI population should be established because of the increasing popularity of the YBT in the research and clinical settings. These tests are being used interchangeably, but there is little evidence to support that assumption. Providing researchers and clinicians with evidence for or against similarity can standardize testing and interpretation of results.

Additionally, postural control deficits have been previously identified in the CAI population using a variety of force plate measures. Traditionally, postural control is evaluated using the center of pressure (COP), dynamic postural stability index (DPSI), and time-to-boundary (TTB) either in the static position with eyes open or closed, or in dynamic postural control while maintaining their balance from a single leg landing.<sup>26-28</sup> However, to our knowledge, no study has measured postural control stability on the SEBT in individuals with and without CAI. We already know that performance on the SEBT reach is decreased in a CAI group; however, we do not know what is driving that poor performance. Is it kinematic patterns or/and postural stability ability? Previous COP studies have used only a static single leg stance or a single leg jump landing. It is relevant to know if COP measures are different between the groups while they perform a dynamic postural control test (the SEBT) because this will reveal

movement techniques utilized by individuals with CAI. Static and dynamic postural stability are different constructs and represent different abilities.<sup>29</sup> Applying instrumented measures to dynamic tests can increase our understanding of performance deficits and offer guidance for rehabilitation program development. Specifically, limitations in joint range of motion, strength, or proprioceptive ability, or changes in proximal joint kinematics could influence rehabilitation program design and emphasis.

We believe that it is imperative to determine whether different postural control mechanics exist between the groups while performing the SEBT. Our finding may provide clinicians with not only reach deficits in individuals with CAI but also more specific information about how the reach deficit is caused, which could help establish better rehabilitation protocols.

#### Statement of purpose

Investigating differences between reach performance on the SEBT and the YBT in individuals with CAI and postural control stability while performing the SEBT in individuals with and without CAI may help clinicians know how performance may differ on the SEBT and the YBT for their specific population, as well as help determine how to best implement the SEBT in the management of CAI. Therefore, the purposes of our study were (1) to determine if there was a significant difference in performance in 3 reach directions and in kinematic patterns of individuals with and without CAI while performing the SEBT and the YBT, and (2) to determine if there was a significant difference in dynamic postural control stability between the groups while performing the SEBT as a clinical tool for the quantification of dynamic postural deficits from lower extremity impairment.

### Significance of the study

The different techniques required for performing on the SEBT and the YBT could lead to differences in performance and movement strategy. Therefore, the kinematic information from our study might be helpful to clinicians when deciding which reach directions and type of test (SEBT or YBT) to use in individuals with a specific range of motion (ROM) impairment. Also, investigating postural control stability while performing the SEBT may identify the root cause of the deficits in reach distance and offer suggestions for targeted rehabilitation that addresses postural stability deficits in the CAI population. Therefore, we believe that identifying the different mechanics between groups while performing the SEBT may aid clinicians in determining better rehabilitation interventions.

### Research questions and hypotheses

1. Is there a difference in reach distance performances for AN, PM, and PL directions of the SEBT and the YBT in the CAI group and the control group?  
  
H1: The CAI group would have significantly shorter reach distance on the SEBT and the YBT than the control group.  
  
H2: The CAI group would have significantly less reach distance on the SEBT than on the YBT.  
  
H3: The control group would have significantly less reach distance on the SEBT than on the YBT.
2. Are there statistically significant differences ( $\alpha \leq 0.05$ ) between the CAI group and the control group in kinematics while performing the SEBT and the YBT?

H1: The CAI group would have significantly decreased joint angles at the point of maximum reach and angular displacements at the hip, knee, and ankle joints in the three planes (sagittal, transverse, and frontal) on the SEBT.

H2: The CAI group would have significantly less joint angles at the point of maximum reach and angular displacements at the hip, knee, and ankle joints in the three planes (sagittal, transverse, and frontal) on the YBT.

H3: The CAI group would have greater joint angles at the point of maximum reach and angular displacements at the hip, knee, and ankle joints in the three planes (sagittal, transverse, and frontal) on the YBT than on the SEBT.

H4: The control group would have greater joint angles at the point of maximum reach and angular displacements at the hip, knee, and ankle joints in the three planes (sagittal, transverse, and frontal) on the YBT than on the SEBT.

3. Are there statistically significant differences between the CAI group and the control group in dynamic postural stability during performance on the SEBT?

H1: There is a statistically significant difference in the dynamic postural stability measures between the CAI group and the control group.

H1a: The CAI group would have significantly greater COP displacement in the medial-lateral (ML) and anterior-posterior (AP) directions.

H1b: The CAI group would have significantly greater distance of COP total excursion (TE).

H1c: The CAI group would have significantly faster COP-TE velocity.

H1d: The CAI group would have a significantly greater value of the COP ellipse (area).

### Operational definitions

CAI = Chronic Ankle Instability: a condition with repetitive episodes of instability, loss of function, or/and a sensation of giving way of the ankle.<sup>6,7</sup>

CONTROL = Individuals who do not have a history of ankle sprain also known as healthy participants.

SEBT = Star Excursion Balance Test: a non-instrumented dynamic postural stability test to assess the ability of postural control.<sup>18</sup>

YBT = Y-Balance Test: a single-leg dynamic postural stability test also known as a modified version of SEBT.<sup>18</sup>

COP = Center of Pressure: a pressure point where the total sum of a pressure acts on the force plate.<sup>30</sup>

### Limitations

This study has some limitations. The self-report recall for ankle injury history may be inaccurate and incomplete when the participants are asked about their ankle sprain history. Also, the different physical activity levels of the participants may possibly affect the outcome of this study. Generalizability may be limited to the population who were recruited. Most of the participants were college age from the surrounding community. Additionally, human errors in testing and inherent errors in instrumentation cannot be removed and are related to biomechanical human motion research.

## CHAPTER 2

### REVIEW OF LITERATURE

Lateral ankle sprain is one of the most common lower extremity injuries in the physically active population.<sup>1</sup> An initial lateral ankle sprain may lead to developing chronic ankle instability (CAI).<sup>31</sup> Dynamic postural stability deficits have been reported in individuals with CAI.<sup>24</sup> The Star Excursion Balance Test (SEBT) has been used to measure dynamic postural stability in individuals with CAI and has been modified as the Y-Balance Test™ (YBT) (Functional Movement.com, Danville, VA) to improve the efficiency of administration in clinical and research environments.<sup>32</sup> However, differences in performance and kinematic patterns between the SEBT and YBT resulting from the inherent nature of each test and the evaluation of postural stability through biomechanical measures while performing the SEBT are unclear.<sup>32</sup> Identifying how individuals with and without CAI differently perform on the SEBT and the YBT and determining different postural control mechanics that exist between the two groups may lead to the development of more effective prevention, assessment, and intervention in rehabilitation for CAI.

This literature review addresses the following topics: 1) pathomechanics of lateral ankle sprain, 2) anatomical features, 3) epidemiology of lateral ankle sprain, 4) incidence and prevalence of repeated ankle sprain, 5) pathomechanics of CAI, 6) biomechanical factors associated with CAI, 7) dynamic postural stability test (SEBT and YBT), 8) review of literature related to methods, and 9) review of literature related to statistics.

### Pathomechanics of lateral ankle sprain

The most common mechanism of lateral ankle sprain is excessive rearfoot supination combined with external rotation of the tibia at the initial contact to ground with the rear foot.<sup>33</sup> Increased plantar flexion with supination may increase the risk of ankle sprain.<sup>6,33</sup> Forty-five percent of the ankle injuries have occurred during the landing phase.<sup>34</sup> These motions increase the tension load on the ligament in the lateral aspect of the ankle and cause lateral ankle sprain if the tension exceeds the yield point of ligaments.<sup>6,33</sup>

Increased ground reaction force (GRF) pushing against the foot may lead to an inversion motion in the ankle, which may result in lateral ankle sprain.<sup>6,33</sup> Asymmetrical muscle strength between the anterior-posterior and medial-lateral muscles may be a risk factor to increase GRF on the foot.<sup>6,33</sup> Additionally, decreased proprioceptive and neuromuscular function may lead to poor postural control, which may affect GRF.<sup>6,35</sup>

The mechanoreceptors in the lateral ligaments of the ankle provide the proprioceptive function in the ankle.<sup>36-38</sup> Damaged mechanoreceptors in the ligaments of the ankle may cause decreased proprioceptive and neuromuscular functions.<sup>36,37</sup> Therefore, a lateral ankle sprain may negatively affect sensorimotor control in the lower extremity.<sup>39</sup> This may decrease postural control stability due to the decrease in an individual's ability to adjust to maintain their balance.<sup>39</sup> Damaged mechanoreceptors may also result in a delayed feedforward-feedback loop function in the injured joint.<sup>39</sup> This may cause inappropriate muscle responses.<sup>39</sup> These negative alterations after an initial lateral ankle sprain may lead to a vicious circle of repeated lateral ankle sprains and/or future injuries. Alterations in the feedforward and feedback functions have been reported at the injured joints in individuals with CAI.<sup>39-42</sup>

## Anatomy

The ankle joint consists of the tibia, fibula, talus, and calcaneus, which are stabilized by ligaments, the joint capsule, cartilage, bony geometry within the articulation, and friction between the cartilage surfaces.<sup>43</sup> The joint between the talus and tibia is called the talocrural joint, also known as the true ankle joint, while the subtalar joint is located between the talus and calcaneus.<sup>44</sup> The talocrural joint allows sagittal plane movement such as plantar and dorsiflexion in the ankle.<sup>6</sup> The subtalar joint also allows multiple plane movement, including the frontal and horizontal planes, such as pronation and supination in the ankle.<sup>6</sup>

The major ligaments in the ankle are the anterior talofibular (ATF), the posterior talofibular (PTF), and the calcaneofibular (CF) on the lateral aspect of the ankle, and the deltoid ligament of the medial aspect of the ankle.<sup>6</sup> Those major ligaments in the ankle mainly provide stabilization in the ankle. Especially, three ligaments on the lateral aspect of the ankle help to protect the ankle against excessive inversion motion, while the deltoid ligament on the medial aspect of the ankle helps to protect the ankle against excessive eversion motion. The ATF is the most commonly injured ligament by lateral ankle sprain because it prevents the excessive anterior translation and internal rotation of the talus, which is the exact mechanism.<sup>45</sup> Approximately 80% of all lateral ankle sprains involve damage of the ATF.<sup>6</sup> The CF in the ankle is the second most common injured ligament, as the tension in the CF can be increased during supination in the talocrural and subtalar joints.<sup>6,46</sup>

Both intrinsic and extrinsic muscles also provide stabilization and mobilization in the four primary motions in the ankle. The tibialis anterior, extensor hallucis longus, and the extensor digitorum longus are the primary muscles for dorsiflexion. The primary muscles

responsible for plantarflexion include the gastrocnemius and soleus muscles. The peroneus longus, brevis, and terius produce eversion of the ankle. These eversion muscles may help to protect against an excessive inversion force.<sup>6,47,48</sup> Inversion of the ankle is produced by the tibialis posterior, flexor digitorum longus, and flexor hallucis longus.

### Epidemiology

The ankle joint is the most common site of joint injury during sporting activities. The most common type of ankle sprain is lateral ankle sprain and the most common mechanism of injury is inversion including adduction, supination, and plantarflexion of the foot.<sup>2,6,49</sup> An estimated 10,000 ankle sprains per day have been reported in the United States.<sup>3,50</sup> Approximately 15% of athletes registered in the National Collegiate Athletic Association (NACC) reported that they had had an ankle sprain.<sup>51,52</sup> An estimated total 5,373 ankle sprains in 17,172,376 athletes have occurred in high schools during the 2005-2010 academic years in the United States. This is equivalent to 3.13 ankle sprains per 10,000 athlete-exposures.

The lateral ankle sprain is the single musculoskeletal injury, which may lead to the most time-loss in sport participation.<sup>53,54</sup> The time-loss in sport participation can vary from a few days to months depending on the severity of the ankle sprain.<sup>34</sup> An average 6.5 days was required to recover from lateral ankle sprain in the National Football League (NFL) over a 15-year period.<sup>55</sup> An estimated 50% of athletes had time-loss for 1 or more weeks due to ankle sprains.<sup>34</sup>

Lateral ankle sprains not only result in time-loss in sport participation, but they can also cause an increase in healthcare costs. The United States Consumer Products Safety Commission estimated that \$70 million in direct costs and \$1.1 billion in indirect costs have been spent to treat ankle sprains just for athletes in high schools.<sup>56</sup>

### Incidence and prevalence of repeated ankle sprain

Over 80% of athletes report repeated ankle sprains with half of them reporting residual symptoms, such as “giving way,” persistent pain, and losing function.<sup>1</sup> The primary predisposing factor of ankle sprain is a history of ankle sprain.<sup>6,34</sup> Individuals with a history of ankle sprain are more likely to have repeated ankle sprains later.<sup>34,57</sup> Although athletes return to play with full physical function, they still have the increased risk of subsequent ankle sprains.<sup>6,34</sup> Current research is targeting ways to prevent index sprain and avoid repeated spraining.

### Pathomechanics of CAI

The repeated ankle sprains, persistent pain, residual symptoms, and loss of function following an initial lateral ankle sprain are the major signs and symptoms of chronic ankle instability (CAI).<sup>6</sup> CAI can be classified as either mechanical or functional instability.<sup>6</sup> Lateral ankle sprain by excessive force may cause an overstretch of the ligaments in the lateral aspect of the ankle. This may result in laxity in the ankle joint. Ligamentous laxity may cause the mechanical ankle instability at the ankle joint.<sup>37</sup> Individuals with CAI tend to have greater anterior joint displacement in the injured limb compared to the non-injured limb.<sup>58</sup> Greater anterior-posterior joint displacement in the ankle with functional instability has been reported.<sup>58</sup> The mechanical laxity of the ankle joint may decrease the dorsiflexion range of motion at the ankle.<sup>6</sup> Decreased availability of the ankle dorsiflexion range of motion may prevent the ankle from reaching its closed-pack-position, which is the most stable position of the ankle.<sup>6</sup>

An abnormal position of the distal fibula, known as the lateral malleoli and talus, may be one of the risk factors that result in mechanical instability at the ankle.<sup>6</sup> ATF can be slack in the

distal fibula anterior position. This may cause more inversion motion at the ankle, which leads to repeated ankle sprains and mechanical ankle instability.<sup>6</sup> Increased laxity of the ATF may result in increased anterior displacement of the talus and fibula.<sup>6</sup> Increased anterior displacement of talus may lead to a decrease in the ankle dorsiflexion range of motion.<sup>6</sup> Increased anterior displacement of the fibula can also lead to decreased ankle dorsiflexion range of motion, and then further alterations to compensate for that lack of motion.<sup>6</sup> A previous study<sup>59</sup> found that the fibula sits more anteriorly in those with CAI compared with the uninjured limb and matched controls. Denegar et al.<sup>60</sup> also found an increased anterior joint displacement in the distal fibular or decreased posterior joint displacement in the talus (posterior talar guide). Both previous studies found that displacement of the talus and fibula following ankle sprain.<sup>59,60</sup>

Decreased flexibility in the gastrocnemius and soleus can also cause a decreased ankle dorsiflexion range of motion.<sup>60</sup> These abnormal alterations following a lateral ankle sprain may result in chronic inflammation in the ankle joint due to inappropriate healing processes.<sup>61</sup> A previous study<sup>62</sup> found that individuals with CAI had decreased ankle dorsiflexion range of motion.

The limited ankle dorsiflexion range of motion by abnormal displacement of the fibula and talus and decreased flexibility in the gastrocnemius and soleus may decrease anterior reach distance on the SEBT.<sup>63</sup> Ankle dorsiflexion range of motion is one of the major contributing factors to performing the SEBT.<sup>63,64</sup> Therefore, these alterations may impact kinematic patterns on the SEBT in individuals with CAI.

Functional deficits in the ankle include proprioceptive function, neuromuscular control, sensorimotor function, and overall postural control.<sup>6,65,66</sup> The mechanoreceptors in the ankle ligaments could be damaged, which may lead to decreased proprioceptive function following an

ankle sprain.<sup>6,43</sup> The proprioceptive function in the ankle provides the brain with information about where the ankle joint is positioned. Therefore, if the proprioceptive function in the ankle is diminished, risk of injury could be increased due to compromising positions at the ankle. A previous study found that participants showed greater error to replicate the plantar flexion position in the injured limb compared to the uninjured limb.<sup>67</sup> This study showed that altered joint position is associated with the injury. Individuals with CAI have alteration of joint position sense in the knee, which indicate that damaged mechanoreceptors may be associated with central mediated alterations.<sup>68</sup>

Neuromuscular control is another functional factor in the ankle. If a healthy individual is asked to perform a functional performance test such as the jump-landing task, there is not only muscle activation after landing, but also pre-activation.<sup>65</sup> Pre-activation in individuals with CAI is still present, but it is not the same as in healthy individuals.<sup>69</sup> Decreased activation of the peroneal muscle in individuals with CAI following an inversion perturbation has been reported.<sup>69</sup> The peroneal is the primary muscle to pull the ankle into eversion if the inversion in the ankle accidentally occurs. This indicates alteration in the feedback response after an ankle sprain. Alterations in the neuromuscular control function after an ankle sprain also affects the proximal joints in the knee and hip joints. A previous study found that individuals with CAI had less knee flexion movement compared to the healthy control while they performed a jump-landing task.<sup>70</sup> Therefore, researchers should pay attention to differences in kinematic patterns in proximal joints between individuals with and without CAI.

All these proprioceptive and neuromuscular deficits may contribute to chronic ankle instability as a combined factor.<sup>14</sup> Individuals with CAI showed decreased performance in postural stability tests, such as the SEBT, compared to healthy control individuals.<sup>14,16</sup>

The altered sensorimotor control function may lead to postural control deficits.<sup>71</sup> Postural control deficits may cause an ankle sprain.<sup>72</sup> Individuals with functional performance deficits in the ankle use more hip musculature to maintain postural control instead of ankle musculature.<sup>71</sup> Postural control training may decrease the risk of future injury in individuals with CAI.<sup>73-76</sup> Previous studies found that at least 6 weeks of postural control training intervention in individuals with CAI increased dynamic postural control and decreased the number of injuries.<sup>73,75,76</sup>

Alteration of postural control can be detected by postural control measures.<sup>77</sup> The center of pressure (COP) during single leg standing may be assessed postural control through the biomechanical force plate.<sup>29</sup> COP measurements represent the location and movement of the net ground reaction force vector in response to the corrective action being taken to maintain postural control.<sup>78</sup> The displacement of the COP in the anteroposterior (AP) and mediolateral (ML) directions have been used to assess distance between maximal and minimal positions of COP in the sagittal and frontal planes.<sup>79</sup> Pope et al. found that individuals with CAI had a more anteriorly and laterally centered COP with eyes open and more anterior-posterior changes in the COP with eyes closed.<sup>27</sup> Therefore, individuals with CAI had more sway motion while they performed a static balance measure. The COP excursion path length and velocity are also used to measure how far and fast the COP travels during the trial.<sup>80</sup> The COP excursion path length may be calculated as the sum of the linear distance between consecutive data points. The velocity of COP may be calculated as total COP excursion path length in centimeters divided by the trial time.<sup>6,80</sup> The COP area would also be calculated as the area estimated by fitting a 95% ellipse to the amount of movement of the COP.<sup>81</sup> Tropp et al.<sup>81</sup> found that individuals with CAI have

demonstrated increased COP area. Postural control deficits may be a predisposing factor to CAI, or central mediated alterations after ankle sprain.

All these mechanical and functional factors may contribute to chronic ankle instability. However, these contributing factors do not usually affect stability as a single factor, as the factors may be intertwined.<sup>31</sup> Individuals with CAI may have deficiencies in balance, joint stability, and force production in the sagittal plane in the ankle as a multifactorial complication.<sup>31</sup>

#### Biomechanical factors associated with chronic ankle instability

Currently, much of the research regarding kinematic observations on chronic ankle has focused on the contributing factors. Brown et al.<sup>82</sup> investigated differences among individuals with mechanical ankle instability (MAI), functional ankle instability (FAI), and copers who do not have any symptoms and signs after an initial ankle sprain in the kinematic pattern during a variety of dynamic tasks. They reported that individuals with MAI had less plantarflexion range of motion (ROM) at initial contact and at maximum angular displacement compared to copers. This may lead to greater stability at the ankle due to anatomical features.<sup>82</sup> Individuals with MAI also showed less joint displacement in the sagittal plane and greater eversion compared to both individuals with FAI and copers.<sup>82</sup> Individuals with MAI had less joint displacement in the sagittal plane than did the copers and greater joint displacement in the frontal plane compared to both the FAI individuals and copers. This outcome may indicate that individuals with MAI tend to have greater motion in the frontal plane due to the ligament laxity in the lateral aspect of the ankle.<sup>82</sup>

In one study, 63 physically active individuals with MAI or FAI, and copers were asked to perform a stop jump task while ground reaction force data and kinematic data were taken.<sup>83</sup> The

researchers examined the variability of motion in the ankle, knee, and hip in the sagittal and frontal planes. Individuals with FAI had a greater degree of variability in ankle joint motion in the frontal plane compared to those with MAI and the copers.<sup>83</sup> This result may indicate that individuals with FAI have a risk of potential ankle injury during the landing phase.<sup>83</sup>

Additionally, individuals with MAI had a greater variability of ground reaction force (GRF) in the anterior-posterior direction (sagittal plane) compared to the FAI group, which may decrease stability at the ankle joint.<sup>29,83-85</sup> Another previous study found alteration in the hip kinematic pattern among the MAI, FAI, and coper groups while they performed the stop jump task.<sup>86</sup>

Several studies also found that CAI may be associated with kinematic alterations in the knee and trunk. Delahunt et al.<sup>87</sup> found that individuals with FAI showed less eversion at the ankle and posterior GRF while they performed the single-leg hop task compared to the healthy control group. Brown et al.<sup>88</sup> found that individuals with FAI and copers showed lesser variability in knee rotation than the healthy control at pre-initial contact during single-leg jump landings in different directions including anterior, medial, and lateral. The increased variability in the knee may reduce GRF and increase stability in the injured ankle.<sup>88</sup> Another previous study also found that individuals with CAI had a decreased knee flexion angle at the pre-initial contact.<sup>89</sup> This result may indicate that alteration of the feed-forward response may be associated with CAI. The authors proposed that the central nerve system (CNS) in the human body may respond, leading to a decreased knee flexion angle at the pre-initial contact to protect the ankle. Although several previous studies proposed that alterations of the feedforward and feedback functions are present in individuals with CAI, it is not clear whether the alterations are caused by the injury or inherently affected by it. It may be that compromised feedback responses caused by the initial ankle sprain contribute to the altered feedforward control.<sup>90</sup>

Brown et al.<sup>83</sup> attempted to find differences in the movement variability of individuals with CAI in the trunk during the stop jump task. However, they did not find any differences among the MAI, FAI and copers individuals in trunk motions. Brown et al.<sup>88</sup> found that the MAI and healthy control individuals showed less variability of lateral flexion in the trunk compared to individuals with FAI. This result may indicate that individuals with CAI tend to have less variability in proximal joints to compensate for ankle instability.

Overall, the previous literature indicates that individuals with CAI (either MAI and FAI) showed altered kinematic patterns and variability in walking, running, and jumping compared to healthy individuals. They would also demonstrate altered kinematic patterns while performing the dynamic postural control measures.

#### Dynamic postural stability tests (SEBT and YBT)

The Star Excursion Balance Test (SEBT) has been popularly utilized to detect dynamic postural control deficits in individuals with CAI.<sup>41,70</sup> The SEBT originally consisted of 8 reach directions including anterior, anteromedial, anterolateral, lateral, medial, posterolateral, posteromedial, and posterior while participants stood on each limb.<sup>91</sup> The 8 reach directions extend in 45-degree increments from the center of the star. Participants attempt to reach as far as they can with one leg while standing on the opposite leg. Six practice trials in each direction, followed by three test trials, are completed to avoid a practice effect.<sup>18,91,92</sup> The maximum reach distance is marked and measured by the examiner as well as normalized by the participant's leg length.<sup>93</sup>

Hertel et al.<sup>94</sup> found that individuals with CAI performed significantly less reach distances in anteromedial, medial, and posteromedial directions compared to the healthy control

group. Hubbard et al.<sup>31</sup> also found that the anteromedial and posteromedial directions of the SEBT may detect reach deficiency in individuals with CAI. The three directions of the SEBT including anterior, posteromedial, and posterolateral were associated with lower extremity injury occurrence in high school athletes.<sup>18</sup> Most researchers attempted to simplify the directions of the SEBT to the anterior, posteromedial, and posterolateral for shorter testing time.<sup>18</sup> Additionally, a previous study found that the vastus medialis, vastus lateralis, medial hamstring, biceps femoris, anterior tibialis, and gastrocnemius were primarily engaged while performing the SEBT.<sup>95</sup>

The SEBT is a highly reliable clinical tool with test-retest intra-class correlation ranging from 0.89 to 0.93 and coefficients of variation ranging from 3.0% to 4.6%, thus indicating good measurement stability.<sup>17,18,93</sup>

The Y-Balance Test™ (YBT) (FunctionalMovement.com, Danville, VA) has been developed based on the SEBT to improve the efficiency of administration of the anterior (AN), posteromedial (PM), and posterolateral (PL) reach directions in the clinical and research fields.<sup>32</sup> The YBT consists of a raised platform and three reach arms attached to the platform with an indicator box attached to all three reach arms. The angle between the AN and PM and PL reach arms is 135 degrees and 45 degrees between the PM and PL reach arms. Participants are asked to push the indicator box as far as possible with a single leg stance on the platform. The YBT usually follows the same protocol as that for the SEBT. The three test trials after 6 practice trials on each are measured and the average three trials are normalized by their leg length. The YBT also showed high inter-rater (0.99 – 1.00) and intra-rater (0.85 – 0.91) reliability.<sup>32</sup> Also, a previous study<sup>19</sup> reported the minimum level of measurement error among multiple examiners with limited knowledge of health care.

Although both the SEBT and YBT require similar movements and physical challenges to maintain the participant's posture (balance), the outcomes from each test could be different.<sup>20</sup> Individuals with MAI had flexion and external rotation of the hip at the initial contact and at maximum joint displacement compared to copers. This result may be interpreted as indicating that the joint motion in the proximal joint may be affected in individuals with CAI.<sup>83</sup>

### Review of literature related to methods

A high-speed digital video motion measurement system is commonly utilized for three-dimensional human movement analysis. The plug-in-gait module marker set has been commonly used and previously established as a reliable and sensitive measure for such three-dimensional analysis of human movement.<sup>96</sup> Originally, the plug-in-gait module marker set for lower extremity included 16 retro-reflective markers on the anterior superior iliac spine (ASIS), posterior superior iliac spine (PSIS), lateral aspect of the thighs, lateral knees, lateral aspects of the shanks, lateral malleoli, heels, and toes in the lower extremity.<sup>96,97</sup> Repeatability and error in kinematic measures could be affected by marker placement.<sup>98</sup> The repeatability of kinematic and moment data in the sagittal plane is superior to that in the transverse and frontal planes. The between-day observation for kinematic data had correlational coefficient values ranging from 0.737 to 0.994, while within-day data consistently showed better correlations between 0.853 and 0.996.<sup>98</sup>

The force plate is commonly used in biomechanics research to assess the GRF while the participant is performing on the force plate. The number, size, and brand of the force plate could be selected depending on the purpose of the laboratory. A Bertec 4060-NC force platform® (Bertec Corporation, Columbus, OH) was used for this research. The 4060-NC series is made of

fiberglass known as a non-conductive force plate. The 4060-NC force platform has 0.2% of the full-scale output signal maximum error due to hysteresis and/or linearity. All output should be calibrated and adjusted for any cross talk due to the calibration matrix installed within the force platform.

Gribble et al.<sup>99</sup> recommended that the Cumberland Ankle Instability Tool (CAIT) and Identification Functional Ankle Instability (IdFAI) should be utilized to identify those individuals with CAI. Researchers have utilized the cut-off score of the CAIT  $\leq 24$ , and the IdFAI  $\geq 11$  as inclusion criteria for classifying the CAI and health control groups.<sup>99-101</sup> The CAIT and IdFAI have been shown to be reliable, valid, and sensitive tools in the assessment of ankle instability.<sup>101,102</sup>

#### Review of literature related to statistics

A previous study<sup>103</sup> used an independent sample t-test to assess the impact of testing type on performing the AN, PM, and PL reach directions of the SEBT in the uninjured and healthy control groups. The reach distances in the AN, PM, and PL directions were the dependent variables and the group (the injured and uninjured) was the independent variable.<sup>103</sup> A Bonferroni correction was applied, with significance set *a priori* at  $P < 0.025$ .<sup>103</sup> Paired-sample t-tests were also performed to assess the impact of testing type (the SEBT and YBT) for the hip, knee, and ankle joint angular displacement at the point of maximum reach in the sagittal plane.<sup>21</sup>

## CHAPTER 3

### METHODS

Seventy participants were recruited for this study, 35 of whom with a history of chronic ankle instability (CAI) and 35 without a history of ankle sprain (healthy controls). Following the initial contact, participants were consented during their visit for a single session of data collection at the Biomechanics Laboratory at the University of Georgia and underwent a screening to determine whether they met the inclusion/exclusion criteria.<sup>99</sup> Participants responded to a questionnaire regarding their perceived ankle function and physical activity level and performed functional performance tests for total participation time of approximately 1 hour.

#### Participants

Potential participants were initially identified among the university and community populations through announcements made in club sports, kinesiology courses, and basic physical education courses in which the instructors allowed recruitment, via email listserves or flyers distributed to university classes and club sports athletes. Participants interested in the study contacted the researcher or the researcher contacted participants who had indicated interest on the sign-up sheets. All participants were recruited based on inclusion and exclusion criteria, which included a comprehensive description of and critical information about the research participants, as recommended by the International Ankle Consortium.<sup>99</sup>

Inclusion criteria<sup>99</sup>

- Overall
  - Age 18 to 35 years old
  - Physically active, defined as participating in  $\geq 90$  minutes or more of physical activity per week
- Healthy control group
  - No history of ankle sprain within the last 24 months
  - No complaints of ankle rolling, spraining, or “giving way” with activity
  - A Cumberland Ankle Instability Tool Score of 28 or greater, indicating good ankle joint function
  - An Identification of Functional Ankle Instability (IdFAI) score of 10 or less, indicating good ankle joint function
- Chronic Ankle Instability (CAI) group
  - Self-report history of 1 or more unilateral mild-moderate ankle sprains at least 12 months prior to study enrollment
  - Missed at least 1 day of physical activity due to an ankle sprain, associated with inflammatory symptoms such as pain and swelling
  - The most recent ankle sprain must have occurred more than 3 months prior to participating in the study
  - At least 2 self-reported episodes of ankle rolling, spraining, or “giving way” in the past 12 months
  - A Cumberland Ankle Instability Tool (CAIT) score of 25 or less, indicating decreased ankle joint function

- An Identification of Functional Ankle Instability (IdFAI) score of 11 or greater, indicating decreased ankle joint function

Exclusion criteria<sup>99</sup> (both control and CAI groups)

- History of lower extremity surgery or fracture
- Acute injury to musculoskeletal structure of other joints of the lower extremity in the previous 3 months that impacted joint integrity and function, resulting in at least 1 interrupted day of desired physical activity
- Signs or symptoms of an acute ankle sprain, including swelling, discoloration, heat, or pain
- Current injury to another lower extremity joint characterized by swelling, discoloration, heat, or pain
- Pregnancy; associated hormonal changes that may affect ligamentous laxity and interfere with screening procedure
- Diagnosis of vestibular disorder, Charcot-Marie Tooth disorder, Ehlers-Danlos disorder or other nerve or connective tissue disorders which could affect test results

#### Sample size justification

A priori sample size calculations were performed (G\*Power, Version 3.1.5, Kiel, Germany) with statistical power = 0.80,  $\alpha \leq 0.05$ . For comparison of reach distance in all 3 directions between the SEBT and YBT, a total 39 to 7,179 participants were needed for an effect size from -0.13 to 0.76 using mean and standard deviation tabled data from a similar study on the YBT and SEBT to compare the reach distance in a healthy population.<sup>20</sup> Based on table data

from another similar study<sup>21</sup> comparing kinematic patterns of the SEBT and YBT, a total sample size from 66 to 266 were needed for an effect size from 0.24 to 0.50 with healthy participants. However, these studies only included a healthy population. Therefore, we have calculated an a priori sample size based on our pilot data with 4 participants (1 in the control and 3 in the CAI group). A total of 35 to 47 participants were needed for comparing reach distance in all 3 directions, and a total of 13 and 68 participants for comparing the kinematic patterns in the knee and ankle, respectively, were needed for an effect size from 0.05 to 1.2 using mean and standard deviation data from our pilot study. A total 9,835 participants for comparing the kinematic patterns in the hip joint were needed for an effect size of 1.1. Although a prior power calculation for comparing the kinematic patterns of the hip joint indicated that over 9,000 participants were needed, our targeted sample size of 70 (35 in each group) would allow sufficient power to assess major kinematic observations (ankle and knee) at the lower extremity between groups. Also, it would be a more feasible number for completing this study.

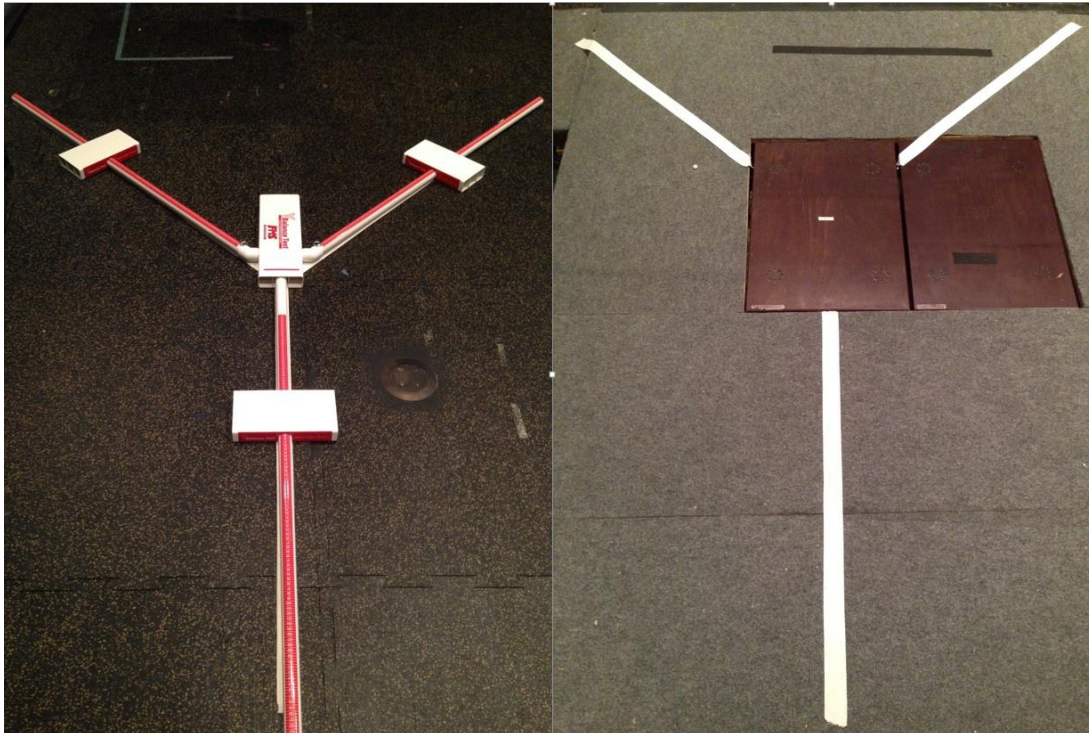
### Research protocol

The total time of participation was approximately 60 minutes during a single test session. Participants were consented during their visit to the Biomechanics Laboratory and completed questionnaires including the Cumberland Ankle Instability Tool (CAIT) (Appendix A)<sup>102</sup> and Identification Functional Ankle Instability (IdFAI) (Appendix B)<sup>101</sup>. All demographic information, including age, gender, dominant limb, mass, and height, were collected. Height was measured by a wall-mounted stadiometer and mass was measured by a digital weight scale. Also, leg length was assessed in a supine position from the medial malleolus to anterior superior iliac spine (ASIS) of each limb to later normalize the reach distance.<sup>104</sup>

## Instruments

### Dynamic Postural Stability Measures

The Y-Balance Test™ (YBT) (Functional Movement.com, Danville, VA), with reach arm pipes extending from the stance platform in the anterior (AN), posteromedial (PM), and posterolateral (PL) directions, was one of two tests used to measure dynamic postural control (Figure 3.1). Athletic white-tape was used to mark the three reach arms on the Bertec 4060-NC force platform® (Bertec Corporation, Columbus, OH) to show where the participant should place the testing foot in different reach directions while performing the Star Excursion Balance Test (SEBT) (Figure 3.2). A Baseline® Hi-Res™ 12-inch goniometer (Fabrication Enterprises, Inc., White Plains, NY) was also used to measure the appropriate angles for the reach arms in the AN, PM, and PL directions for the SEBT.



*Figure 3.1. Y-Balance Test™ (YBT) and Star Excursion Balance Test (SEBT)*

## Motion analysis

The International Society of Biomechanics (ISB) guidelines were followed for global axis (X-Y-Z) set-up.<sup>105</sup> Twenty-nine retro-reflective markers were attached to anatomical landmarks of the sternum, clavicle, 7<sup>th</sup> cervical vertebrae, right back, and 10<sup>th</sup> thoracic vertebrae in the upper body and the anterior superior iliac spines (ASIS), posterior superior iliac spines, lateral aspect of the thighs, lateral and medial knees, lateral aspects of the shanks, lateral and medial malleoli, heels, 2<sup>nd</sup> metatarsal head and 5 metatarsal head in the lower extremity (both side) based on the Plug-in-Gait Module of the data collection software (Figure 3.3). Marker trajectories were recorded via an MX-40 Vicon™ camera system (Vicon, Ltd., Oxford, UK), comprised of seven high-speed cameras in a Nexus software (Vicon Motion Systems, Oxford, England) with a sampling rate of 120 Hz and mean residual error of  $\leq 0.05\text{mm}$ .<sup>91</sup> Cardan angle was used to calculate joint angles in a rotation order of X (flexion [+] and extension [-]), Y (adduction [+] and abduction [-]), and Z (internal [+] and external rotation [-]) for knee and hip joint; X (dorsiflexion [+] and plantarflexion [-]), Y (inversion [+] and eversion [-]), and Z (internal [+] and external rotation [-]) for ankle joint.<sup>106</sup>



*Figure 3.2.* Location of reflective markers

### Force platform

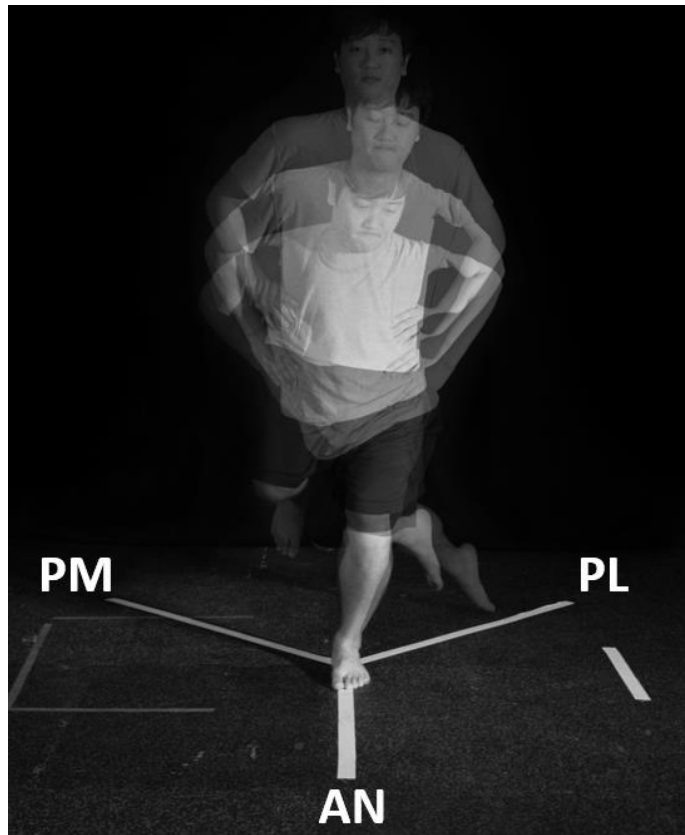
A single Bertec 4060-NC force platform® (Bertec Corporation, Columbus, OH) was used to collect (960 Hz) ground reaction force (GRF) in three directions— anterior-posterior ( $GRF_{A-P}$ ), medio-lateral ( $GRF_{M-L}$ ), and vertical ( $GRF_V$ ).<sup>29,100,107</sup> We collected GRF data at a sampling rate of 180Hz while participants performed the SEBT because this was commonly used in previous postural stability measures.<sup>29,107,108</sup>

## Procedure

For a given balance test, the test procedures were demonstrated before the participant completed 2 practice trials. A trial was classified as a fail if the participant removed his or her hands from the hips, did not return to the starting position, touched the ground with the reach foot, lifted up or moved the stance foot during the test, or kicked the indicator box to gain more distance during the YBT test. If a trial was classified as a fail, the data were not analyzed and the participant repeated the trial.

Prior to testing, all participants completed the self-report questionnaires, performed a 5-minute warm-up of bike exercise and self-selected stretches, and were instrumented with retro-reflective markers, and a standing static trial was captured based on the Plug-in-Gait Module.<sup>98</sup> Participants completed either the SEBT or YBT first. The participants completed 2 practice trials in each of 3 reach directions on the first test limb (6 practice trials total). Then the participants reached with the first test limb for 3 test trials in the anterior (AN), posteromedial (PM), and posterolateral (PL) directions in a counterbalanced order (9 total test trials) (Figure 3.3).

Participants received a 5-minute break in between directions and in between limb sides. Then, they repeated the testing procedure on the other limb. This consisted of 30 repetitions including 12 practice and 18 test trials. The participants then repeated the practice and test trials for the SEBT or YBT, whichever was not completed initially, for a grand total of 60 repetitions. A 30-second rest break was completed in between each practice and test trial.



*Figure 3.3. Three reach directions*

#### Data reduction

Prior to data scoring, we demonstrated excellent intra-class correlation coefficient values ( $ICC_{2,1} = 0.89 - 0.97$ ) and good standard error measures ( $SEM = 2.2$  and  $1.6$  cm) on the SEBT and YBT, respectively. All data were collected and processed through Nexus 20.0 (Vicon Motion Systems, Oxford, England) modeling software. Visual 3D<sup>®</sup> (C-Motion, Inc., Germantown, MD) biomechanical modeling software was used to determine joint kinematics. Marker data at the point of maximum reach at the reach-foot marker was processed through the Vicon Nexus 20.0 software (Vicon Motion Systems, Oxford, England). The built-in function “gap filling” in the Nexus program was utilized to fill minor gaps in coordinate positions of

reflective markers if a reflective marker disappeared. Group differences on COP (COP: displacement anteroposterior [AP]/mediolateral [ML], excursion path length, velocity, and area) while performing the SEBT (dynamic postural control test) on the force plate were determined. We used a custom-written MATLAB software (Mathwork Inc., Natick, MA) to process the data and calculate postural stability measures (COP displacement in the AP and ML direction, excursion path length, velocity, and area) from the GRF data. All these traditional COP measures were calculated during SEBT performance. The displacement of the COP in the AP and ML directions was calculated as the distance between maximal and minimal position of COP in the sagittal and frontal planes.<sup>79</sup> The COP excursion path length was calculated as the sum of the linear distance between consecutive data points collected during the trial.<sup>80</sup> The velocity of COP excursion was calculated as the total COP excursion path length in centimeters divided by the trial time.<sup>80</sup> The COP area was also calculated as the area estimated by fitting a 95% ellipse to the amount of movement of the COP.<sup>81</sup>

For the GRF data, a 4<sup>th</sup>-order lower-pass Butterworth filter with a cutoff frequency of 15Hz was used to filter noise out from the raw GRF data.<sup>29,100,107,108</sup> The filtered GRF data in all three directions including GRF<sub>A-P</sub>, GRF<sub>M-L</sub>, and GRF<sub>V</sub> was analyzed and used for inverse dynamic calculations. All GRF data reduction procedures were performed using Visual 3D® (C-Motion, Inc., Germantown, MD).

Kinematic data at the point of max reach for each SEBT and YBT trial were extracted, with the average of the 3 trials for each participant for each direction.<sup>21</sup> Group differences on reach distance and hip, knee, and ankle joint angles in the 3 planes at maximum reach in the 3 directions on the SEBT and YBT were determined. To standardize the kinematic data, joint angles were calculated as the difference between heel-off (the instant the heel of the reach-foot

was off the ground) to the point of maximum reach by the frame at the heel marker on the reach-foot that was farthest away from the body.<sup>100,109</sup> The hip, knee, and ankle in both frontal and sagittal plane kinematics were calculated and analyzed. Also, sagittal-plane and frontal-plane angular displacement of the hip, knee, and ankle joints during performance on the three reach directions of the SEBT and Y-balance test was measured.<sup>21,109,110</sup>

For kinematic data, a 4<sup>th</sup>-order, Butterworth low-pass filter with a 5 Hz cutoff frequency was used to filter noise out from the raw marker coordinates.<sup>103</sup> The three-dimensional coordinates of the reflective markers were generated via a proprietary algorithm (Nexus 20.0, Vicon Motion Systems, Oxford, England) modeling software. All calculations were performed using Visual 3D® (C-Motion, Inc., Germantown, MD). A joint coordinate system (Cardan-Euler angle) was used to determine joint angles for the ankle, knee, and hip. Joint angles in all three directions (X, Y, Z) for each trial were determined, including the knee, hip, and ankle angles from heel-off to the point of maximum reach in the reach-foot and maximum angular displacement.<sup>106</sup>

### Statistical analysis

Separate independent sample t-tests were performed to compare the reach distance for the involved limb in the unilateral CAI group and the matched limb in the control group between tests and to determine if group differences exist for the kinematic patterns including

- Reach distance between groups on both the SEBT and YBT
- Joint angle of ankle, knee, and hip joint of standing limb at the point of maximum reach

- Sagittal, transverses, and frontal-plane angular displacement between the CAI and control groups and the tests (SEBT vs YBT) differences exist for all kinematic data between the SEBT and the YBT within each group (CAI and Control).

A series of independent sample t-tests was also used to determine if group differences exist for the instrumented dynamic postural stability measures between the CAI and control groups.

One to four series of independent sample t-test was performed for each research question ( $P < 0.05$  or  $0.008$ ).

## CHAPTER 4

# KINEMATIC PATTERNS ON THE STAR EXCURSION BALANCE TEST AND Y-BALANCE TEST

Jupil Ko, Kathy J. Simpson, Seock-Ho Kim, Cathleen Brown. To be submitted to the *Clinical Biomechanics*

## ABSTRACT

*Background:* The Star Excursion Balance Test (SEBT) and Y-Balance Test (YBT) have been commonly applied to assess dynamic postural stability deficits in the Chronic Ankle Instability (CAI) population. These two tests are utilized interchangeably in various settings. However, they could in fact require different task performance and/or movements to assess dynamic postural stability, as one uses a platform and different measuring techniques than the other. The purpose of this study was to determine if there was a significant difference in performance in the 3 reach directions and in the kinematic patterns of individuals with and without CAI while performing the SEBT and the YBT. *Methods:* From 80 initial participants, 70 participants (35 in the CAI and 35 in the control group) performed 3 test trials in the Anterior (AN), Posteromedial (PM), and Posterolateral (PL) directions of the SEBT and the YBT. For reach distance, the average of 3 trials in each direction was normalized to % leg length. The kinematics of hip, knee, and ankle in sagittal, frontal, and transverse planes were calculated and analyzed. Also, sagittal, frontal, and transverse plane angular displacement of the hip, knee, and ankle joints during performance on the 3 reach directions of the SEBT and the YBT were measured. Separate independent sample t-tests were performed to compare the reach distance for the involved limb in the unilateral CAI group and the matched limb in the control group. Paired-sample t-tests were performed to compare the reach distance in the 3 directions, joint angles at maximum reach, and joint angular displacement in the ankle, knee, and hip in the 3 planes, between the SEBT and the YBT within each group. *Findings:* The CAI group achieved significantly shorter reach distance in the AN (CON:  $73.05 \pm 22.70\%$ ; CAI:  $61.97 \pm 5.93\%$ ,

$P=0.007$ ) and PM ( $110.41\pm30.92\%$ ;  $93.90\pm8.82\%$ ,  $P=0.003$ ) reach directions on the SEBT, compared with the control group. On the YBT, the CAI group had significantly shorter reach distance in the PM ( $103.77\pm9.39\%$ ;  $94.61\pm10.48\%$ ,  $P=0.001$ ) and PL ( $96.54\pm10.76\%$ ;  $88.03\pm11.43\%$ ,  $P=0.002$ ) directions compared with the control group. In the CAI group, participants had significantly greater reach distance in the PL (SEBT:  $82.77\pm11.53\%$ ; YBT:  $88.03\pm11.43\%$ ,  $P=0.003$ ) direction on the YBT compared with the SEBT. In the control group, participants achieved a significantly further reach distance in the AN ( $73.05\pm22.70\%$ ;  $64.74\pm5.73\%$ ,  $P=0.007$ ) reach direction on the SEBT compared with the YBT. Significant differences in angular displacement and joint angle at the point of maximum reach at the hip, knee, and ankle joints in the 3 planes between performance on the SEBT and on the YBT within each group were observed. *Interpretation:* Clinicians and researchers should not apply these dynamic postural control tasks interchangeably or compare reach distances from one task to another. There appear to be performance and kinematic differences between tests among and within groups.

## INTRODUCTION

The ankle joint is one of the most common musculoskeletal injury sites in the human body.<sup>111</sup> Approximately 75% of all ankle injuries are ankle sprains.<sup>111</sup> The most common type of ankle sprain is a lateral ankle sprain, also known as an inversion ankle sprain.<sup>112</sup> An estimated 23,000 lateral ankle sprains occur per day in the United States.<sup>50</sup> Ankle sprains may result in significant lost time, delayed return-to-play, and long-term disability.<sup>1,4</sup> An estimated 40% of individuals who experienced a lateral ankle sprain reported the sensation of “giving way,” a feeling of ankle instability, and repeated ankle sprains after the initial ankle sprain.<sup>6,7</sup> Individuals with chronic ankle instability (CAI) typically complain of deficits in ankle proprioception, cutaneous sensation, nerve-conduction velocity, neuromuscular response times, postural control, and strength.<sup>8-10</sup> Furthermore, previous studies reported that individuals with CAI presented with deficits in dynamic postural control known as “dynamic balance deficits”.<sup>80,103</sup>

Functional performance testing is one clinical tool used to identify those with CAI and quantify its severity.<sup>14</sup> Functional performance tests (FPTs) are useful assessment tools because they assess multiple components of function, including muscular strength, neuromuscular coordination, and joint stability, which could be affected by musculoskeletal injury.<sup>14,15</sup> Also, FPTs can be quickly and simply applied by a variety of providers with minimum resources.<sup>16</sup> The Star Excursion Balance Test (SEBT) is one of the most popular functional performance tests to measure dynamic postural control in a variety of settings.<sup>17</sup> A combination of musculoskeletal strength, range of motion (flexibility), and neuromuscular control function is required to perform the SEBT.<sup>18</sup> The original format of the SEBT consisted of 8 reach directions including the

anterior, anteromedial, medial, posteromedial, posterior, posterolateral, lateral, and anterolateral, but has since been simplified to 3 reach directions.<sup>18,32,113</sup> The SEBT showed high reliability with test-retest intra-class correlation ranging from 0.82 to 0.96 and coefficients of variation ranging from 3.0% to 4.6%.<sup>18,92</sup> The SEBT can be easily set up with white athletic tape or measuring tape on any flat floor surface.<sup>25</sup>

The Y-Balance Test™ (YBT) (Functional Movement.com, Danville, VA) is a modified version of the SEBT to enhance the efficiency of application of the SEBT by using a standardized platform with a moveable measurement system. The advantages of the YBT are time efficiency for both the rater to measure and the performer to complete, an established standardized protocol, and ease of reach measurement via a moveable device.<sup>32</sup> The YBT is only composed of 3 reach directions including anterior (AN), posteromedial (PM), and posterolateral (PL). A previous study<sup>19</sup> reported excellent inter-rater (0.99 – 1.00), intra-rater (0.85 – 0.91), and test-retest reliability, and standard error measure (SEM) among multiple raters on the YBT.

The SEBT and YBT have been commonly applied to assess dynamic postural stability deficits in CAI groups.<sup>16-18</sup> In clinical and research settings, these two tests are utilized interchangeably. Although the YBT was developed as a modified version of the SEBT, there is no evidence that indicates that these two tests require a similar task performance and movement strategy. Previous studies found that performers demonstrated greater reach distance in the AN direction on the SEBT than on the YBT and greater hip flexion at the point of maximum reach on the YBT than on the SEBT.<sup>20,21</sup> However, these previous studies<sup>20,21</sup> only compared the SEBT and the YBT in a healthy population and only investigated kinematic patterns of the sagittal plane.

A CAI population may perform the tests differently, in both reach distance and kinematic pattern. This could include differences in ankle, knee, or hip joint movements in the three planes (sagittal, frontal, and transverse). A previous study<sup>114</sup> found that the CAI group presented less dorsiflexion range of motion (ROM) in the ankle and reach distance on the AN reach direction of the SEBT. Additionally, other previous studies<sup>115,116</sup> found strong positive relationships between dorsiflexion ROM and the AN reach distance in the CAI group. However, to our knowledge, no studies have compared the kinematic patterns between the YBT and the SEBT in a CAI population even though these two tests have been mainly utilized to identify functional performance deficits in the CAI group. Therefore, a comparison of any differences between reaching performance on the SEBT and the YBT in the CAI population should be investigated. If differences exist between reach performance on the SEBT and the YBT in the CAI group, this may help clinicians and researchers identify that the tests may not be used interchangeably, or that specific kinematic patterns are contributing to performance. Therefore, the primary purpose of this study is to determine if there is a significant difference in performance in the 3 reach directions (AN, PM, and PL) and in the kinematic patterns of individuals with and without CAI while performing the SEBT and the YBT.

We hypothesized that the CAI group would have shorter reach distances in all three reach directions on both the SEBT and the YBT than the control group. Both groups would have shorter reach distances on the SEBT compared to the YBT in all 3 directions. Also, the CAI group would have significantly decreased joint angle values at the point of maximum reach and decreased angular displacements at the hip, knee, and ankle joints in the three planes on both the SEBT and the YBT compared to the control group. Additionally, both groups would have greater

joint angle values at the point of maximum reach and greater angular displacements at the hip, knee, and ankle joints in the three planes on the YBT than on the SEBT.

## METHODS

### Participants

Tabled data from similar previous studies comparing the reach distance on the SEBT and the YBT in a healthy population and comparing kinematic patterns in the sagittal plane on the SEBT and the YBT in a healthy population were used to perform *a priori* sample size calculation (G\*Power, Version 3.1.5, Kiel, Germany) with statistical power = 0.80,  $P \leq 0.05$ .<sup>20,21</sup> A total sample size from 66 to 266 per group was required to compare the kinematic patterns in the hip, knee, and ankle joint for an effect size from 0.05 to 0.24. However, these previous studies only included a healthy population. Therefore, an *a priori* sample size was also calculated based on means and standard deviations from pilot data from our lab with individuals with and without CAI. A total of 35 to 47 participants per group were required to compare reach distance in all 3 reach directions, and a total of 13 to 68 per group were required to compare the kinematic patterns for an effect size from 0.05 to 1.2. Therefore, our feasible targeted sample size of 70 participants (35 in the healthy control and 35 in the CAI group) was set within the established limits of a meaningful sample size for the comparisons of interest.

A total of 80 participants, between 18 to 35 years of age, who participated in physical activity for at least 90 minutes per week, were recruited from the university and community population, via club sports, kinesiology courses, and basic physical education courses at a large southeastern U.S. university. Then, specific inclusion and exclusion criteria were applied as recommended by the International Ankle Consortium.<sup>99</sup> A total of 70 participants were included

for data analysis after screening based on inclusion and exclusion criteria, presented in Figure 4.1. All participants were informed of the test procedures and provided an informed consent form during orientation as approved by the local Institutional Review Board.

Participants were classified into healthy control (n=35) and CAI groups (n=35) based on self-reported injury criteria. Inclusion criteria for the CAI group included the following: reported  $\leq 25$  on the Cumberland Ankle Instability Tool (CAIT)<sup>102,117</sup> and  $\geq 11$  on the Identification of Functional Ankle Instability (IdFAI)<sup>101</sup>; a history of moderate-severe ankle sprain(s) at least 12 months prior to study enrollment which caused missing at least one day of physical activity due to ankle sprain, associated with inflammatory symptoms such as pain and swelling; and at least 2 self-reported episodes of “giving way” and/or ankle spraining. Also, the most recent ankle sprain should not have occurred within 3 months prior to participating in the study.<sup>99</sup> Participants who reported  $\geq 28$  on the CAIT and  $< 11$  on the IdFAI questionnaires, no history of ankle sprain(s) within the last 24 months, and no complaints of either ankle “giving way” were classified into the healthy control group who were matched to participants in the CAI group according to height, mass, age, gender, and limb dominance.<sup>99,118</sup> Exclusion criteria for either group included the following: a history of lower extremity surgery or fracture, current signs and symptoms of an acute ankle sprain, and diagnosis of vestibular disorder, Charcot-Marie Tooth disorder, Ehlers-Danlos disorder, or other nerve or connective tissue disorder.<sup>99,119</sup> Also, participants who reported  $\leq 28$  CAIT scores in the healthy control group and  $\geq 25$  CAIT scores in the CAI group were excluded because the self-report function levels did not match group criteria.

## Procedures

A single test session of 45 – 60 minutes was scheduled in a biomechanics laboratory. Participants completed the demographic questionnaire on injury history and activity, the CAIT, and the IdFAI after they signed the consent form. The participants' demographic information was measured including height, mass, gender, leg length, and dominant side of limb. Leg length was also assessed from the anterior superior iliac spine (ASIS) of each limb to the medial malleolus in a supine position.<sup>104</sup> Participants were asked the question “With which limb (right or left) would you prefer to kick a ball?” to determine their dominant side.<sup>120</sup>

Twenty-nine retro-reflective markers based on the Plug-in-Gait Module<sup>98</sup> were applied on the participants' body before they performed the FPTs in Figure 4.2. Marker trajectories were recorded via an MX-40 Vicon<sup>TM</sup> camera system (Vicon, Ltd, Oxford, UK), comprised of seven high-speed cameras (240Hz) using Nexus 2.2.3 software (Vicon Motion Systems, Oxford, England) with a sampling rate of 120Hz and mean residual error of  $\leq 0.05\text{mm}$ .<sup>91</sup> The International Society of Biomechanics (ISB) guidelines were applied for setting up the global axis (X-Y-Z).<sup>105</sup>

Participants performed the SEBT and the YBT in a pre-determined counterbalanced order. The test was demonstrated by a single tester before the participants completed 2 practice trials in each of 3 reach directions including AN, PM, and PL, as illustrated in Figure 4.3. After the practice trials, the participants performed 3 test trials with the first limb in each direction in a counterbalanced order (a total 9 test trials). A trial was classified as failed if the participant removed his or her hands from the hips, did not bring back their reach foot to the starting position, lifted their test foot up or moved their test foot during the test, or kicked the indicator box at the end of the reach to gain more reach distance during the YBT.<sup>32</sup> If a trial was classified

as failing, the participant was asked to repeat the trial.<sup>104</sup> A single-rater reliability for the SEBT and the YBT was measured prior to data collection. The intra-class correlation coefficient (ICC<sub>2,1</sub>=0.89-0.97) and standard error measure (SEM=2.2cm and 1.6cm) were excellent.

### Data reduction and analysis

Means and standard deviations of participants' demographics, the CAIT and IdFAI scores, and performance (reach distances) on the SEBT and the YBT were calculated as exploratory descriptive data. For reach distance, the average of 3 trials in each direction was normalized to % leg length.<sup>92</sup> Greater reach distance indicated better dynamic postural stability.<sup>92</sup>

All kinematic data were processed through Nexus 2.2.3 (Vicon Motion System, Oxford, England) modeling software. Visual 3D® (C-Motion, Inc., Germantown, MD) biomechanical modeling software was utilized to determine joint kinematics.<sup>121</sup> Kinematic data at the point of maximum reach for each SEBT and YBT trial were obtained with the average of the 3 trials for each participant for each direction via Visual 3D®.<sup>21</sup> To standardize the kinematic data, joint angles were presented as the difference between heel-off to the point of maximum reach by the frame at the heel marker on the reach-foot that was farthest away from the body in the sagittal plane via Vicon 3D®.<sup>100,109</sup> The kinematics of hip, knee, and ankle in sagittal, frontal, and transverse planes were calculated and analyzed. Also, sagittal, frontal, and transverse plane angular displacement of the hip, knee, and ankle joint during performance on the 3 reach directions of the SEBT and the YBT were measured.<sup>21,91,109</sup> Joint angular displacement in the ankle, knee, and hip was defined as the difference between the initial and final angular positions of the joint ( $\Delta\theta = \theta_{\text{final}} - \theta_{\text{initial}}$ ).<sup>116</sup> The initial angle was determined as the angular position of the ankle, knee, and hip joints when the heel marker on the reaching limb initiated movement to

begin the reach. The final joint angle was determined as when the heel marker on the reaching limb was at the point of maximum reach. Cardan angles were used to calculate joint angles in a rotation order of X (flexion and extension), Y (adduction and abduction), and Z (internal and external rotation) for knee and hip joints; and X (dorsiflexion and plantarflexion), Y (inversion and eversion), and Z (internal and external rotation) for ankle joint.<sup>106</sup>

A 4<sup>th</sup> order (zero-phase) Butterworth low-pass filter with a 5Hz cutoff frequency was used to filter the raw marker coordinates for kinematic data.<sup>103</sup> The “fill-gap” function in the Vicon Nexus 2.2.3 (Vicon Motion System, Oxford, England) was utilized to fill minor gaps in coordinate positions of reflective markers if a marker was dropped for some frames.<sup>122</sup> The fill-gap functions of “rigid body fill,” “spline fill,” or “pattern fill” were used to fill gaps in the marker path of fewer than 20 frames, depending on which method provided the most similar predicted movement pattern to actual movement pattern.<sup>122</sup>

Group differences were determined in reach distance in 3 directions on the SEBT and the YBT, joint angles at maximum reach, and joint angular displacement in the ankle, knee, and hip in 3 planes on the SEBT and YBT. Using SPSS Version 22.0 (SPSS Inc, Chicago, IL), separate independent sample t-tests were performed to compare the reach distance for the involved limb in the unilateral CAI group and the matched limb in the control group. Paired-sample t-tests were also performed to compare the reach distance in 3 directions, joint angles at maximum reach, and joint angular displacement in the ankle, knee, and hip in 3 planes between on the SEBT and the YBT within each group. A Bonferroni correction ( $\alpha < 0.008$ ) was applied to reduce the chance of type I error (false-positive) based on the number of comparisons completed.<sup>123</sup>

## RESULTS

Demographic data are presented with no statistically significant differences in Table 4.1. There were statistically significant differences in the CAIT and IdFAI scores between the CAI and control groups, which verified the presence of the pathology (Table 4.1). Group means and standard deviations with powers, *P*-values, and effect sizes (*Cohen's d*) for the SEBT and YBT are reported in Table 4.2. The CAI group demonstrated significantly shorter reach distance than controls in the AN and PM directions on the SEBT and the PM and PL directions on the YBT ( $p < 0.008$ ). Within the control group, there was a statistically significant difference between SEBT and YBT tests in the AN direction, and within the CAI group in the PL direction ( $p < 0.008$ ). No other comparisons were statistically significantly different.

Means and standard deviations for joint angular displacements and joint angle at the point of maximum reach for the hip, knee, and ankle while performing the AN, PM, and PL reach direction of the SEBT (Table 4.3) and the YBT (Table 4.4) between the CAI and the control group were reported with powers, *P*-values, and effect sizes (*Cohen's d*).

For inter-limb comparisons, means and standard deviations for the joint angular displacement and joint angle at the point of maximum reach at the hip, knee, and ankle joint for the CAI group (Table 4.5) and the control group (Table 4.6) were also reported with powers, *P*-values, and effect sizes (*Cohen's d*).

## DISCUSSION

The primary aim of the current study was to compare the reach distances in 3 reach directions (AN, PM, and PL) and to investigate the kinematic patterns of the CAI group and the control group while performing the SEBT and the YBT. The results of the current study reject the original hypotheses that the CAI group would have shorter reach distances in all three reach directions on both the SEBT and the YBT, compared with the control group. Both the CAI group and the control group performed significantly shorter reach distances on the SEBT compared to the YBT in all 3 directions. The CAI group displayed significantly less joint angular displacement and joint angle at the point of maximum reach at the hip, knee, and ankle in the three planes on both the SEBT and YBT compared with the control group. Also, all participants, in both groups, exhibited significantly greater angular displacement and joint angle at the point of maximum reach at the hip, knee, ankle joints in the three planes on the YBT than on the SEBT.

### Between groups on the SEBT

#### *Reach distance*

In this study, the CAI group achieved significantly shorter reach distance in the AN and PM reach directions on the SEBT than did the control group, as shown in Table 4.2. Although it was not statistically significant ( $P < 0.008$ ), the CAI group also achieved shorter reach distance in the PL reach direction on the SEBT, compared to the control group. The approximate 14% difference in the PL reach distance between the groups could be a meaningful indication from

the clinical standpoint. Previous studies<sup>18,25</sup> strongly support the findings of this study as well. They also found that the CAI group demonstrated decreased reach distances on the SEBT compared to the control group.<sup>18,25</sup> Therefore, the results completely support our hypothesis that, compared with the control group, the CAI group would have shorter reach distance in all three reach directions on the SEBT.

#### *Anterior reach direction*

The current study found that, compared with the control group, the CAI group had significantly greater hip adduction angular displacement and hip adduction angle at the point of maximum reach in the AN reach direction on the SEBT, as shown in Table 4.3. The results partially contradict our hypothesis that the CAI group would show significantly decreased joint angles at the point of maximum reach and angular displacement at the hip, knee, and ankle joints in the three planes on the SEBT, compared with the control group. A previous study<sup>91</sup> reported that the control group used greater hip and knee flexion angular displacement to achieve greater reach distance when performing the AN reach direction on the SEBT. However, another previous study<sup>21</sup> claimed that ankle dorsiflexion angular displacement in the control group had the strongest correlation to reach distance while they performed the AN reach direction on the SEBT. However, these two previous studies only investigated a control group.

Hoch et al.<sup>116</sup> also found that a CAI group tended to utilize greater hip adduction and ankle eversion angular displacement to achieve greater reach distance while performing the AN reach direction on the SEBT. The CAI group in the current study, however, displayed less hip adduction angular displacement when performing the AN direction on the SEBT. Although it was not statistically significant, the CAI group in the current study had less hip, knee, ankle

angular displacement in the sagittal plane when performing the AN direction on the SEBT compared with the control group, as shown in Table 4.3. The CAI group may have adopted movement strategies that were different from those of the control group when performing the AN reach direction of the SEBT.

However, the results in the current study indicated large variability (standard deviation) in the knee angular displacement in the frontal plane and knee and ankle internal rotation angle at the point of maximum reach. Previous studies<sup>109,116</sup> also indicated that there may be variability in the frontal and transverse plane movement on the SEBT. Anecdotally, we observed the knee and ankle joints were wobbling in the frontal and transverse planes while participants were performing the AN reach direction of the SEBT, even within the control group. This may have contributed to the large variability we observed. The current study indicates that the CAI group might tend to collapse into hip adduction during the AN reach on the SEBT. We did not measure muscle strength or electromyography (EMG) activity, but the literature provides evidence of decreased hip strength in CAI populations and altered hip kinematics during movements.<sup>86,124</sup> Therefore, clinicians need to assess dynamic postural control strategies in patients with CAI to ensure no compensations or alterations are occurring. Then, an appropriate rehabilitation intervention should be applied to regain a kinematic pattern similar to that of the control group during the dynamic postural control task.

#### *Posteromedial reach direction*

In the PM reach direction, the CAI group in the current study demonstrated less hip flexion angular displacement than the control group. Also, they had greater hip external rotation and knee valgus angular displacement while the control group conversely had hip internal

rotation and knee varus angular displacement, as presented in Table 4.3. The CAI group also displayed significantly less hip and knee flexion and internal rotation angle at the point of maximum reach. However, they had greater knee valgus angle while the control group had greater knee varus angle at the point of maximum reach (see Table 4.3). The results also partially contradict our hypothesis that the CAI group would display significantly decreased joint angles at the point of maximum reach and angular displacement at the hip, knee, and ankle joints in the three planes on the SEBT compared with the control group.

While a previous study<sup>109</sup> reported no group differences in the hip, knee, and ankle angles at the point of maximum reach in the three planes, the current study found that the CAI group had less hip and knee flexion and internal rotation angles at the maximum reach. The previous study<sup>109</sup> also reported no group difference in the reach distance in the PM direction. Another previous study<sup>91</sup> found that, in the control group, greater reach distance in the PM direction on the SEBT was achieved primarily through greater hip flexion. The results of the current study also showed that the CAI group achieved less reach distance in the PM direction with less hip flexion angular displacement and angle at the point of maximum reach. However, we also demonstrated greater hip external rotation and knee valgus angular displacement. The CAI group had shorter reach distances in the PM direction on the SEBT coupled with less hip angular displacement in the sagittal plane. They might have used the hip external rotation and knee valgus to compensate for the limited hip angular displacement in the sagittal plane while performing the PM direction on the SEBT. Knee valgus and less hip flexion during the landing is generally considered a poor movement pattern in jump landings<sup>125</sup>. Although participants in the current study did not perform a landing, performing the PM reach direction on the SEBT also requires the same dynamic postural control strategies to maintain posture as does the landing

task. Therefore, it is important for clinicians to address issues of knee and hip frontal and transverse plane movement during the dynamic postural control task as a proper rehabilitation intervention.

### *Posterolateral reach direction*

The results of the current study indicated that the CAI participants demonstrated significantly decreased hip flexion, knee varus, and ankle eversion angular displacement compared to the controls when performing the PL direction on the SEBT. However, the CAI group had greater ankle external rotation while performing the PL direction on the SEBT. Also, the CAI group displayed significantly decreased hip and knee flexion angles, knee varus angle, and ankle eversion, and greater hip external rotation and ankle internal rotation angles at the point of maximum reach compared with the control group (see Table 4.3). The results of the current study partially rejected our hypothesis that the CAI group would have significantly decreased joint angles at the point of maximum reach and angular displacement at the hip, knee, and ankle in the three planes on the SEBT compared to the control group.

A previous study<sup>91</sup> reported that the control group utilized greater hip flexion to achieve greater reach distance in the PL direction. Our study also found that the CAI group had less hip flexion angular displacement and joint angles at the point of maximum reach when they performed the SEBT. Also, the CAI group had less knee varus (more valgus) and ankle eversion angular displacement. However, the CAI group had significantly greater ankle external rotation. The CAI participants showed decreased reach distance in the PL direction on the SEBT coupled with decreased hip flexion, knee varus, and ankle eversion angular displacement. Performing the PL direction on the SEBT requires that participants rotate their pelvis opposite to the reaching

direction of the reaching limb. Due to the nature of the PL direction on the SEBT, the CAI group might have tended to collapse their knee into valgus and ankle eversion, compared with the control group. The CAI group also used greater ankle external rotation, which may indicate that the CAI group tried to rotate (tibia internal rotation in the close kinetic chain) their body into the PL direction to accomplish the task. Therefore, clinicians should focus on restoring appropriate kinematic movement patterns during the PL direction on the SEBT in the CAI population similar to the control group.

The current study demonstrates the importance of measuring multiple joints in multiple planes through a multi-dimensional movement task, which previous studies have not demonstrated, as they focused on sagittal plane.<sup>21,116</sup> Our results indicated revealed several potentially negative movement pattern differences in the frontal and transverse planes at the knee and ankle in the CAI group. These movement patterns may be correctible via rehabilitation interventions.

#### Between groups on the YBT

##### *Reach distance*

The current study found that the CAI group had significantly shorter reach distance ( $P < 0.008$ ) in the PM and PL directions on the YBT compared with the control group (see Table 4.2). We noted no statistical difference between groups in reach distance in the AN direction. Therefore, the results partially supported our hypothesis that the CAI group would have shorter reach distance in all three reach directions on the SEBT than the control group. To the best of our knowledge, this is the first investigation to find differences in the reach distance in the three reach directions on the YBT between the CAI individuals and the controls.

### *Anterior reach direction*

Our findings indicated no statistically significant differences between the groups in any kinematic values while performing the AN direction on the YBT. Therefore, both groups performed similar reach distances in the AN reach direction on the YBT with similar movement patterns.

### *Posteromedial reach direction*

In the PM reach direction on the YBT, the results indicated that the CAI group demonstrated significantly less hip flexion angular displacement and angle at the point of maximum reach, and ankle external rotation angular displacement, compared with the control group. However, the CAI group showed significantly greater hip adduction and external rotation angular displacement and joint angles at the point of maximum reach than the control group. In the knee joint angles at the point of maximum reach, the CAI group displayed significantly less flexion and internal rotation angles. However, they showed significantly greater knee valgus angle at the point of maximum reach than the control group. The results also rejected our hypothesis that the CAI group would have significantly decreased angular displacement and joint angles at the point of maximum reach distance at the hip, knee, and ankle when performing the PM direction on the YBT.

The CAI group might have tended to collapse their hip into adduction and external rotation and knee into valgus to compensate for the limited hip and knee flexion during the PM direction on the YBT. Also, a previous study<sup>124</sup> found that the CAI group had weaker hip abduction strength. The weakness of hip abduction strength in the CAI group may have led to

increased hip adduction as they performed a dynamic postural control task. While we did not measure muscle electrical activity or hip abduction strength, clinicians may consider applying an appropriate rehabilitation intervention to increase hip abduction strength in the CAI group or restore better pelvis and lower extremity kinematic patterns, avoiding medial collapse.

#### *Posterolateral reach direction*

The CAI participants had decreased reach distance in the PL direction on the YBT with less hip flexion, knee varus, and ankle external rotation angles at the point of maximum reach compared with the control group. However, they had greater hip adduction and external rotation angles at the point of maximum reach even though they had lesser reach distance than the control group. Also, the results rejected our hypothesis that the CAI group would show decreased joint angular displacement and joint angles at the point of maximum reach at the hip, knee, and ankle. The CAI participants also had different movement patterns to perform the PL reach direction on the YBT. They may have used greater hip external rotation to compensate for the limited hip flexion and knee varus angular displacement. However, they had shorter reach distances with lesser hip flexion, knee varus, and ankle external rotation angles at the point of maximum reach than the control group.

The CAI group continuously demonstrated significantly greater hip adduction and lesser hip flexion in most of the reach directions on the SEBT and YBT. The CAI group might have had greater hip adduction due to either compensation for reach distance against the limited hip flexion and/or other kinematic deficits or weakness of hip abduction strength.<sup>124</sup> This may be an area to be targeted for rehabilitation.

### Between tests in the CAI group

#### *Reach distance*

The current study found that the CAI group had statistically significantly greater reach distance ( $P=0.003$ ) in the PL direction on the YBT compared with the SEBT. However, in the CAI group, there were no statistically significant differences in reach distances between the SEBT and YBT in the AN and PM reach directions. Previous studies<sup>20,21</sup> reported that the healthy controls reached farther in the AN direction on the SEBT than on the YBT, but they only had a healthy population in their study. The results from the current study partially supported our hypothesis that the CAI group had significantly shorter reach distance in all three reach directions on the SEBT compared with the YBT.

#### *Anterior reach direction*

In the AN reach direction, the CAI group displayed significantly greater hip flexion and internal rotation, knee flexion, and ankle dorsiflexion angular displacement on the SEBT compared to the YBT. However, they showed significantly greater ankle eversion angular displacement on the YBT. Although no difference was found in reach distance between tests, the CAI group demonstrated greater hip flexion and knee varus angles at the point of maximum reach on the YBT compared with the SEBT. But, they had greater hip internal rotation angle at the point of maximum reach on the SEBT than on the YBT. Therefore, the SEBT may require/allow greater hip flexion and internal rotation, knee flexion, and ankle dorsiflexion to achieve similar reach distance on the YBT in the CAI population. The results from the current study rejected our hypothesis that the CAI group would have significantly greater angular

displacement and joint angle at the point of maximum reach distance at the hip, knee, and ankle when performing the AN direction on the YBT, compared with the SEBT.

Fullam et al.<sup>21</sup> reported that participants achieved further reach distance in the AN direction on the SEBT than on the YBT. Also, they utilized significantly greater hip flexion while reaching in the AN direction on the YBT compared with the SEBT.<sup>21</sup> Although all participants were healthy individuals in this previous study<sup>21</sup>, the results partially support our finding that participants (CAI group) exhibited significantly greater hip flexion angle at the point of maximum reach when performing the AN direction on the SEBT compared with the YBT.

#### *Posteromedial reach direction*

The CAI group had significantly greater hip flexion, knee flexion, and ankle internal rotation angular displacement on the SEBT compared with the YBT. However, they showed significantly greater hip adduction and external rotation, knee valgus, and ankle eversion angular displacement on the YBT than on the SEBT. The CAI group had significantly greater knee flexion, ankle dorsiflexion, hip adduction, and knee valgus angles at the point of maximum reach on the YBT compared with the SEBT even though there was no difference in reach distance between the SEBT and YBT. The results of the current study also rejected our hypothesis that the CAI group would have significantly greater angular displacement and joint angle at the point of maximum reach distance at the hip, knee, and ankle when performing the PL direction on the YBT compared with the SEBT.

Though no difference was found in reach distance between the SEBT and YBT, the CAI group showed different kinematic strategies to perform the PM reach direction on the SEBT and YBT. The CAI group utilized more joint angular displacement in the sagittal plane at the hip and

knee on the SEBT compared with the YBT as they performed the PM reach direction. However, they utilized greater angular displacement in the frontal and transverse planes at the hip, knee, and ankle on the YBT compared with the SEBT.

#### *Posterolateral reach direction*

The CAI group's reach distance in the PL reach direction on the SEBT was significantly less than that on the YBT. In addition to the differences in reach distance achieved in the PL direction, the CAI group also had significantly less hip flexion, hip adduction, hip external rotation, knee flexion, knee varus, ankle dorsiflexion, ankle eversion, and ankle external rotation angles at the point of maximum reach on the SEBT. Also, the CAI group demonstrated significantly lesser hip flexion and external rotation, and ankle eversion and external rotation angular displacement on the SEBT than on the YBT. The CAI group had greater amounts of hip flexion and external rotation, and ankle eversion and external rotation to maintain contact with the indicator box while performing the YBT.

While the YBT required pushing the indicator box to achieve further reach distance, the participants only needed to tap (touch) the floor at the end of the reach excursion. The nature of the YBT test could have participants use greater amounts of hip flexion. The difference in the nature of the SEBT and YBT tests appears to affect all three reach directions. Therefore, it is suggested that clinicians and researchers separately apply these two tests in a CAI group.

## Between tests in the control group

### *Reach distance*

The control group achieved a significantly longer reach distance ( $P=0.007$ ) in the AN reach direction on the SEBT compared with the YBT. Previous studies<sup>20,21</sup> concur with this finding of the current study, in which the control group demonstrated significantly greater reach distance in the AN direction on the SEBT than on the YBT. However, no differences were found in the PM and PL reach directions between the SEBT and YBT. Also, our findings are supported by previous studies.<sup>20,21</sup> The control group likely performs differently on these two different tasks.

### *Anterior reach direction*

In addition to the differences in reach distance in the AN reach direction between the SEBT and the YBT, we also observed that the control group displayed significantly greater hip flexion, knee flexion, and internal rotation, and ankle dorsiflexion angular displacement when performing the SEBT compared with the YBT. The controls also had significantly greater ankle inversion and internal rotation angular displacement and hip adduction angles at the point of maximum reach on the YBT than on the SEBT.

A similar previous study<sup>21</sup> reported opposite results; that is, the control group only had significantly less hip flexion angular displacement when performing the AN direction on the SEBT compared with the YBT. Fullam et al.<sup>21</sup> also found that the control group showed less knee flexion and ankle dorsiflexion on the SEBT compared with the YBT even though this was not statistically significant. Additionally, a previous study<sup>91</sup> concurred that the hip and knee joint

angular displacement in the sagittal plane provided important contributions to performance in selected reach directions of the SEBT.

The results of the current study also revealed that the CAI group required a greater amount of hip flexion, knee flexion, and ankle dorsiflexion angular displacement on the SEBT compared to the YBT. These findings may indicate that the SEBT requires greater sagittal plane angular displacement at the hip, knee, and ankle in both groups than the YBT. Therefore, clinicians and researchers should not use these dynamic postural control tasks interchangeably or compare reach distances from one task to another. They appear to be distinct and separate tasks, at least in the AN reach direction.

#### *Posteromedial reach direction*

The control group exhibited significantly greater hip internal rotation, knee varus, and internal rotation angular displacement and less ankle eversion and external rotation on the SEBT than on the YBT. The control group also had significantly less hip adduction, knee flexion, and ankle dorsiflexion angles at the point of maximum reach on the SEBT than on the YBT. However, they had greater hip internal rotation and knee varus angles at the point of maximum reach on the SEBT than on the YBT.

The control group utilized more joint angular displacements in the frontal and transverse planes on the SEBT. While the reaching limb reached out at the further point in the PM reach direction on the SEBT, the testing limb in the control group used greater hip and knee internal rotation and knee varus to complete dynamic postural control tasks, compared with the YBT. However, the reach distance was not significantly different between the tests in the control group, despite kinematic pattern differences.

### *Posterolateral reach direction*

The control group exhibited significantly greater knee external rotation and ankle dorsiflexion angular displacement on the SEBT than on the YBT. However, they had significantly greater hip flexion and external rotation and ankle eversion on the YBT than on the SEBT. Although no differences were found in reach distances between the tests, the control group exhibited significantly greater hip internal rotation and knee external rotation angles at the point of maximum reach on the SEBT. Also, they had significantly greater hip and knee flexion, and ankle dorsiflexion angles at the point of maximum reach on the YBT compared with the SEBT.

The control group demonstrated significantly greater knee external rotation and ankle dorsiflexion angular displacement, and hip internal rotation and knee external rotation angles at the point of maximum reach on the SEBT. Also, the control group displayed significantly greater hip flexion and external rotation, and ankle eversion angular displacement and greater hip and knee flexion, and ankle dorsiflexion angles at the point of maximum reach on the YBT.

Although there was no difference in reach distance in the PM and PL reach directions between the SEBT and YBT, the control group exhibited many kinematic pattern differences. Therefore, it is suggested that the SEBT and YBT be considered separately as different dynamic postural control tests.

### Limitations

The authors acknowledge several limitations of this study. Some kinematic comparisons for the CAI and the control group had low power and effect sizes. Differences in physical ability

level between participants may exist. Findings on our recreationally physical active population may not be transferable to other active or non-active populations.

## CONCLUSIONS

The results of the current study indicate there are multiple significant differences in reach distance performance between CAI and control groups on the SEBT and YBT, and within groups on each task depending on reach direction. These performance differences may be attributable to the differences in kinematic patterns in the multiple joints and planes we observed. The CAI group demonstrated a number of potentially deleterious patterns, including decreased hip flexion and greater hip adduction and knee valgus than control groups. These differences may be modified via rehabilitation interventions and could improve with treatment. Because of the differences in performance and kinematic pattern noted here, clinicians and researchers should be cautious and likely not use the SEBT and YBT tests interchangeably.

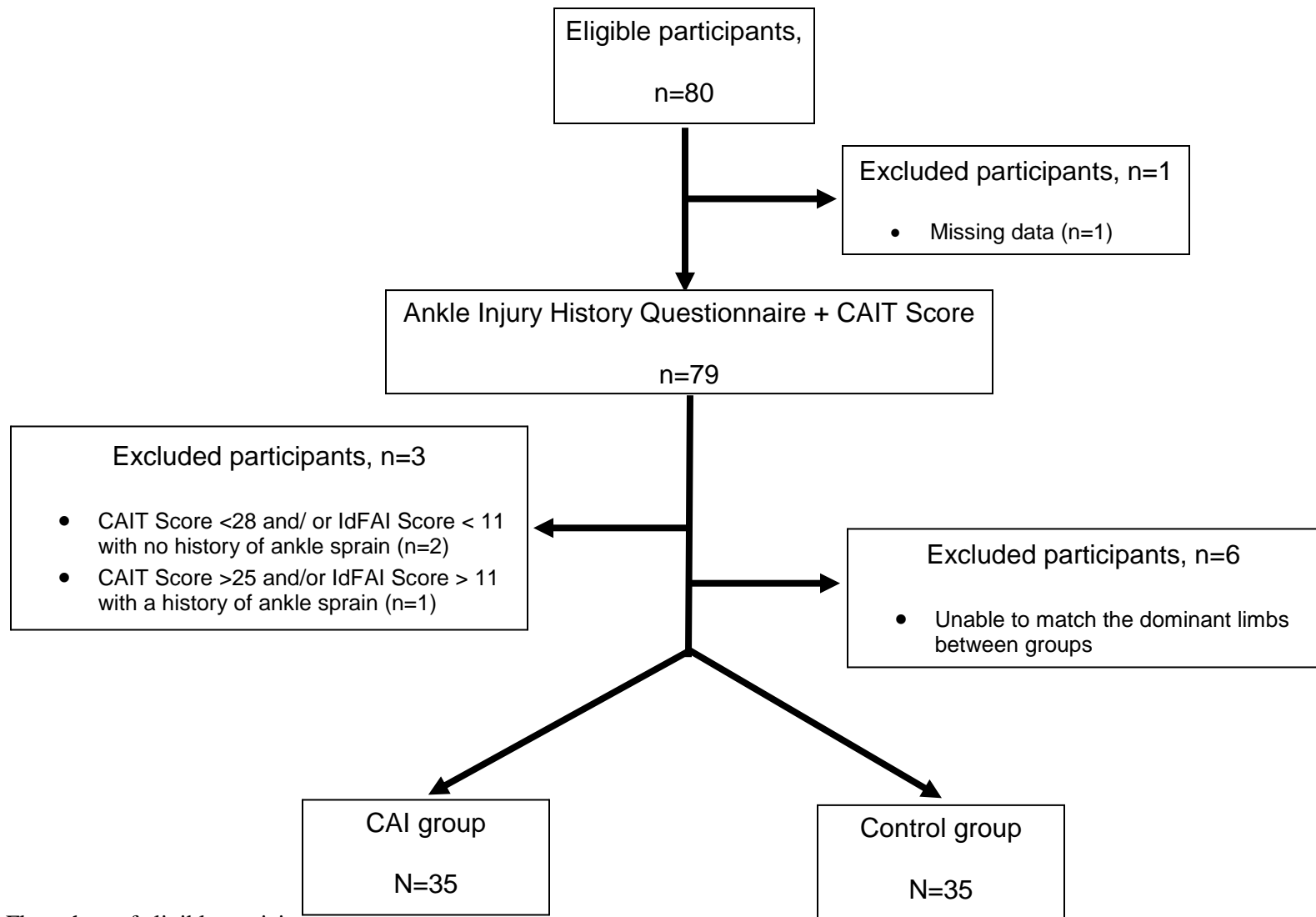


Figure 4.1. Flow chart of eligible participants.

Abbreviations: CAI, Chronic Ankle Instability; CAIT, Cumberland Ankle Instability Tool; IdFAI, Identification Functional Ankle Instability



Figure 4.2. Location of reflective markers

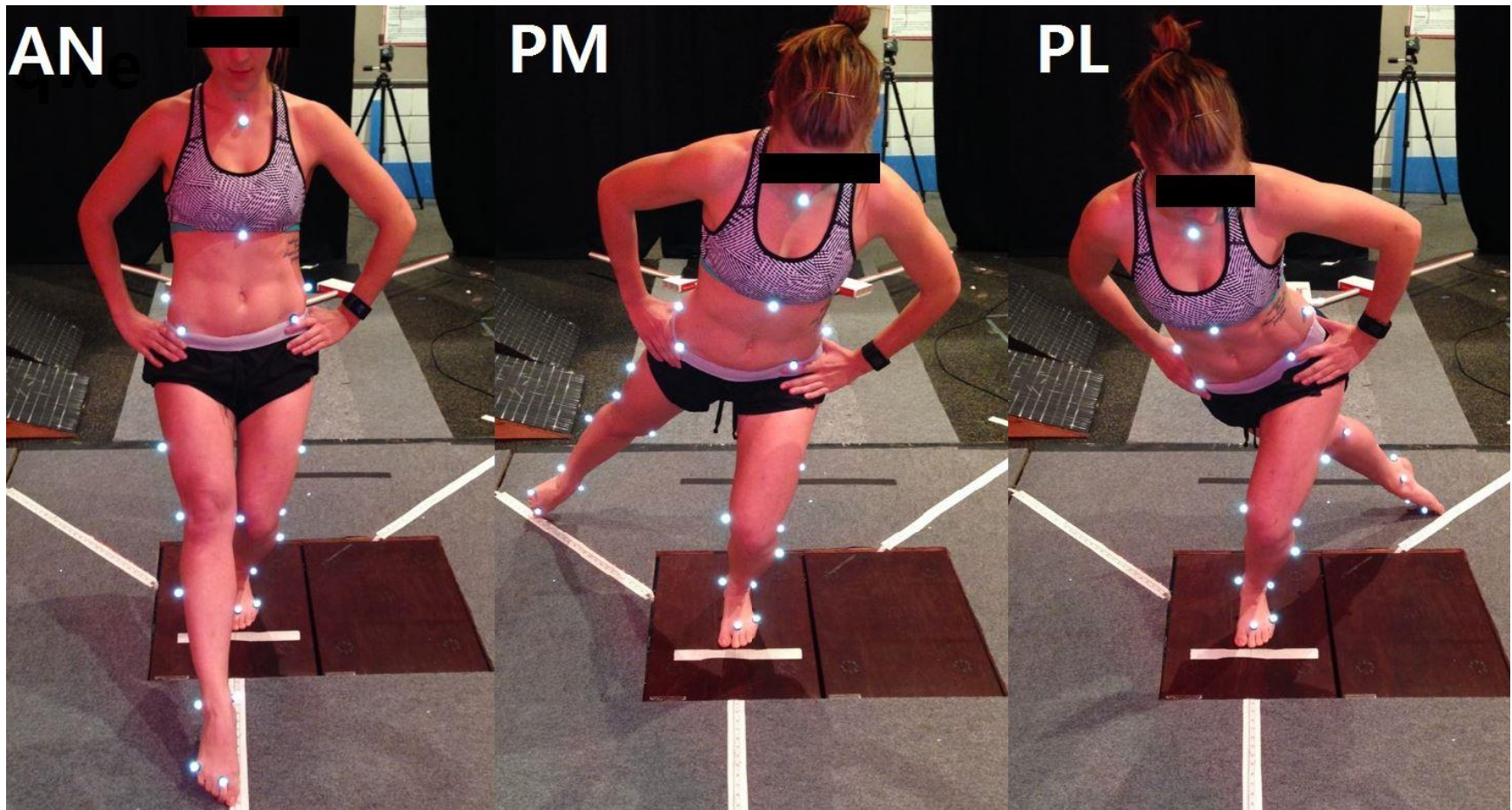


Figure 4.3. Three reach directions (AN: Anterior, PM: Posteromedial, and PL: Posterolateral) on the star excursion balance test for the left foot.

Table 4.1. Mean ( $\pm$ standard deviation) of participants' demographics

| Group          | Age (yr)            | Height (cm)           | Mass (kg)            | Test Limb              |
|----------------|---------------------|-----------------------|----------------------|------------------------|
| Control (N=35) | 21.63 ( $\pm$ 2.92) | 169.17 ( $\pm$ 10.36) | 69.30 ( $\pm$ 14.21) | Right = 29<br>Left = 6 |
| Female (23)    | 21.36 ( $\pm$ 3.16) | 163.65 ( $\pm$ 6.75)  | 63.30 ( $\pm$ 11.55) |                        |
| Male (12)      | 22.17 ( $\pm$ 2.44) | 179.75 ( $\pm$ 7.41)  | 80.79 ( $\pm$ 11.73) |                        |
| CAI (N=35)     | 21.17 ( $\pm$ 2.32) | 169.30 ( $\pm$ 10.77) | 70.15 ( $\pm$ 14.95) | Right = 29<br>Left = 6 |
| Female (23)    | 20.95 ( $\pm$ 1.99) | 163.35 ( $\pm$ 7.09)  | 63.11 ( $\pm$ 12.26) |                        |
| Male (12)      | 21.54 ( $\pm$ 2.84) | 179.36 ( $\pm$ 8.12)  | 82.05 ( $\pm$ 11.23) |                        |

CAI = Chronic Ankle Instability

Table 4.2. Mean ( $\pm$ standard deviation) of % maximal reach distance on the SEBT and YBT

| Group    | Anterior          |                  |          | Posteromedial      |                   |          | Posterolateral    |                   |          |
|----------|-------------------|------------------|----------|--------------------|-------------------|----------|-------------------|-------------------|----------|
|          | SEBT              | YBT              | <i>P</i> | SEBT               | YBT               | <i>P</i> | SEBT              | YBT               | <i>P</i> |
| Control  | 73.05 $\pm$ 22.70 | 64.74 $\pm$ 5.73 | 0.007*   | 110.41 $\pm$ 30.92 | 103.77 $\pm$ 9.39 | 0.178    | 96.79 $\pm$ 31.58 | 96.54 $\pm$ 10.76 | 0.959    |
| CAI      | 61.97 $\pm$ 5.93  | 62.59 $\pm$ 6.43 | 0.676    | 93.90 $\pm$ 8.82   | 94.61 $\pm$ 10.48 | 0.457    | 82.77 $\pm$ 11.53 | 88.03 $\pm$ 11.43 | 0.003*   |
| <i>P</i> | 0.007*            | 0.144            |          | 0.003*             | 0.001*            |          | 0.016             | 0.002*            |          |

SEBT = Star Excursion Balance Test; CAI = Chronic Ankle Instability

\*Significantly different ( $P < 0.008$ )

Table 4.3. Kinematic values on the Star Excursion Balance Test

| Reach direction | Joint                           | Plane                                 | Group                         |              | P-value      | Cohen's <i>d</i> | Power |      |
|-----------------|---------------------------------|---------------------------------------|-------------------------------|--------------|--------------|------------------|-------|------|
|                 |                                 |                                       | Control                       | CAI          |              |                  |       |      |
| AN              | Angular displacement            | Hip                                   | Sagittal                      | 9.83±9.22    | 8.91±12.19   | 0.724            | 0.08  | 0.01 |
|                 |                                 |                                       | Frontal                       | 9.95±3.40    | 12.77±4.06   | 0.002            | 0.75  | 0.66 |
|                 |                                 |                                       | Transverse                    | 4.21±4.62    | 5.18±5.45    | 0.428            | 0.19  | 0.03 |
|                 |                                 | Knee                                  | Sagittal                      | 43.62±10.71  | 41.30±19.15  | 0.534            | 0.15  | 0.02 |
|                 |                                 |                                       | Frontal                       | 0.13±6.06    | 0.56±3.01    | 0.705            | 0.09  | 0.01 |
|                 |                                 |                                       | Transverse                    | 13.28±6.27   | 15.03±5.19   | 0.206            | 0.30  | 0.08 |
|                 | Ankle                           | Sagittal                              | 21.09±7.52                    | 18.24±6.94   | 0.104        | 0.40             | 0.15  |      |
|                 |                                 | Frontal                               | 6.57±3.48                     | 7.13±3.38    | 0.499        | 0.16             | 0.02  |      |
|                 |                                 | Transverse                            | 8.71±4.01                     | 11.03±6.75   | 0.840        | 0.42             | 0.17  |      |
|                 | Angle at the Point of Max Reach | Hip                                   | Flexion (+) / Extension (-)   | 30.12±15.65  | 23.51±12.92  | 0.058            | 0.46  | 0.22 |
|                 |                                 |                                       | Adduction (+) / Abduction (-) | 9.24±4.83    | 12.84±6.08   | 0.008*           | 0.66  | 0.50 |
|                 |                                 |                                       | Internal (+) / External (-)   | 10.92±7.10   | 11.36±4.64   | 0.757            | 0.07  | 0.01 |
|                 |                                 | Knee                                  | Flexion (+) / Extension (-)   | 57.41±10.14  | 50.92±20.36  | 0.096            | 0.40  | 0.15 |
|                 |                                 |                                       | Varus (+) / Valgus (-)        | 4.86±5.54    | 2.68±3.49    | 0.054            | 0.47  | 0.23 |
|                 |                                 |                                       | Internal (+) / External (-)   | 2.88±10.21   | 0.07±5.17    | 0.151            | 0.35  | 0.10 |
|                 | Ankle                           | Dorsiflexion (+) / Plantarflexion (-) | 27.49±8.83                    | 25.60±8.21   | 0.357        | 0.22             | 0.04  |      |
|                 |                                 | Inversion (+) / Eversion (-)          | -10.95±5.86                   | -12.13±3.57  | 0.312        | 0.24             | 0.05  |      |
|                 |                                 | Internal (+) / External (-)           | -4.91±15.26                   | 0.05±6.78    | 0.083        | 0.42             | 0.17  |      |
| PM              | Angular displacement            | Hip                                   | Sagittal                      | 54.35±8.98   | 43.05±13.53  | 0.001*           | 0.98  | 0.91 |
|                 |                                 |                                       | Frontal                       | 4.40±4.14    | 3.27±7.43    | 0.432            | 0.19  | 0.03 |
|                 |                                 |                                       | Transverse                    | 5.21±5.22    | -2.44±5.73   | 0.001*           | 1.39  | 0.99 |
|                 |                                 | Knee                                  | Sagittal                      | 46.41±5.90   | 40.59±20.22  | 0.107            | 0.39  | 0.14 |
|                 |                                 |                                       | Frontal                       | 0.14±6.01    | -5.33±7.67   | 0.001*           | 0.80  | 0.72 |
|                 |                                 |                                       | Transverse                    | 15.70±9.36   | 12.24±5.02   | 0.058            | 0.46  | 0.22 |
|                 | Ankle                           | Sagittal                              | 14.25±4.92                    | 12.76±9.38   | 0.407        | 0.20             | 0.03  |      |
|                 |                                 | Frontal                               | -7.18±2.72                    | -7.48±3.23   | 0.682        | 0.10             | 0.01  |      |
|                 |                                 | Transverse                            | -13.79±4.04                   | -14.37±3.12  | 0.501        | 0.16             | 0.02  |      |
|                 | Angle at the Point of Max Reach | Hip                                   | Flexion (+) / Extension (-)   | 85.75±10.62  | 64.59±16.88  | 0.001*           | 1.50  | 0.99 |
|                 |                                 |                                       | Adduction (+) / Abduction (-) | 1.06±3.60    | 2.02±6.52    | 0.449            | 0.18  | 0.02 |
|                 |                                 |                                       | Internal (+) / External (-)   | 11.71±6.88   | 1.24±7.97    | 0.001*           | 1.41  | 0.99 |
|                 |                                 | Knee                                  | Flexion (+) / Extension (-)   | 65.38±4.81   | 53.67±19.29  | 0.001*           | 0.83  | 0.77 |
|                 |                                 |                                       | Varus (+) / Valgus (-)        | 4.28±6.99    | -3.33±7.08   | 0.001*           | 1.08  | 0.96 |
|                 |                                 |                                       | Internal (+) / External (-)   | 8.14±12.60   | 0.31±6.89    | 0.002*           | 0.77  | 0.69 |
|                 | Ankle                           | Dorsiflexion (+) / Plantarflexion (-) | 21.37±8.09                    | 19.49±10.94  | 0.415        | 0.19             | 0.03  |      |
|                 |                                 | Inversion (+) / Eversion (-)          | -11.69±4.40                   | -13.81±3.23  | 0.024        | 0.55             | 0.34  |      |
|                 |                                 | Internal (+) / External (-)           | -11.48±17.74                  | -4.37±2.53   | 0.022        | 0.56             | 0.36  |      |
| PL              | Angular displacement            | Hip                                   | Sagittal                      | 46.77±6.19   | 33.93±11.19  | 0.001*           | 1.41  | 0.99 |
|                 |                                 |                                       | Frontal                       | 14.47±2.33   | 15.89±3.76   | 0.062            | 0.45  | 0.21 |
|                 |                                 |                                       | Transverse                    | -2.64±4.22   | -5.34±7.95   | 0.081            | 0.39  | 0.14 |
|                 |                                 | Knee                                  | Sagittal                      | 19.99±5.61   | 18.95±12.72  | 0.660            | 0.10  | 0.01 |
|                 |                                 |                                       | Frontal                       | 25.05±2.40   | 15.09±7.62   | 0.001*           | 1.76  | 0.99 |
|                 |                                 |                                       | Transverse                    | -4.77±9.01   | -5.16±8.41   | 0.852            | 0.04  | 0.01 |
|                 | Ankle                           | Sagittal                              | 8.06±3.96                     | 8.89±6.57    | 0.487        | 0.15             | 0.02  |      |
|                 |                                 | Frontal                               | -13.22±3.06                   | -8.07±4.47   | 0.001*       | 1.34             | 0.99  |      |
|                 |                                 | Transverse                            | -3.36±3.60                    | -14.76±5.64  | 0.001*       | 2.41             | 1.00  |      |
|                 | Angle at the Point of Max Reach | Hip                                   | Flexion (+) / Extension (-)   | 75.75±6.87   | 54.32±14.83  | 0.001*           | 1.85  | 1.00 |
|                 |                                 |                                       | Adduction (+) / Abduction (-) | 13.08±3.34   | 14.03±5.03   | 0.355            | 0.22  | 0.04 |
|                 |                                 |                                       | Internal (+) / External (-)   | 4.04±5.14    | -2.88±7.94   | 0.001*           | 1.03  | 0.94 |
|                 |                                 | Knee                                  | Flexion (+) / Extension (-)   | 35.53±5.45   | 26.88±15.38  | 0.003*           | 0.75  | 0.65 |
|                 |                                 |                                       | Varus (+) / Valgus (-)        | 28.33±3.74   | 16.79±8.04   | 0.001*           | 1.04  | 0.94 |
|                 |                                 |                                       | Internal (+) / External (-)   | -13.86±13.88 | -19.48±13.37 | 0.089            | 0.41  | 0.17 |
|                 | Ankle                           | Dorsiflexion (+) / Plantarflexion (-) | 14.43±7.95                    | 13.87±7.69   | 0.762        | 0.07             | 0.01  |      |
|                 |                                 | Inversion (+) / Eversion (-)          | -16.43±2.25                   | -12.67±4.70  | 0.001*       | 1.02             | 0.93  |      |
|                 |                                 | Internal (+) / External (-)           | -18.34±17.05                  | 0.15±4.88    | 0.001*       | 1.47             | 0.99  |      |

\*Significantly different ( $P<0.008$ )

Table 4.4. Kinematic values on the Y-balance Test

| Reach direction | Joint                           | Plane                                 | Group                         |              | P-value      | Cohen's <i>d</i> | Power |      |
|-----------------|---------------------------------|---------------------------------------|-------------------------------|--------------|--------------|------------------|-------|------|
|                 |                                 |                                       | Control                       | CAI          |              |                  |       |      |
| AN              | Angular displacement            | Hip                                   | Sagittal                      | 3.47±13.11   | 5.66±12.85   | 0.483            | 0.17  | 0.02 |
|                 |                                 |                                       | Frontal                       | 10.15±4.89   | 11.39±3.61   | 0.230            | 0.29  | 0.07 |
|                 |                                 |                                       | Transverse                    | 4.29±3.97    | 3.20±4.73    | 0.300            | 0.25  | 0.05 |
|                 |                                 | Knee                                  | Sagittal                      | 32.70±6.93   | 34.53±22.86  | 0.652            | 0.08  | 0.01 |
|                 |                                 |                                       | Frontal                       | 0.03±5.32    | 0.68±2.62    | 0.521            | 0.15  | 0.02 |
|                 |                                 |                                       | Transverse                    | 10.90±6.99   | 13.89±5.54   | 0.051            | 0.47  | 0.23 |
|                 | Ankle                           | Sagittal                              | 14.13±7.42                    | 16.19±9.56   | 0.318        | 0.24             | 0.04  |      |
|                 |                                 | Frontal                               | 10.07±3.16                    | 12.02±5.99   | 0.094        | 0.40             | 0.16  |      |
|                 |                                 | Transverse                            | 10.82±3.17                    | 8.36±6.31    | 0.043        | 0.49             | 0.25  |      |
|                 | Angle at the Point of Max Reach | Hip                                   | Flexion (+) / Extension (-)   | 31.10±22.66  | 26.94±15.81  | 0.376            | 0.21  | 0.04 |
|                 |                                 |                                       | Adduction (+) / Abduction (-) | 11.11±5.68   | 13.91±4.61   | 0.027            | 0.54  | 0.33 |
|                 |                                 |                                       | Internal (+) / External (-)   | 10.07±6.72   | 8.59±5.31    | 0.311            | 0.24  | 0.05 |
|                 |                                 | Knee                                  | Flexion (+) / Extension (-)   | 57.10±15.15  | 51.62±24.91  | 0.270            | 0.27  | 0.06 |
|                 |                                 |                                       | Varus (+) / Valgus (-)        | 4.52±5.68    | 4.35±2.20    | 0.876            | 0.04  | 0.01 |
|                 |                                 |                                       | Internal (+) / External (-)   | 4.37±12.38   | -1.68±8.66   | 0.021            | 0.57  | 0.37 |
| Ankle           |                                 | Dorsiflexion (+) / Plantarflexion (-) | 26.27±6.89                    | 26.04±11.70  | 0.919        | 0.02             | 0.01  |      |
|                 |                                 | Inversion (+) / Eversion (-)          | -10.73±5.63                   | -12.16±3.71  | 0.213        | 0.29             | 0.08  |      |
|                 |                                 | Internal (+) / External (-)           | -5.05±16.35                   | 1.77±6.33    | 0.025        | 0.55             | 0.34  |      |
| PM              | Angular displacement            | Hip                                   | Sagittal                      | 56.13±7.85   | 39.06±13.59  | 0.001*           | 1.54  | 0.99 |
|                 |                                 |                                       | Frontal                       | 5.63±3.94    | 9.43±4.86    | 0.001*           | 0.86  | 0.80 |
|                 |                                 |                                       | Transverse                    | 2.55±5.69    | -8.31±9.83   | 0.001*           | 1.35  | 0.99 |
|                 |                                 | Knee                                  | Sagittal                      | 42.77±16.42  | 32.73±18.54  | 0.019            | 0.57  | 0.37 |
|                 |                                 |                                       | Frontal                       | -2.63±7.17   | -7.37±7.86   | 0.011            | 0.63  | 0.47 |
|                 |                                 |                                       | Transverse                    | 14.19±7.34   | 12.27±4.02   | 0.179            | 0.32  | 0.09 |
|                 | Ankle                           | Sagittal                              | 12.18±10.13                   | 10.41±8.57   | 0.433        | 0.19             | 0.03  |      |
|                 |                                 | Frontal                               | -11.81±3.62                   | -12.75±6.13  | 0.439        | 0.18             | 0.03  |      |
|                 |                                 | Transverse                            | -16.51±4.09                   | -11.86±3.50  | 0.001*       | 1.22             | 0.98  |      |
|                 | Angle at the Point of Max Reach | Hip                                   | Flexion (+) / Extension (-)   | 86.67±11.42  | 65.11±16.96  | 0.001*           | 1.49  | 0.99 |
|                 |                                 |                                       | Adduction (+) / Abduction (-) | 5.67±3.97    | 11.49±4.96   | 0.001*           | 1.29  | 0.99 |
|                 |                                 |                                       | Internal (+) / External (-)   | 7.89±5.89    | -0.05±12.05  | 0.001*           | 0.83  | 0.77 |
|                 |                                 | Knee                                  | Flexion (+) / Extension (-)   | 68.65±5.72   | 56.65±15.81  | 0.001*           | 1.00  | 0.92 |
|                 |                                 |                                       | Varus (+) / Valgus (-)        | 1.55±7.77    | -4.54±7.66   | 0.002*           | 0.79  | 0.71 |
|                 |                                 |                                       | Internal (+) / External (-)   | 8.00±13.23   | 0.62±5.16    | 0.003*           | 0.73  | 0.63 |
| Ankle           |                                 | Dorsiflexion (+) / Plantarflexion (-) | 24.36±7.24                    | 22.61±9.24   | 0.383        | 0.21             | 0.03  |      |
|                 |                                 | Inversion (+) / Eversion (-)          | -11.76±5.61                   | -13.54±4.25  | 0.142        | 0.36             | 0.12  |      |
|                 |                                 | Internal (+) / External (-)           | -10.49±16.26                  | -4.64±3.82   | 0.042        | 0.49             | 0.26  |      |
| PL              | Angular displacement            | Hip                                   | Sagittal                      | 52.46±8.25   | 40.69±14.27  | 0.001*           | 1.00  | 0.93 |
|                 |                                 |                                       | Frontal                       | 13.19±4.17   | 16.50±6.30   | 0.012            | 0.62  | 0.45 |
|                 |                                 |                                       | Transverse                    | -6.32±7.09   | -13.93±6.70  | 0.001*           | 1.10  | 0.97 |
|                 |                                 | Knee                                  | Sagittal                      | 18.87±6.71   | 19.80±17.02  | 0.763            | 0.07  | 0.01 |
|                 |                                 |                                       | Frontal                       | 23.64±2.92   | 15.50±6.50   | 0.001*           | 1.62  | 0.99 |
|                 |                                 |                                       | Transverse                    | -2.40±10.42  | -1.38±10.42  | 0.683            | 0.09  | 0.01 |
|                 | Ankle                           | Sagittal                              | 4.82±6.30                     | 8.12±7.23    | 0.045        | 0.49             | 0.25  |      |
|                 |                                 | Frontal                               | -17.25±4.04                   | -15.37±6.30  | 0.143        | 0.36             | 0.11  |      |
|                 |                                 | Transverse                            | -23.06±6.14                   | -18.35±10.23 | 0.022        | 0.56             | 0.36  |      |
|                 | Angle at the Point of Max Reach | Hip                                   | Flexion (+) / Extension (-)   | 81.90±12.89  | 64.63±17.07  | 0.001*           | 1.14  | 0.97 |
|                 |                                 |                                       | Adduction (+) / Abduction (-) | 13.94±4.65   | 19.96±7.51   | 0.001*           | 0.95  | 0.89 |
|                 |                                 |                                       | Internal (+) / External (-)   | 1.61±5.08    | -4.77±8.66   | 0.001*           | 0.90  | 0.84 |
|                 |                                 | Knee                                  | Flexion (+) / Extension (-)   | 44.91±8.89   | 39.25±17.34  | 0.090            | 0.41  | 0.16 |
|                 |                                 |                                       | Varus (+) / Valgus (-)        | 27.54±6.96   | 18.50±5.81   | 0.001*           | 1.41  | 0.99 |
|                 |                                 |                                       | Internal (+) / External (-)   | -8.36±17.07  | -14.34±14.53 | 0.119            | 0.37  | 0.13 |
| Ankle           |                                 | Dorsiflexion (+) / Plantarflexion (-) | 17.75±5.59                    | 18.31±9.11   | 0.756        | 0.07             | 0.01  |      |
|                 |                                 | Inversion (+) / Eversion (-)          | -16.87±2.90                   | -15.96±4.76  | 0.338        | 0.23             | 0.04  |      |
|                 |                                 | Internal (+) / External (-)           | -17.09±15.71                  | -8.41±3.41   | 0.002*       | 0.76             | 0.68  |      |

\*Significantly different ( $P < 0.008$ )

Table 4.5. Kinematic values for the CAI group

| Reach direction | Joint                           | Plane                                 | Test                          |              |                 | Cohen's <i>d</i> | Power |      |
|-----------------|---------------------------------|---------------------------------------|-------------------------------|--------------|-----------------|------------------|-------|------|
|                 |                                 |                                       | SEBT                          | YBT          | <i>P</i> -value |                  |       |      |
| AN              | Angular displacement            | Hip                                   | Sagittal                      | 8.91±12.19   | 5.66±12.85      | 0.002*           | 0.26  | 0.06 |
|                 |                                 |                                       | Frontal                       | 12.77±4.06   | 11.39±3.61      | 0.071            | 0.36  | 0.12 |
|                 |                                 |                                       | Transverse                    | 5.18±5.45    | -1.20±4.73      | 0.001*           | 1.25  | 0.99 |
|                 |                                 | Knee                                  | Sagittal                      | 41.30±19.15  | 34.53±22.86     | 0.001*           | 0.32  | 0.09 |
|                 |                                 |                                       | Frontal                       | 0.56±3.01    | 0.68±2.62       | 0.776            | 0.04  | 0.01 |
|                 |                                 |                                       | Transverse                    | 15.03±5.19   | 13.89±5.54      | 0.148            | 0.21  | 0.03 |
|                 | Ankle                           | Sagittal                              | 18.24±6.94                    | 16.19±9.56   | 0.001*          | 0.24             | 0.05  |      |
|                 |                                 | Frontal                               | 7.13±3.38                     | 12.02±5.99   | 0.001*          | 1.00             | 0.93  |      |
|                 |                                 | Transverse                            | 11.03±6.75                    | 8.36±6.31    | 0.031           | 0.41             | 0.16  |      |
|                 | Angle at the Point of Max Reach | Hip                                   | Flexion (+) / Extension (-)   | 23.51±12.92  | 26.94±15.81     | 0.001*           | 0.24  | 0.05 |
|                 |                                 |                                       | Adduction (+) / Abduction (-) | 12.84±6.08   | 13.91±4.61      | 0.037            | 0.20  | 0.03 |
|                 |                                 |                                       | Internal (+) / External (-)   | 11.36±4.64   | 8.59±5.31       | 0.001*           | 0.56  | 0.35 |
|                 |                                 | Knee                                  | Flexion (+) / Extension (-)   | 50.92±20.36  | 51.62±24.91     | 0.511            | 0.03  | 0.01 |
|                 |                                 |                                       | Varus (+) / Valgus (-)        | 2.68±3.49    | 4.35±2.20       | 0.005*           | 0.57  | 0.37 |
|                 |                                 |                                       | Internal (+) / External (-)   | 0.07±5.17    | -1.68±8.66      | 0.018            | 0.24  | 0.05 |
| Ankle           |                                 | Dorsiflexion (+) / Plantarflexion (-) | 25.60±8.21                    | 26.04±11.70  | 0.516           | 0.04             | 0.01  |      |
|                 |                                 | Inversion (+) / Eversion (-)          | -12.13±3.57                   | -12.16±3.71  | 0.947           | 0.01             | 0.01  |      |
|                 |                                 | Internal (+) / External (-)           | 0.05±6.78                     | 1.77±6.33    | 0.055           | 0.26             | 0.06  |      |
| PM              | Angular displacement            | Hip                                   | Sagittal                      | 43.05±13.53  | 39.06±13.59     | 0.003*           | 0.30  | 0.07 |
|                 |                                 |                                       | Frontal                       | 3.27±7.43    | 9.43±4.86       | 0.001*           | 0.98  | 0.91 |
|                 |                                 |                                       | Transverse                    | -2.44±5.73   | -8.31±9.83      | 0.001*           | 0.73  | 0.63 |
|                 |                                 | Knee                                  | Sagittal                      | 40.59±20.22  | 32.73±18.54     | 0.001*           | 0.41  | 0.16 |
|                 |                                 |                                       | Frontal                       | -5.33±7.67   | -7.37±7.86      | 0.001*           | 0.26  | 0.05 |
|                 |                                 |                                       | Transverse                    | 12.24±5.02   | 12.27±4.02      | 0.961            | 0.01  | 0.01 |
|                 | Ankle                           | Sagittal                              | 12.76±9.38                    | 10.41±8.57   | 0.001*          | 0.26             | 0.05  |      |
|                 |                                 | Frontal                               | -7.48±3.23                    | -12.75±6.13  | 0.001*          | 1.07             | 0.95  |      |
|                 |                                 | Transverse                            | -14.37±3.12                   | -11.86±3.50  | 0.001*          | 0.75             | 0.67  |      |
|                 | Angle at the Point of Max Reach | Hip                                   | Flexion (+) / Extension (-)   | 64.59±16.88  | 65.11±16.96     | 0.608            | 0.03  | 0.01 |
|                 |                                 |                                       | Adduction (+) / Abduction (-) | 2.02±6.52    | 11.49±4.96      | 0.001*           | 1.63  | 0.99 |
|                 |                                 |                                       | Internal (+) / External (-)   | 1.24±7.97    | -0.05±12.05     | 0.122            | 0.13  | 0.01 |
|                 |                                 | Knee                                  | Flexion (+) / Extension (-)   | 53.67±19.29  | 56.65±15.81     | 0.003*           | 0.16  | 0.04 |
|                 |                                 |                                       | Varus (+) / Valgus (-)        | -3.33±7.08   | -4.54±7.66      | 0.001*           | 0.16  | 0.04 |
|                 |                                 |                                       | Internal (+) / External (-)   | 0.31±6.89    | 0.62±5.16       | 0.528            | 0.05  | 0.01 |
| Ankle           |                                 | Dorsiflexion (+) / Plantarflexion (-) | 19.49±10.94                   | 22.61±9.24   | 0.001*          | 0.31             | 0.08  |      |
|                 |                                 | Inversion (+) / Eversion (-)          | -13.81±3.23                   | -13.54±4.25  | 0.297           | 0.07             | 0.01  |      |
|                 |                                 | Internal (+) / External (-)           | -4.37±2.53                    | -4.64±3.82   | 0.411           | 0.08             | 0.01  |      |
| PL              | Angular displacement            | Hip                                   | Sagittal                      | 33.93±11.19  | 40.69±14.27     | 0.001*           | 0.53  | 0.31 |
|                 |                                 |                                       | Frontal                       | 15.89±3.76   | 16.50±6.30      | 0.407            | 0.12  | 0.02 |
|                 |                                 |                                       | Transverse                    | -5.34±7.95   | -13.93±6.70     | 0.001*           | 1.17  | 0.98 |
|                 |                                 | Knee                                  | Sagittal                      | 18.95±12.72  | 19.80±17.02     | 0.622            | 0.05  | 0.01 |
|                 |                                 |                                       | Frontal                       | 15.09±7.62   | 15.50±6.50      | 0.477            | 0.05  | 0.01 |
|                 |                                 |                                       | Transverse                    | -5.16±8.41   | -1.38±10.42     | 0.026            | 0.40  | 0.15 |
|                 | Ankle                           | Sagittal                              | 8.89±6.57                     | 8.12±7.23    | 0.392           | 0.11             | 0.01  |      |
|                 |                                 | Frontal                               | -8.07±4.47                    | -15.37±6.30  | 0.001*          | 1.34             | 0.99  |      |
|                 |                                 | Transverse                            | -14.76±5.64                   | -18.35±10.23 | 0.001           | 0.43             | 0.19  |      |
|                 | Angle at the Point of Max Reach | Hip                                   | Flexion (+) / Extension (-)   | 54.32±14.83  | 64.63±17.07     | 0.001*           | 0.64  | 0.50 |
|                 |                                 |                                       | Adduction (+) / Abduction (-) | 14.03±5.03   | 19.96±7.51      | 0.001*           | 0.93  | 0.87 |
|                 |                                 |                                       | Internal (+) / External (-)   | -2.88±7.94   | -4.77±8.66      | 0.002*           | 0.23  | 0.04 |
|                 |                                 | Knee                                  | Flexion (+) / Extension (-)   | 26.88±15.38  | 39.25±17.34     | 0.001*           | 0.75  | 0.66 |
|                 |                                 |                                       | Varus (+) / Valgus (-)        | 16.79±8.04   | 18.50±5.81      | 0.002*           | 0.24  | 0.04 |
|                 |                                 |                                       | Internal (+) / External (-)   | -19.48±13.37 | -14.34±14.53    | 0.001*           | 0.37  | 0.12 |
| Ankle           |                                 | Dorsiflexion (+) / Plantarflexion (-) | 13.87±7.69                    | 18.31±9.11   | 0.001*          | 0.53             | 0.30  |      |
|                 |                                 | Inversion (+) / Eversion (-)          | -12.67±4.70                   | -15.96±4.76  | 0.001*          | 0.70             | 0.57  |      |
|                 |                                 | Internal (+) / External (-)           | 0.15±4.88                     | -8.41±3.41   | 0.001*          | 2.03             | 1.00  |      |

\*Significantly different (*P*<0.008)

Table 4.6. Kinematic values for the control group

| Reach direction | Joint                           | Plane                                 | Test                          |              |                 | Cohen's <i>d</i> | Power |      |
|-----------------|---------------------------------|---------------------------------------|-------------------------------|--------------|-----------------|------------------|-------|------|
|                 |                                 |                                       | SEBT                          | YBT          | <i>P</i> -value |                  |       |      |
| AN              | Angular displacement            | Hip                                   | Sagittal                      | 9.83±9.22    | 3.47±13.11      | 0.001*           | 0.56  | 0.36 |
|                 |                                 |                                       | Frontal                       | 9.95±3.40    | 10.15±4.89      | 0.767            | 0.05  | 0.01 |
|                 |                                 |                                       | Transverse                    | 4.21±4.62    | 4.29±3.97       | 0.857            | 0.02  | 0.01 |
|                 | Knee                            | Sagittal                              | 43.62±10.71                   | 32.70±6.93   | 0.001*          | 1.21             | 0.98  |      |
|                 |                                 | Frontal                               | 0.13±6.06                     | 0.03±5.32    | 0.882           | 0.02             | 0.01  |      |
|                 |                                 | Transverse                            | 13.28±6.27                    | 10.90±6.99   | 0.001*          | 0.36             | 0.12  |      |
|                 | Ankle                           | Sagittal                              | 21.09±7.52                    | 14.13±7.42   | 0.001*          | 0.93             | 0.87  |      |
|                 |                                 | Frontal                               | 6.57±3.48                     | 10.07±3.16   | 0.001*          | 1.05             | 0.95  |      |
|                 |                                 | Transverse                            | 8.71±4.01                     | 10.82±3.17   | 0.007*          | 0.58             | 0.39  |      |
|                 | Angle at the Point of Max Reach | Hip                                   | Flexion (+) / Extension (-)   | 30.12±15.65  | 31.10±22.66     | 0.620            | 0.05  | 0.01 |
|                 |                                 |                                       | Adduction (+) / Abduction (-) | 9.24±4.83    | 11.11±5.68      | 0.002*           | 0.35  | 0.11 |
|                 |                                 |                                       | Internal (+) / External (-)   | 10.92±7.10   | 10.07±6.72      | 0.147            | 0.12  | 0.02 |
|                 |                                 | Knee                                  | Flexion (+) / Extension (-)   | 57.41±10.14  | 57.10±15.15     | 0.891            | 0.02  | 0.01 |
|                 |                                 |                                       | Varus (+) / Valgus (-)        | 4.86±5.54    | 4.52±5.68       | 0.429            | 0.06  | 0.01 |
|                 |                                 |                                       | Internal (+) / External (-)   | 2.88±10.21   | 4.37±12.38      | 0.031            | 0.13  | 0.01 |
| Ankle           |                                 | Dorsiflexion (+) / Plantarflexion (-) | 27.49±8.83                    | 26.27±6.89   | 0.201           | 0.15             | 0.02  |      |
|                 |                                 | Inversion (+) / Eversion (-)          | -10.95±5.86                   | -10.73±5.63  | 0.424           | 0.04             | 0.01  |      |
|                 |                                 | Internal (+) / External (-)           | -4.91±15.26                   | -5.05±16.35  | 0.690           | 0.01             | 0.01  |      |
| PM              | Angular displacement            | Hip                                   | Sagittal                      | 54.35±8.98   | 56.13±7.85      | 0.141            | 0.21  | 0.03 |
|                 |                                 |                                       | Frontal                       | 4.40±4.14    | 5.63±3.94       | 0.060            | 0.30  | 0.08 |
|                 |                                 |                                       | Transverse                    | 5.21±5.22    | 2.55±5.69       | 0.001*           | 0.48  | 0.25 |
|                 | Knee                            | Sagittal                              | 46.41±5.90                    | 42.77±16.42  | 0.064           | 0.30             | 0.07  |      |
|                 |                                 | Frontal                               | 0.14±6.01                     | -2.63±7.17   | 0.001*          | 0.42             | 0.17  |      |
|                 |                                 | Transverse                            | 15.70±9.36                    | 14.19±7.34   | 0.007*          | 0.18             | 0.03  |      |
|                 | Ankle                           | Sagittal                              | 14.25±4.92                    | 12.18±10.13  | 0.054           | 0.26             | 0.05  |      |
|                 |                                 | Frontal                               | -7.18±2.72                    | -11.81±3.62  | 0.001*          | 1.44             | 0.99  |      |
|                 |                                 | Transverse                            | -13.79±4.04                   | -16.51±4.09  | 0.003*          | 0.67             | 0.53  |      |
|                 | Angle at the Point of Max Reach | Hip                                   | Flexion (+) / Extension (-)   | 85.75±10.62  | 86.67±11.42     | 0.024            | 0.08  | 0.01 |
|                 |                                 |                                       | Adduction (+) / Abduction (-) | 1.06±3.60    | 5.67±3.97       | 0.001*           | 1.21  | 0.99 |
|                 |                                 |                                       | Internal (+) / External (-)   | 11.71±6.88   | 7.89±5.89       | 0.001*           | 0.60  | 0.41 |
|                 |                                 | Knee                                  | Flexion (+) / Extension (-)   | 65.38±4.81   | 68.65±5.72      | 0.001*           | 0.62  | 0.45 |
|                 |                                 |                                       | Varus (+) / Valgus (-)        | 4.28±6.99    | 1.55±7.77       | 0.001*           | 0.37  | 0.16 |
|                 |                                 |                                       | Internal (+) / External (-)   | 8.14±12.60   | 8.00±13.23      | 0.413            | 0.01  | 0.01 |
| Ankle           |                                 | Dorsiflexion (+) / Plantarflexion (-) | 21.37±8.09                    | 24.36±7.24   | 0.001*          | 0.39             | 0.14  |      |
|                 |                                 | Inversion (+) / Eversion (-)          | -11.69±4.40                   | -11.76±5.61  | 0.726           | 0.01             | 0.01  |      |
|                 |                                 | Internal (+) / External (-)           | -11.48±17.74                  | -10.49±16.26 | 0.116           | 0.06             | 0.01  |      |
| PL              | Angular displacement            | Hip                                   | Sagittal                      | 46.77±6.19   | 52.46±8.25      | 0.001*           | 0.78  | 0.70 |
|                 |                                 |                                       | Frontal                       | 14.47±2.33   | 13.19±4.17      | 0.020            | 0.38  | 0.14 |
|                 |                                 |                                       | Transverse                    | -2.64±4.22   | -6.32±7.09      | 0.001*           | 0.63  | 0.46 |
|                 | Knee                            | Sagittal                              | 19.99±5.61                    | 18.87±6.71   | 0.280           | 0.18             | 0.03  |      |
|                 |                                 | Frontal                               | 25.05±2.40                    | 23.64±2.92   | 0.010           | 0.53             | 0.31  |      |
|                 |                                 | Transverse                            | -4.77±9.01                    | -2.40±10.42  | 0.001*          | 0.24             | 0.05  |      |
|                 | Ankle                           | Sagittal                              | 8.06±3.96                     | 4.82±6.30    | 0.001*          | 0.62             | 0.44  |      |
|                 |                                 | Frontal                               | -13.22±3.06                   | -17.25±4.04  | 0.001*          | 1.12             | 0.97  |      |
|                 |                                 | Transverse                            | -3.36±3.60                    | -3.06±6.14   | 0.653           | 0.05             | 0.01  |      |
|                 | Angle at the Point of Max Reach | Hip                                   | Flexion (+) / Extension (-)   | 75.75±6.87   | 81.90±12.89     | 0.001*           | 0.60  | 0.41 |
|                 |                                 |                                       | Adduction (+) / Abduction (-) | 13.08±3.34   | 13.94±4.65      | 0.057            | 0.21  | 0.01 |
|                 |                                 |                                       | Internal (+) / External (-)   | 4.04±5.14    | 1.61±5.08       | 0.001*           | 0.48  | 0.24 |
|                 |                                 | Knee                                  | Flexion (+) / Extension (-)   | 35.53±5.45   | 44.91±8.89      | 0.001*           | 1.27  | 0.99 |
|                 |                                 |                                       | Varus (+) / Valgus (-)        | 28.33±3.74   | 27.54±6.96      | 0.305            | 0.15  | 0.02 |
|                 |                                 |                                       | Internal (+) / External (-)   | -13.86±13.88 | -8.36±17.07     | 0.001            | 0.35  | 0.11 |
| Ankle           |                                 | Dorsiflexion (+) / Plantarflexion (-) | 14.43±7.95                    | 17.75±5.59   | 0.001*          | 0.48             | 0.25  |      |
|                 |                                 | Inversion (+) / Eversion (-)          | -16.43±2.25                   | -16.87±2.90  | 0.061           | 0.17             | 0.03  |      |
|                 |                                 | Internal (+) / External (-)           | -18.34±17.05                  | -17.09±15.71 | 0.045           | 0.08             | 0.01  |      |

\*Significantly different (*P*<0.008)

## CHAPTER 5

### POSTURAL STABILITY MEASURES DURING THE STAR EXCURSION BALANCE TEST IN INDIVIDUALS WITH CHRONIC ANKLE INSTABILITY

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## ABSTRACT

*Background:* Instrumented postural stability assessments during single-leg stance and/or single-leg jump landing on a biomechanical force platform have been utilized to identify ankle instability in individuals with Chronic Ankle Instability (CAI). However, no studies have measured instrumented postural stability while performing a dynamic postural control task such as the Star Excursion Balance Test (SEBT) in an affected population, and the results and implications for rehabilitation may be different in this testing paradigm. The purpose of this study was to determine if there was a significant difference in dynamic postural control stability between the groups while performing the SEBT. *Methods:* From 80 initial participants, 70 participants (35 in the CAI and 35 in the control group) performed 3 test trials in the Anterior (AN), Posteromedial (PM), and Posterolateral (PL) directions of the SEBT on the single force plate. Center of Pressure (COP) data with a sampling rate of 180Hz were collected while participants were performing the SEBT. A series of independent sample t-tests was used to determine if group differences existed for the instrumented dynamic postural stability measures between the groups. *Findings:* The CAI group had significantly lower A-P  $COP_{SD}$  (cm) and  $COP_{A-95}$  (cm<sup>2</sup>) than the control group while performing the SEBT in the AN (Control: 73.05±22.70%; CAI: 61.97±5.93%, [ $P=0.007$ ]), PM (Control: 110.41±30.93%; CAI: 93.90±8.82%, [ $P=0.003$ ]), and PL (Control: 96.80±31.58%; CAI: 82.78±11.53%, [ $P=0.016$ ]) reach directions. Also, individuals with CAI had significantly lower  $COP_V$  (cm/s) compared with the control group on the SEBT in the PM and PL reach directions. Significantly greater M-L  $COP_{SD}$  (cm) while performing the SEBT in the AN reach direction was found in the CAI group

( $0.71\pm 0.20\text{cm}$ ) than in the control group ( $0.58\pm 0.17\text{cm}$ ; [ $P=0.006$ ]). *Interpretation:* Individuals with CAI present with more constrained COP outcomes than controls during dynamic balance testing. Static and dynamic balance tasks appear to result in different COP variable outcomes between affected and control groups. Clinicians may need to incorporate rehabilitation techniques to challenge COP control during dynamic balance tasks.

## INTRODUCTION

Lateral ankle sprain, also known as an inversion ankle sprain, is one of the most common injuries in a physically active population.<sup>51</sup> Approximately 40% of individuals who experienced a lateral ankle sprain complained of deficits including balance impairments, recurrent ankle instability, recurrent ankle “giving way”, and repeated ankle sprains after their initial ankle sprain.<sup>6,7</sup> Individuals with persistent signs and symptoms and prolonged impairment after an initial ankle sprain have been classified as having chronic ankle instability (CAI).<sup>9</sup> Deficits in dynamic postural control and proprioceptive function, and decreased cutaneous sensation, nerve conductive velocity, neuromuscular response times, and muscular strength have been reported by individuals with CAI.<sup>8,9</sup>

Previous studies found that postural stability deficits may be present in a population with CAI.<sup>16,80,108</sup> Postural stability measures using a force platform have been validated as showing deficits in this population.<sup>16,80,103,108,126,127</sup> Measures included center of pressure standard deviation ( $\text{COP}_{\text{SD}}$ ) in the anterior-posterior (A-P) and the medial-lateral (M-L) directions<sup>16</sup>, COP excursion length ( $\text{COP}_{\text{length}}$ ) and excursion velocity mean ( $\text{COP}_{\text{V}}$ )<sup>80,108</sup>, 95<sup>th</sup> percentile center of pressure area ellipse ( $\text{COP}_{\text{A-95}}$ )<sup>16</sup>, time to stabilization (TTS)<sup>80</sup>, time to boundary (TTB)<sup>16</sup>, and

dynamic postural stability (DPSI).<sup>24</sup> Poor performance in these measures was associated with self-reported ankle instability in individuals with CAI.<sup>16,22-24</sup> However, those instrumented postural stability measures are costly and time consuming for researchers and clinicians.<sup>16</sup>

The Star Excursion Balance Test (SEBT) is one of the most popularly used non-instrumented dynamic postural control tests to measure differences between reach performance in individuals with and without CAI.<sup>17</sup> Previous studies reported that the SEBT presented high reliability with test-retest intra-class correlation ranging from 0.82 to 0.96 and coefficients of variation ranging from 3.0% to 4.6%.<sup>18,92</sup> Deficits in SEBT reach distance in CAI populations have been hypothetically attributed to decreased dynamic postural control, but there is currently little evidence linking reach distance with traditional COP measures. The SEBT is thought to encompass strength, range of motion (ROM), and dynamic postural control in performance, but it is unclear which, if any, of these factors, alone or in combination, is influencing the decreased reach performance in the CAI population.<sup>17</sup> A recent study<sup>103</sup> reported the COP patterns during performance of the SEBT. However, this study only involved individuals who had signs and symptoms of acute lateral ankle sprain and only applied fractal dimension (FD) as a COP measure. It is unclear how a group with CAI performs on traditional COP measures during a dynamic postural stability task.<sup>103</sup>

Investigating differences in postural stability while performing the SEBT may identify the mechanism contributing to deficits in reach distance and provide suggestions for targeted rehabilitation that address postural stability deficits in the CAI population. Historically, COP measures in CAI populations indicated greater path length, area, velocity, and standard deviation (SD), indicating poor control of the COP.<sup>16,128</sup> However, these findings were typically in static balance testing scenarios, not dynamic. A dynamic balance task may present with different COP

results than a static balance task. The single-leg stance while performing the SEBT may introduce additional challenges to the postural-control system and reduce the base of support for stance.<sup>30</sup> The limit of stability while performing the SEBT in a single leg stance may also be decreased compared to a double leg stance due to the decreased base of support.<sup>30</sup> In individuals with CAI, the COP is not well controlled<sup>80</sup> and therefore those subjects may be unable to manipulate it successfully to maximize reach distance. Alternately, in an effort to avoid an error during the SEBT, individuals with CAI may excessively constrain the COP to enhance stability but decrease reach distance. Thus, those with CAI may minimize movement of the COP as a trade-off to perform the task successfully, but sacrifice reach distance. COP group differences may not be similar between CAI and controls in static and dynamic testing scenarios, and may need different rehabilitation techniques. Therefore, the purpose of our study is to determine if a significant difference in the traditional COP measures including  $COP_{SD}$ ,  $COP_{length}$ ,  $COP_V$ , and  $COP_{A-95}$  exists between individuals with CAI and controls while performing the SEBT. Our hypothesis was that individuals with CAI would have greater  $COP_{SD}$  in A-P and M-L directions,  $COP_{length}$ , and  $COP_{A-95}$  while performing the SEBT than the control group. Also, the CAI group would have increased  $COP_V$  compared with the control group. We based these on previous literature.<sup>16,23,128</sup> If differences in COP measures are identified during this dynamic balance task, and found to have different results than static balance tasks, new rehabilitation interventions may be necessary that specifically target control of the COP during a dynamic task.

## METHODS

### Participants

A total of 80 participants, between 18 to 35 years of age, were recruited from the university and community population. Then, based on inclusion and exclusion criteria described below, 35 participants were assigned to each of the two groups, the healthy control group or the CAI group. All participants completed written informed consent, as approved by the institutional review board, at the beginning of the session. The groups were matched for gender, age ( $\pm 2$  yrs), mass ( $\pm 10\%$ ), height ( $\pm 10\%$ ), and limb dominance. A total 70 participants were included for data analysis based on inclusion and exclusion criteria. The flow chart of eligible participants is presented in Figure 5.1.

We performed *an a priori* power calculation (G\*Power, Version 3.1.5, Kiel, Germany) with statistical power = 0.80,  $\alpha \leq 0.05$ , from tabled data in similar studies comparing the  $COP_{SD}$  in the A-P and the M-L directions, and  $COP_{length}$  and  $COP_V$  between CAI and control groups.<sup>16,108</sup> In previous studies, a total of 38 to 76 participants per group were required for effect size from 0.57 to 0.76. However, these previous studies only included static postural stability with single-leg stance with eyes open and/or closed.<sup>16,108</sup> Therefore, we also have calculated an *a-priori* sample size based on our pilot data with the dynamic postural stability measure (SEBT) in individuals with CAI and controls. It was determined that 21 to 28 participants per group were needed for comparing the  $COP_{SD}$  in the A-P and M-L directions, and 22 to 40 participants per group for comparing the  $COP_{length}$  were needed for an effect size from 0.7 to 1.3. We aimed to recruit 35 participants per group because this was a feasible and realistic number for this study based on *a-priori* power calculations.

For both groups, all participants had to be between 18 and 35 years old, had to participate in physical activity at least 90 minutes per week, and had to have no history of lower extremity surgery or fracture and no balance or vestibular dysfunction, such as Charcot-Marie Tooth disorder, Ehlers-Danlos disorder, or other nerve or connective tissue disorders.<sup>99</sup> Additionally, participants were excluded if they had current signs and symptoms of an acute ankle sprain or another lower extremity joint injury, including discoloration, heat, or pain, or were pregnant.<sup>99</sup> For the CAI group, participants had a history of  $\geq 1$  ankle sprain at least 3 months prior to study enrollment, missed  $\geq 1$  day of physical activity due to an ankle sprain, and at least 2 episodes of ankle instability or “giving way” in the previous 12 months. Participants in the control group had no history of ankle sprain, no complaints of ankle rolling, spraining, or “giving way” with physical activity; these participants were matched to those in the CAI group according to height, mass, age, gender, and limb dominance.<sup>118</sup> To determine additional inclusion criteria, participants completed the Cumberland Ankle Instability Tool (CAIT)<sup>102</sup> and Identification Functional Ankle Instability (IdFAI)<sup>101</sup>. Participants in the CAI group scored 25 or less on the CAIT and 11 or greater on the IdFAI, indicating decreased ankle joint function.<sup>93,101,102</sup> Those in the control group scored 28 or greater on the CAIT and 10 or less on the IdFAI.<sup>93,101,102</sup>

### Procedure

Participants reported to the biomechanics laboratory at a large university in the United States for one testing session lasting up to 60 minutes. The height, mass, dominant side, and leg length of each participant were collected prior to data collection. The dominant side was determined by the limb with which participants reported they preferred to use for kicking a soccer ball.<sup>120</sup> The leg length was measured with a tape measure in distance from the anterior

superior iliac spine (ASIS) to the medial malleolus. Also, all participants completed 3 questionnaires, including ankle injury history, the CAIT, and the IdFAI.

Participants performed the SEBT on the single piezoelectric force plate (model 4060A; Bertec Co, Columbus, OH) in a pre-determined counterbalanced order. The COP data were collected at a sampling rate of 960 Hz in anterior-posterior (COP<sub>x</sub>) and medial-lateral (COP<sub>y</sub>) directions while performing the SEBT. The participants performed 3 test trials in each of 3 reach directions, including anterior (AN), posteromedial (PM), and posterolateral (PL) after they completed 2 practice trials in each direction followed by demonstration from a single tester.<sup>17</sup> Participants had a 5-minute break in between direction changes and in between limb side changes. If participants made an error while performing the SEBT, the trial was discarded. An error was defined as a trial in which they removed their hand from the hip, their non-testing foot did not return to the starting position, they touched the ground with the non-testing foot, or they lifted up any portion of the testing foot while performing the SEBT.<sup>17</sup> Prior to data collection, the intra-class correlation coefficient (ICC<sub>2,1</sub> = 0.89 – 0.97) and standard error measure (SEM=2.2cm), excellent, were measured for the single rater.

#### Data reduction and analysis

Descriptive statistics including mean and standard deviation were calculated for participants' demographic, CAIT, and IdFAI scores. The reach distance of the SEBT in each direction was normalized in percentage through the formula ( $[\text{average of three trials in cm} \div \text{the leg length}] \times 100$ ). We used custom-written MATLAB software (Mathwork Inc., Version R2015b, Natick, MA) to process the data and calculate postural stability measures, including COP<sub>SD</sub> in the A-P (A-P COP<sub>SD</sub>) and the M-L (M-L COP<sub>SD</sub>) directions in cm, COP<sub>length</sub> in cm,

COP<sub>v</sub> in cm/s, COP<sub>A-95</sub> in cm<sup>2</sup>, and total performance time in sec from the raw COP data. All traditional COP measures were calculated while performing the SEBT. The definitions of all COP measures are presented in Table 5.1. We used the vertical ground reaction force (GRF<sub>v</sub>) to calculate the time interval of interest while performing the SEBT. The start of the time interval was determined as when the reaching limb was removed from the ground, that is, 100% body mass was distributed to the testing limb. The end was indicated when the reach leg was put back on the ground and GRF<sub>v</sub> returned to equally distributed in both limbs. For the COP data, a 4<sup>th</sup>-order lower-pass Butterworth filter with a cutoff frequency of 10Hz was used to filter noise out from the raw data.<sup>108</sup> The cutoff frequency of 10Hz was determined through visual inspection (a fast Fourier transform [FFT]); the raw data initially displayed minimal noise.<sup>129</sup> No higher power frequency appeared. Therefore, the cutoff frequency of 10Hz was appropriate for adequately capturing the signal without running the risk of excluding meaningful portions of that signal.

A series of independent sample-t tests were performed to determine whether differences existed between the CAI and control groups for the instrumented dynamic postural stability measures and the reach distance in 3 reach directions of the SEBT. Also, Pearson-product moment correlations were used to investigate the relationship between each COP measure and reach distance in the SEBT. Pearson correlation coefficients (*R*) were interpreted as weak (0.00 – 0.40), moderate (0.41 – 0.69), or strong (0.70 – 1.00).<sup>130</sup>

## RESULTS

Participants' demographic information, including age, gender, mass, and height, is reported in Table 5.2. In the CAI group, the CAIT score was significantly lower ( $P < 0.001$ )

compared with the CAIT score in the control group. As shown in Table 5.2, the IdFAI score for the CAI group was significantly greater ( $P < 0.001$ ) than that for the control group. The CAI group performed significantly shorter reach distances in the AN, PM, and PL reach directions of the SEBT than the control group. Means and standard deviations for the SEBT are shown in Table 5.3 with powers,  $P$ -values, and effect sizes (*Cohen's d*). Group means, standard deviations,  $P$ -values, and effect sizes (*Cohen's d*) and powers for each COP measure while performing the SEBT in the AN, PM, and PL directions are reported in Table 5.4.

In the CAI group, the relationships between the reach distance of the SEBT and the COP measures while performing the SEBT in the AN, PM, and PL reach directions are presented in Table 5.6. No statistically significant relationships were found between reach distances and the COP measures, except between the reach distance in the AN direction and the M-L  $COP_{SD}$  ( $r = -0.40$ ,  $n = 35$ ,  $P < 0.05$ ) in the CAI group. In the control group, the relationships between the reach distance achieved on the AN, PM, and PL of the SEBT and corresponding A-P and M-L  $COP_{SD}$ ,  $COP_{length}$ ,  $COP_V$ , and  $COP_{A-95}$  are presented in Table 5.5. No statistically significant relationships were found between reach distances achieved in the three reach directions of the SEBT and all COP measures in the control group.

## DISCUSSION

To our knowledge, this is the first study to investigate traditional COP measures during the SEBT in three reach directions in individuals with CAI. The results of the current study contradict the original hypotheses. The main findings of our study were that the CAI group had lower A-P  $COP_{SD}$  (cm) and  $COP_{A-95}$  (cm<sup>2</sup>) than the control group while performing the SEBT

because these two COP measures were consistent across all three (AN, PM, and PL) reach directions. However, no between-group differences existed in  $COP_{length}$  in all three reach directions, in M-L  $COP_{SD}$  in the PM and PL reach direction, or in  $COP_v$  in the AN reach direction. The secondary findings of our study were that the CAI group had lower  $COP_v$  (cm/s) compared with the control group during the SEBT in the PM and PL reach directions. Greater M-L  $COP_{SD}$  (cm) while performing the SEBT in the AN reach direction was found in the CAI group.

Although four COP measures identified group differences, the A-P  $COP_{SD}$  and  $COP_{A-95}$  were the only measures that identified group differences across all three reach directions of the SEBT. The A-P  $COP_{SD}$  and  $COP_{A-95}$  were significantly lower during the AN, PM, and PL reach directions of the SEBT in the CAI group than in the control group. Also, the CAI group performed significantly shorter reach distances in all three reach directions of the SEBT compared with the control group. The present study does not support previous observations that the CAI group exhibits greater A-P  $COP_{SD}$  and  $COP_{A-95}$  compared with the control group, but that is likely because of the nature of the task.<sup>16,128</sup> Linens et al.<sup>16</sup> found no group differences between the CAI and control groups in A-P  $COP_{SD}$  and  $COP_{A-95}$  during static single-leg stance. Ross et al.<sup>128</sup> also reported that individuals with CAI had greater M-L  $COP_{SD}$ ,  $COP_{length}$ , and  $COP_v$  compared with controls. The main reason for the conflicting results might be related to the dynamic nature of the postural control task used in this study. Performing the SEBT in three reach directions might have been more demanding than standing with single-leg stance<sup>131</sup>, hopping in place<sup>28</sup>, or single-leg jump landing<sup>128</sup>, or it is a completely different task with different constructs and constraints.

Some previous studies have measured postural stability during dynamic balance tasks. Doherty et al.<sup>103</sup> measured fractal dimension (FD) characterizing the complexity of given COP patterns while performing the SEBT and reported that the acutely injured group had reduced FD compared with the control group for all three reach directions. Santos et al.<sup>126</sup> also reported that the CAI group exhibited a significant decrease in  $COP_{A-95}$  and COP displacement during functional tasks (kicking a ball while in a single-leg stance) relative to the control group. In the present study, the CAI group also demonstrated a reduction in the A-P  $COP_{SD}$  and  $COP_{A-95}$  compared with the control group, which may indicate that the CAI group could not adequately utilize the available base of support in completing the dynamic postural stability test, which may require postural control adjustment due to postural stability deficits. Therefore, our findings support observations from previous studies that the COP is constrained during dynamic postural control tasks,<sup>103,126</sup> and demonstrates this in a CAI population.

In the current study, the M-L  $COP_{SD}$  during the AN reach direction was significantly decreased in the CAI group compared with the control group, which may imply that the CAI group constricts their COP movement in the M-L direction to complete the dynamic postural stability test due to being unable to properly utilize the available base of support. Conversely, several previous studies have found that individuals with CAI experienced greater mediolateral range of COP than controls.<sup>28,128</sup> However, these previous studies also measured COP patterns during a single-leg stance and/or single-leg jump landing where GRF was damped as stability was achieved, while the COP measure in the current study was collected during a dynamic postural control task (the SEBT). The task in the current study, where movement was ongoing throughout the duration of the task, is different in nature. The human body utilizes the sensorimotor system, which involves self-organizing based on experiences and constraints to

produce postural control.<sup>132</sup> The CAI group might perform a highly demanding task with different patterns of postural control to correct posture and maximize performance during the task.<sup>103,133</sup>

Additionally, a Pearson correlation was calculated to investigate the relationship between the reach distance achieved in the three reach directions and all COP measures. The results from the current study revealed a positive correlation between the A-P  $COP_{SD}$  and  $COP_V$  and the three reach directions in both the CAI and the control groups. The A-P  $COP_{SD}$  and  $COP_V$  were increased as participants reached further in the three reach direction of the SEBT. The results in the current study may indicate that participants achieved longer reach distances as A-P  $COP_{SD}$  and  $COP_V$  were unrestrained in the three reach directions of the SEBT, regardless of their ankle injury history. However, a negative correlation was observed between the M-L  $COP_{SD}$ ,  $COP_{length}$ , and  $COP_{A-95}$  with reach distance in the three reach directions of the SEBT in the CAI group. The M-L  $COP_{SD}$ ,  $COP_{length}$ , and  $COP_{A-95}$  were decreased as the CAI group reached further in the three reach directions of the SEBT. However, a positive correlation was observed between the M-L  $COP_{SD}$ ,  $COP_{length}$ , and  $COP_{A-95}$  with reach distance in the three reach directions of the SEBT in the control group. Our findings may indicate that the M-L  $COP_{SD}$ ,  $COP_{length}$ , and  $COP_{A-95}$  are constrained to achieve longer reach distances in the three reach directions in the CAI group. Conversely, the M-L  $COP_{SD}$ ,  $COP_{length}$ , and  $COP_{A-95}$  are not constrained in the control group. These findings have implications for interpretation of postural stability while performing the SEBT in the CAI group. CAI participants may need to constrain the M-L the COP during the SEBT, in order to maximize their performance. However, in order to behave more like the control group, the CAI group may need to release the A-P COP, not constrain it, and allow COP to traverse more freely during the task to see gains in performance. Therefore, we need to focus

on training control of the COP in the CAI group in both the A-P and M-L directions to enhance the ability to adjust COP during dynamic postural control tasks such as the SEBT.

The current study also found that the  $COP_V$  during the PM and PL reach directions was significantly decreased in the CAI group compared with the control group. Conversely, previous studies<sup>16,108</sup> found that the CAI group had an increased  $COP_V$  measure during static postural control tasks with the single-leg stance compared with the control group. However, our data from the  $COP_V$  measure were collected during a dynamic postural control task (the SEBT).

As  $COP_V$  increases, it becomes more difficult for the body to adequately correct the excursions and keep the COP within the base of support.<sup>134</sup> In other words, the CAI group likely decreased  $COP_V$  to maintain their COP within the base of support compared with the control while performing the PM and PL directions of the SEBT due to delayed afferent and efferent responses for adjusting postural control. Hertel et al.<sup>135</sup> developed the Time-to-Boundary measure (TTB) to evaluate postural control deficits in the CAI population. The TTB measure is inherently linked to the  $COP_V$  measure due to using the  $COP_V$  in the TTB equation.<sup>77</sup> Hertel et al.<sup>77</sup> also reported that the CAI group exhibited significantly lower TTB measures compared with the control group. In other words, individuals with CAI appeared to maintain the  $COP_V$  slower and more precisely to complete the task without falling; thus, the reach distance achieved in the PM and PL directions of the SEBT could be decreased.

Postural control requires the integration of somatosensory, visual, and vestibular afferent information and appropriate efferent responses to control the trunk and extremity muscles in an effort to maintain balance.<sup>65</sup> Perhaps an initial acute lateral ankle sprain caused damage to the mechanoreceptors and proprioceptors, leading to a decreased awareness of body position.<sup>6,43</sup> Our findings suggest that the presence of CAI may alter sensorimotor function, affecting the human

body's ability to generate new patterns of movement to correct posture and maximize performance during the task, or the CAI group might tend to stay within a safe range that constrains the COP<sub>V</sub>, which may cause decreased performance.<sup>80</sup> Therefore, the CAI group may present with lower and slower amplitude and excursion of COP measures than the control group. Although some COP measures were not statistically significantly different between groups, individuals with CAI consistently exhibited decreased values of A-P/M-L COP<sub>SD</sub>, COP<sub>length</sub>, COP<sub>V</sub>, and COP<sub>A-95</sub> in the AN, PM, and PL reach directions.

COP measures during single-leg stance and/or single-leg jump landing are typically greater in the CAI group than in the control group, in static stance tasks.<sup>16,108</sup> Clinicians have been advised to constrain the COP as part of a rehabilitation program during static stance. However, the inverse appears to be true during dynamic postural control tasks in which COP is already constrained in an effort to successfully remain upright, but performance is decreased. Therefore, rehabilitation may need to include exercises that enhance the ability of those with CAI to manipulate the COP successfully toward the outer limits of stability during dynamic balance tasks. This may be more relative to actual performance in many sports. Our findings indicate this is true in the anterior-posterior orientation, but CAI participants may still need to constrain in the medial-lateral direction in order to improve performance. The CAI group may need to restore correct arthrokinematics and ROM (particularly with ankle dorsiflexion) to achieve this. Future studies should examine if COP measures in CAI become more comparable to controls after training for dynamic balance tasks, just as in static balance tasks.<sup>16,23,128</sup>

The authors acknowledge several limitations that may arise with this study. The first is that EMG activity was not examined while performing the three reach directions of the SEBT. EMG activity could reveal some modifications in muscular activity. Further, low power and

effect sizes were reported in some comparisons. Additionally, we used a sample of convenience from a large university, with participants between 18 to 35 years of age, which may not be generalizable to other populations. Another limitation may be the possibility of differences in physical activity level among the participants.

## CONCLUSION

In conclusion, participants with CAI had decreased A-P  $COP_{SD}$  and  $COP_{A-95}$  in all three reach directions including AN, PM, and PL,  $COP_v$  in the PM and PL reach directions, and M-L  $COP_{SD}$  in the AN reach direction while performing the SEBT compared with healthy controls. During dynamic balance tasks, individuals with CAI may excessively constrain the COP in an effort to successfully complete the reach, trading off a reach distance for remaining upright or steadier. The clinical implications of this study are that clinicians may need to focus on constraining COP in individuals with CAI during static postural control tasks such as single-leg stance, whereas they may focus on enhancing the ability to adjust COP successfully toward the outer limits of stability in individuals with CAI during dynamic postural control tasks such as the SEBT.

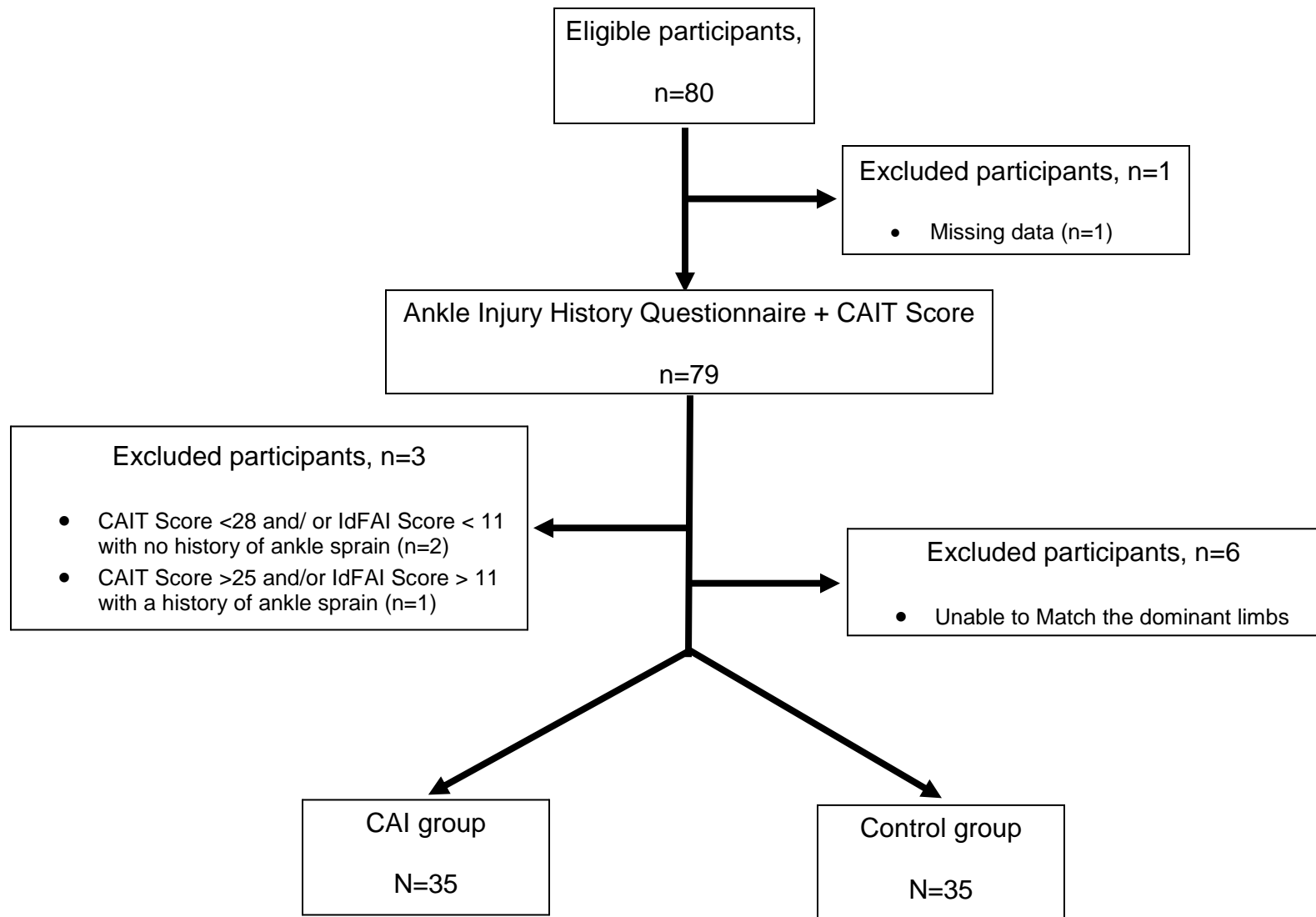


Figure 5.1. Flow chart of eligible participants.

Abbreviations: CAI, Chronic Ankle Instability; CAIT, Cumberland Ankle Instability Tool; IdFAI, Identification Functional Ankle Instability

Table 5.1 Definitions of center of pressure measures

| Measure   | Definition   |
|---|--|
| COP standard deviation ( $COP_{SD}$ )                         | Standard deviation of the COP in a given direction for each trial  |
| Total COP excursion length ( $COP_{length}$ )                 | The length of the accumulated distance between consecutive COP data points collected during the trial    |
| Mean COP velocity (COPV)                                      | The $COP_{length}$ divided by total performing time, representing the average velocity during the trial. |
| 95 <sup>th</sup> percentile COP area ellipse ( $COP_{A-95}$ ) | The area of the 95 <sup>th</sup> percentile ellipse, which encompasses 95% of the COP data points.       |

COP = Center of Pressure

Table 5.2. Mean ( $\pm$ standard deviation) of participants' demographics and CAIT & IdFAI

| Group          | Age (yr)       | Height (cm)      | Mass (kg)       | CAIT           | IdFAI          | Test Limb       |
|----------------|----------------|------------------|-----------------|----------------|----------------|-----------------|
| Control (N=35) | 21.6 $\pm$ 2.9 | 169.1 $\pm$ 10.3 | 69.3 $\pm$ 14.2 | 29.4 $\pm$ 0.8 | 1.9 $\pm$ 2.5  | R = 29<br>L = 6 |
| Female 23      | 21.3 $\pm$ 3.1 | 163.6 $\pm$ 6.7  | 63.3 $\pm$ 11.5 | 21.8 $\pm$ 2.5 | 1.1 $\pm$ 2.2  |                 |
| Male 12        | 22.1 $\pm$ 2.4 | 179.7 $\pm$ 7.4  | 80.7 $\pm$ 11.7 | 22.6 $\pm$ 2.9 | 3.3 $\pm$ 2.7  |                 |
| CAI (N=35)     | 21.1 $\pm$ 2.3 | 169.3 $\pm$ 10.7 | 70.1 $\pm$ 14.9 | 22.1 $\pm$ 2.6 | 17.4 $\pm$ 4.6 | R = 29<br>L = 6 |
| Female 23      | 20.9 $\pm$ 1.9 | 163.3 $\pm$ 7.0  | 63.1 $\pm$ 12.2 | 29.7 $\pm$ 0.6 | 17.7 $\pm$ 4.8 |                 |
| Male 12        | 21.5 $\pm$ 2.8 | 179.3 $\pm$ 8.1  | 82.0 $\pm$ 11.2 | 29.0 $\pm$ 0.8 | 16.8 $\pm$ 4.4 |                 |

CAI = Chronic Ankle Instability; CAIT = Cumberland Ankle Instability Tool; IdFAI = Identification Functional Ankle Instability; R = Right; L = Left.

Table 5.3. Mean ( $\pm$ standard deviation) of % maximized reach distance on the SEBT

| Group                    | Anterior          | Posteromedial      | Posterolateral    |
|--------------------------|-------------------|--------------------|-------------------|
| Control                  | 73.05 $\pm$ 22.70 | 110.41 $\pm$ 30.93 | 96.80 $\pm$ 31.58 |
| CAI                      | 61.97 $\pm$ 5.93  | 93.90 $\pm$ 8.82   | 82.78 $\pm$ 11.53 |
| <i>P</i>                 | 0.007*            | 0.003*             | 0.016*            |
| Effect Size ( <i>d</i> ) | 0.67              | 0.73               | 0.59              |
| Power                    | 0.79              | 0.85               | 0.68              |

SEBT = Star Excursion Balance Test; CAI = Chronic Ankle Instability; *d* = Cohen *d*

\*Significantly different ( $P < 0.05$ )

Table 5.4. Mean ( $\pm$ standard deviation) of COP measures

| Reach Direction | Dependent Measure                      | Group             |                   | <i>P</i> | Effect Size | Power |
|-----------------|--|-------------------|-------------------|----------|-------------|-------|
|                 |  | Control (n=35)    | CAI (n=35)        |          |             |       |
| Anterior        | A-P COP <sub>SD</sub> (cm)             | 2.46 $\pm$ 0.83   | 2.04 $\pm$ 0.56   | 0.016*   | 0.60        | 0.69  |
|                 | M-L COP <sub>SD</sub> (cm)             | 0.71 $\pm$ 0.20   | 0.58 $\pm$ 0.17   | 0.006*   | 0.70        | 0.82  |
|                 | COP <sub>length</sub> (cm)             | 21.72 $\pm$ 8.64  | 19.67 $\pm$ 8.18  | 0.312    | 0.12        | 0.17  |
|                 | COP <sub>V</sub> (cm/s)                | 9.62 $\pm$ 10.26  | 9.43 $\pm$ 2.01   | 0.670    | 0.02        | 0.05  |
|                 | COP <sub>A-95</sub> (cm <sup>2</sup> ) | 17.45 $\pm$ 8.51  | 11.95 $\pm$ 5.41  | 0.002*   | 0.77        | 0.89  |
|                 | Time (sec)                             | 2.31 $\pm$ 1.02   | 2.20 $\pm$ 1.08   | 0.672    | 0.10        | 0.07  |
| Posteromedial   | A-P COP <sub>SD</sub> (cm)             | 1.55 $\pm$ 0.40   | 1.25 $\pm$ 0.31   | 0.001*   | 0.84        | 0.93  |
|                 | M-L COP <sub>SD</sub> (cm)             | 0.64 $\pm$ 0.26   | 0.59 $\pm$ 0.27   | 0.352    | 0.19        | 0.12  |
|                 | COP <sub>length</sub> (cm)             | 21.11 $\pm$ 11.01 | 18.61 $\pm$ 10.26 | 0.329    | 0.23        | 0.16  |
|                 | COP <sub>V</sub> (cm/s)                | 10.06 $\pm$ 1.96  | 8.23 $\pm$ 1.28   | 0.001*   | 1.11        | 0.99  |
|                 | COP <sub>A-95</sub> (cm <sup>2</sup> ) | 10.82 $\pm$ 5.16  | 7.84 $\pm$ 4.51   | 0.012*   | 0.61        | 0.72  |
|                 | Time (sec)                             | 2.16 $\pm$ 1.14   | 2.31 $\pm$ 1.30   | 0.622    | 0.12        | 0.08  |
| Posterolateral  | A-P COP <sub>SD</sub> (cm)             | 1.48 $\pm$ 0.38   | 1.27 $\pm$ 0.25   | 0.009*   | 0.65        | 0.77  |
|                 | M-L COP <sub>SD</sub> (cm)             | 0.92 $\pm$ 0.24   | 0.83 $\pm$ 0.18   | 0.103    | 0.42        | 0.42  |
|                 | COP <sub>length</sub> (cm)             | 26.24 $\pm$ 10.13 | 26.10 $\pm$ 12.49 | 0.961    | 0.01        | 0.05  |
|                 | COP <sub>V</sub> (cm/s)                | 10.44 $\pm$ 2.13  | 9.08 $\pm$ 1.76   | 0.005*   | 0.70        | 0.82  |
|                 | COP <sub>A-95</sub> (cm <sup>2</sup> ) | 14.64 $\pm$ 5.68  | 11.22 $\pm$ 3.58  | 0.004*   | 0.72        | 0.84  |
|                 | Time (sec)                             | 2.59 $\pm$ 1.09   | 2.98 $\pm$ 1.53   | 0.221    | 0.29        | 0.23  |

CAI = Chronic Ankle Instability; COP = Center of Pressure

\*Significantly different ( $P < 0.05$ )

Table 5.5. Correlation ( $r$ ) between reach distance and COP measures.

| Group   | Reach Distance | COP measures          | Correlation ( $r$ ) | $P$ -value    |
|---------|----------------|-----------------------|---------------------|---------------|
| Control | Anterior       | A-P COP <sub>SD</sub> | 0.17                | 0.324         |
|         |                | M-L COP <sub>SD</sub> | 0.08                | 0.668         |
|         |                | COP <sub>length</sub> | 0.02                | 0.914         |
|         |                | COP <sub>V</sub>      | 0.03                | 0.864         |
|         |                | COP <sub>A-95</sub>   | 0.04                | 0.836         |
|         | Posteromedial  | A-P COP <sub>SD</sub> | 0.19                | 0.283         |
|         |                | M-L COP <sub>SD</sub> | 0.04                | 0.844         |
|         |                | COP <sub>length</sub> | 0.10                | 0.581         |
|         |                | COP <sub>V</sub>      | 0.18                | 0.304         |
|         |                | COP <sub>A-95</sub>   | 0.17                | 0.321         |
|         | Posterolateral | A-P COP <sub>SD</sub> | 0.16                | 0.353         |
|         |                | M-L COP <sub>SD</sub> | 0.14                | 0.436         |
|         |                | COP <sub>length</sub> | 0.17                | 0.337         |
|         |                | COP <sub>V</sub>      | 0.30                | 0.085         |
|         |                | COP <sub>A-95</sub>   | 0.22                | 0.203         |
| CAI     | Anterior       | A-P COP <sub>SD</sub> | 0.21                | 0.235         |
|         |                | M-L COP <sub>SD</sub> | -0.40               | <b>0.017*</b> |
|         |                | COP <sub>length</sub> | -0.49               | 0.782         |
|         |                | COP <sub>V</sub>      | 0.17                | 0.333         |
|         |                | COP <sub>A-95</sub>   | -0.64               | 0.717         |
|         | Posteromedial  | A-P COP <sub>SD</sub> | 0.19                | 0.280         |
|         |                | M-L COP <sub>SD</sub> | -0.07               | 0.588         |
|         |                | COP <sub>length</sub> | -0.23               | 0.178         |
|         |                | COP <sub>V</sub>      | 0.31                | 0.087         |
|         |                | COP <sub>A-95</sub>   | -0.05               | 0.770         |
|         | Posterolateral | A-P COP <sub>SD</sub> | 0.02                | 0.891         |
|         |                | M-L COP <sub>SD</sub> | -0.31               | 0.069         |
|         |                | COP <sub>length</sub> | -0.01               | 0.982         |
|         |                | COP <sub>V</sub>      | 0.01                | 0.998         |
|         |                | COP <sub>A-95</sub>   | -0.12               | 0.505         |

CAI = Chronic Ankle Instability; COP = Center of Pressure; SEBT = Star Excursion Balance Test

\*Significantly different ( $P < 0.05$ )

## APPENDIX A

### Cumberland ankle instability tool (CAIT) questionnaire

Form 2. Cumberland Ankle Instability Tool

| Please mark the ONE statement in EACH question that BEST describes your ankles.    | SUBJECT ID _____         |                          |
|--|--------------------------|--------------------------|
|  | Left                     | Right                    |
| 1. I have pain in my ankle   |                          |                          |
| Never  | <input type="checkbox"/> | <input type="checkbox"/> |
| During sport   | <input type="checkbox"/> | <input type="checkbox"/> |
| Running on uneven surfaces   | <input type="checkbox"/> | <input type="checkbox"/> |
| Running on level surfaces  | <input type="checkbox"/> | <input type="checkbox"/> |
| Walking on uneven surfaces   | <input type="checkbox"/> | <input type="checkbox"/> |
| Walking on level surfaces  | <input type="checkbox"/> | <input type="checkbox"/> |
| 2. My ankle feels UNSTABLE   |                          |                          |
| Never  | <input type="checkbox"/> | <input type="checkbox"/> |
| Sometimes during sport (not every time)  | <input type="checkbox"/> | <input type="checkbox"/> |
| Frequently during sport (every time)   | <input type="checkbox"/> | <input type="checkbox"/> |
| Sometimes during daily activity  | <input type="checkbox"/> | <input type="checkbox"/> |
| Frequently during daily activity   | <input type="checkbox"/> | <input type="checkbox"/> |
| 3. When I make SHARP cuts, my ankle feels UNSTABLE                                 |                          |                          |
| Never  | <input type="checkbox"/> | <input type="checkbox"/> |
| Sometimes when running   | <input type="checkbox"/> | <input type="checkbox"/> |
| Often when running   | <input type="checkbox"/> | <input type="checkbox"/> |
| When walking   | <input type="checkbox"/> | <input type="checkbox"/> |
| 4. When going down the stairs, my ankle feels UNSTABLE                             |                          |                          |
| Never  | <input type="checkbox"/> | <input type="checkbox"/> |
| If I go fast   | <input type="checkbox"/> | <input type="checkbox"/> |
| Occasionally   | <input type="checkbox"/> | <input type="checkbox"/> |
| Always   | <input type="checkbox"/> | <input type="checkbox"/> |
| 5. My ankle feels UNSTABLE when standing on ONE leg                                |                          |                          |
| Never  | <input type="checkbox"/> | <input type="checkbox"/> |
| On the ball of my foot   | <input type="checkbox"/> | <input type="checkbox"/> |
| With my foot flat  | <input type="checkbox"/> | <input type="checkbox"/> |
| 6. My ankle feels UNSTABLE when  |                          |                          |
| Never  | <input type="checkbox"/> | <input type="checkbox"/> |
| I hop from side to side  | <input type="checkbox"/> | <input type="checkbox"/> |
| I hop in one spot  | <input type="checkbox"/> | <input type="checkbox"/> |
| When I jump  | <input type="checkbox"/> | <input type="checkbox"/> |
| 7. My ankle feels UNSTABLE when  |                          |                          |
| Never  | <input type="checkbox"/> | <input type="checkbox"/> |
| I run on uneven surfaces   | <input type="checkbox"/> | <input type="checkbox"/> |
| I jog on uneven surfaces   | <input type="checkbox"/> | <input type="checkbox"/> |
| I walk on uneven surfaces  | <input type="checkbox"/> | <input type="checkbox"/> |
| I walk on a flat surface   | <input type="checkbox"/> | <input type="checkbox"/> |
| 8. TYPICALLY, when I start to roll over (or "twist") my ankle, I can stop it       |                          |                          |
| Immediately  | <input type="checkbox"/> | <input type="checkbox"/> |
| Often  | <input type="checkbox"/> | <input type="checkbox"/> |
| Sometimes  | <input type="checkbox"/> | <input type="checkbox"/> |
| Never  | <input type="checkbox"/> | <input type="checkbox"/> |
| I have never rolled over on my ankle   | <input type="checkbox"/> | <input type="checkbox"/> |
| 9. After a TYPICAL incident of my ankle rolling over, my ankle returns to "normal" |                          |                          |
| Almost immediately   | <input type="checkbox"/> | <input type="checkbox"/> |
| Less than one day  | <input type="checkbox"/> | <input type="checkbox"/> |
| 1-2 days   | <input type="checkbox"/> | <input type="checkbox"/> |
| More than 2 days   | <input type="checkbox"/> | <input type="checkbox"/> |
| I have never rolled over on my ankle   | <input type="checkbox"/> | <input type="checkbox"/> |

## APPENDIX B

### Identification functional ankle instability (IdFAI) questionnaire

**IDENTIFICATION OF FUNCTIONAL ANKLE INSTABILITY (IdFAI)** Participant ID \_\_\_\_\_

Instructions: Please fill out the form completely and if you have any questions, please ask the administrator.

|   | <u>Left</u>              | <u>Right</u>             |
|---|--------------------------|--------------------------|
| 1. Approximately how many times have you sprained your ankle?   | _____                    | _____                    |
| 2. When was the last time you sprained your ankle?  |                          |                          |
| Never   | <input type="checkbox"/> | <input type="checkbox"/> |
| >2 years  | <input type="checkbox"/> | <input type="checkbox"/> |
| 1-2 years   | <input type="checkbox"/> | <input type="checkbox"/> |
| 6-12 months   | <input type="checkbox"/> | <input type="checkbox"/> |
| 1-6 months  | <input type="checkbox"/> | <input type="checkbox"/> |
| <1 month  | <input type="checkbox"/> | <input type="checkbox"/> |
| 3. If you have seen an athletic trainer, physician, or healthcare provider, how did he/she categorize your most serious ankle sprain? |                          |                          |
| Have <b>not</b> seen someone  | <input type="checkbox"/> | <input type="checkbox"/> |
| Mild (Grade I)  | <input type="checkbox"/> | <input type="checkbox"/> |
| Moderate (Grade II)   | <input type="checkbox"/> | <input type="checkbox"/> |
| Severe (Grade III)  | <input type="checkbox"/> | <input type="checkbox"/> |
| 4. If you have ever used crutches, or other device, due to an ankle sprain, how long did you use it?                                  |                          |                          |
| Never used a device   | <input type="checkbox"/> | <input type="checkbox"/> |
| 1-3 days  | <input type="checkbox"/> | <input type="checkbox"/> |
| 4-7 days  | <input type="checkbox"/> | <input type="checkbox"/> |
| 1-2 weeks   | <input type="checkbox"/> | <input type="checkbox"/> |
| 2-3 weeks   | <input type="checkbox"/> | <input type="checkbox"/> |
| >3 weeks  | <input type="checkbox"/> | <input type="checkbox"/> |
| 5. When was the last time you had "giving way" in your ankle?   |                          |                          |
| Never   | <input type="checkbox"/> | <input type="checkbox"/> |
| >2 years  | <input type="checkbox"/> | <input type="checkbox"/> |
| 1-2 years   | <input type="checkbox"/> | <input type="checkbox"/> |
| 6-12 months   | <input type="checkbox"/> | <input type="checkbox"/> |
| 1-6 months  | <input type="checkbox"/> | <input type="checkbox"/> |
| <1 month  | <input type="checkbox"/> | <input type="checkbox"/> |
| 6. How often does the "giving way" sensation occur in your ankle?   |                          |                          |
| Never   | <input type="checkbox"/> | <input type="checkbox"/> |
| Once a year   | <input type="checkbox"/> | <input type="checkbox"/> |
| Once a month  | <input type="checkbox"/> | <input type="checkbox"/> |
| Once a week   | <input type="checkbox"/> | <input type="checkbox"/> |
| Once a day  | <input type="checkbox"/> | <input type="checkbox"/> |
| 7. Typically when you start to roll over (or 'twist') on your ankle can you stop it?  |                          |                          |
| Never rolled over   | <input type="checkbox"/> | <input type="checkbox"/> |
| Immediately   | <input type="checkbox"/> | <input type="checkbox"/> |
| Sometimes   | <input type="checkbox"/> | <input type="checkbox"/> |
| Unable to stop it   | <input type="checkbox"/> | <input type="checkbox"/> |
| 8. Following a typical incident of your ankle rolling over, how soon does it return to normal?  |                          |                          |
| Never rolled over   | <input type="checkbox"/> | <input type="checkbox"/> |
| Immediately   | <input type="checkbox"/> | <input type="checkbox"/> |
| <1 day  | <input type="checkbox"/> | <input type="checkbox"/> |
| 1-2 days  | <input type="checkbox"/> | <input type="checkbox"/> |
| >2 days   | <input type="checkbox"/> | <input type="checkbox"/> |
| 9. During "Activities of daily life" how often does your ankle feel <i>UNSTABLE</i> ?   |                          |                          |
| Never   | <input type="checkbox"/> | <input type="checkbox"/> |
| Once a year   | <input type="checkbox"/> | <input type="checkbox"/> |
| Once a month  | <input type="checkbox"/> | <input type="checkbox"/> |
| Once a week   | <input type="checkbox"/> | <input type="checkbox"/> |
| Once a day  | <input type="checkbox"/> | <input type="checkbox"/> |
| 10. During "Sport or recreational activities" how often does your ankle feel <i>UNSTABLE</i> ?  |                          |                          |
| Never   | <input type="checkbox"/> | <input type="checkbox"/> |
| Once a year   | <input type="checkbox"/> | <input type="checkbox"/> |
| Once a month  | <input type="checkbox"/> | <input type="checkbox"/> |
| Once a week   | <input type="checkbox"/> | <input type="checkbox"/> |
| Once a day  | <input type="checkbox"/> | <input type="checkbox"/> |

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