# **Rotational Dynamic Postural Stability Test**

by

Megan Hufnagel

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This thesis was presented

by

Megan Hufnagel

It was defended on

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and approved by

Timothy C. Sell, PhD, PT, Assistant Professor

John P. Abt, PhD, ATC, Assistant Professor

Mita T. Lovalekar, PhD, MBBS, Assistant Professor

David G. Tumbas, MS, ATC

Jon Pederson, MS, ATC

Thesis Director: Timothy C. Sell, PhD, PT, Assistant Professor

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Dynamic postural stability is an important measurement that is used in valuable clinical assessments, such as evaluating risk factors for injury or determining the progress of neuromuscular rehabilitation. One way to effectively measure dynamic postural stability is the dynamic postural stability index (DPSI). The DPSI is based on single-leg hop stabilization and is a combination of the stability indices of the medial-lateral, anterior-posterior, and vertical directions. Currently, single-leg hop stabilization tasks are only conducted in uniplanar directions which fail to replicate the athletic environment. A single-leg hop stabilization task that incorporates a rotational component of the body would be more challenging and more closely resemble mechanisms of injury, particularly to the anterior cruciate ligament (ACL). Therefore, the goal of this study was to develop a test of dynamic postural stability that includes a rotational component and measure its reliability and precision.

The task was performed by fourteen college club and intramural athletes. Each subject performed two test sessions, with thirty minutes in between. In each session, five trials in both rotation directions were collected for each subject. To determine intersession reliability, the intraclass correlation (ICC 2,k and 2,1) and the standard error of measurement (SEM) were calculated for the DPSI scores between sessions. For rotation medially, the ICC (2,k) was 0.885 and the SEM was 0.086. For rotation laterally, the ICC (2,k) was 0.926 and the SEM was 0.139. These results support that the DPSI, assessed using a rotational jump landing task, is a reliable and precise measurement that is acceptable to use in future research.

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## PREFACE

I would like to thank my thesis committee, Dr. Mita Lovalekar, Dr. John Abt, David Tumbas, and Jon Pederson for their guidance throughout this research project. I would also like to thank my thesis advisor and chair, Dr. Timothy Sell, for his continuous support and advice throughout these past two years. Additionally, I would like to thank Jon Pederson for his countless reviews, practice sessions, and guidance during data collection. I would also like to thank all of the graduate student researchers working in the NMRL for their assistance and kindness while I was working in the lab. I want to thank the School of Health and Rehabilitation Sciences for their Research Development Fund and the University of Pittsburgh Honors College for providing funding for the completion of this project. Lastly, I would like to thank my family for their constant support throughout my undergraduate career.

# 1.0 INTRODUCTION

One integral measurement that can be used for assessment after injury and to prospectively examine risk factors for injury is the dynamic postural stability index, determined by measuring the ground reaction forces during a stabilizing period of a single-leg jump landing task. Typically these tasks only involve uniplanar movement. Since anterior cruciate ligament (ACL) injuries tend to occur during athletic movements that require quick change in direction, with increased strain placed on the ACL during tibial rotation,[63, 10, 68] a multiplanar test should be developed to help examine risk factors for ACL injury. A test that involves rotation of the body 90 degrees before landing would mirror athletic motions and increase demand on internal/external tibial rotation. Therefore, the purpose of this study was to assess the reliability and precision of a single-leg rotational jump landing test to measure dynamic postural stability. In order to determine the reliability and precision of this test, a total of 14 college club-level or intramural athletes were tested.

## 1.1 FUNCTION OF THE ANTERIOR CRUCIATE LIGAMENT

Injury to the ACL has damaging consequences because of its important functions. It provides both mechanical stability and proprioceptive feedback to the knee.[125] It is the primary restraint against anterior loads and internal rotation of the tibia.[117] The ACL has two functional bundles, the anteromedial (AM) and the posterolateral (PL) bundles.[31] These bundles, functioning at different knee flexion angles, work together to provide both anterior and internal/external tibial rotational stability of the knee.[117] Other stabilizing functions include preventing hyperextension of the knee and acting as a secondary stabilizer to valgus stress.[20] In addition to providing mechanical stability of the knee, the ACL has been shown to have a significant role in proprioception,[19, 27, 87] which contributes to postural control, joint stability, and several other conscious sensations.[85]

### 1.1.1 The Role of the ACL in Resisting Tibial Rotation

One of the most important functions of the ACL is the restraint it provides relative to tibial rotation. Its significant role in resisting internal/external tibial rotation has been demonstrated in cadaveric and biomechanical studies.[67,4,1] Several cadaveric studies have demonstrated significant increases in internal tibial rotation upon transection of the ACL.[67,121,28] It has also been demonstrated that upon ACL transection, internal tibial torque significantly increased coupled anterior tibial translation by as high as 94% when compared to the uninjured knee,[41] which is important given that the addition of internal tibial torque to a knee already loaded by anterior tibial force is a critical force combination commonly found during ACL injury.[10, 50, 56] The role of the ACL in limiting tibial rotation has also been demonstrated in-vivo in subjects with ACL deficiency. Three-dimensional radiographic techniques have shown increased internal and external tibial rotation in subjects with ACL deficiency.[29, 42] Additionally, subjects with ACL deficiency demonstrate significantly increased tibial rotation range of motion and different maximum tibial rotation angles during normal gait and upon pivoting[29, 86, 100]

## 1.2 EPIDEMIOLOGY OF ANTERIOR CRUCIATE LIGAMENT INJURY

### 1.2.1 Prevalence of ACL Injury

The knee joint is the site of the highest injury rates among young athletes,[73] with the ACL as the most common knee ligament injury.[47] In addition to the increasing prevalence of ACL injury in athletes, the cost of repair and the long recovery process have brought ACL injury into the spotlight. Currently, an estimated 80,000 ACL tears occur annually in the United States.[33] More than half of these injuries are treated surgically, at an annual cost of nearly one billion dollars.[33]

Studies have shown that ACL injury can have lasting debilitating effects. It has been demonstrated that approximately 50% of patients with an ACL injury develop knee osteoarthritis 10-20 years later.[30, 47, 49, 63] Additionally, patients have reported reduced activity levels and decreased knee-related quality of life for several years following the injury.[48, 102] ACL injury and reconstructive surgery have also been associated with psychological consequences and significant decreases in academic performance among collegiate athletes.[26, 90] These long-term and damaging consequences help demonstrate the need for a tool to examine risk factors in order to increase injury prevention.

## 1.3 MECHANISM OF ACL INJURY

The complex mechanisms surrounding ACL injury are continuously researched and proposed. Numerous studies indicate that the most common motions that involve ACL injury include side step cutting movements, movements with small knee valgus angles and low ankle pronation, and those with narrow stance.[10, 23, 68, 83] In addition to following a pattern of certain athletic movements, the mechanisms leading to ACL injury seem to be directly affected by the intensity of play. There is a 3 to 5 times greater risk of sustaining an ACL injury in a game compared to practice,[16] which illustrates the need for an assessment tool that closely mimics athletic movements and is more challenging for the athlete.

ACL injury mechanisms in athletic competition occur either with or without contact. Noncontact mechanisms can be defined as motions that apply excessive strain to the ACL and result in injury without contact between players.[10] A contact injury occurs when one athlete's body makes contact with another or with an object, typically resulting in valgus collapse of the knee leading to ACL injury.[10] This type of injury mechanism only accounts for approximately 30% of all ACL injuries.[10] From an injury prevention standpoint, it cannot be prevented through physical training interventions. On the other hand, the majority of ACL injuries occur via a noncontact mechanism and researchers continue to examine modifiable risk factors in order to develop methods of injury prevention.

### 1.3.1 Noncontact ACL Injury

The most common motions that have resulted in noncontact ACL injury include quick changes of direction, especially pivoting with the knee in extension, uneven deceleration, and jump landings with the knee extended.[10] Additional mechanisms involve knee hyperextension and hyperflexion.[25, 34] These mechanisms can result in anterior tibial translation, tibial rotation, valgus of the leg while the knee joint is in extension, and high force on the leg while it is away from the center of mass.[83] Numerous studies have shown that it is the combination of these forces, such as anterior tibial translation coupled with internal rotation of the tibia, that results in the most damage.[6, 22, 105]

### 1.3.2 Tibial Rotational Motion as a Mechanism of ACL Injury

Rotation is a major component of ACL injury for two main reasons. The first is that athletic motions that result in injury usually involve rotation of the lower extremity, such as plant-and-cut or pivot maneuvers.[10, 43] Secondly, the forces that cause significant strain to the ACL include tibial rotation. Several cadaveric studies have demonstrated that the ACL is strained upon internal tibial rotation, particularly when the knee is near full extension.[1, 41, 51] In-vivo studies have also shown that internal tibial rotation in a common occurrence during injury.[10, 23, 95] Therefore, the important role of the ACL in resisting internal/external tibial rotation illustrates the need for a dynamic postural stability test that includes landing after rotating the body during a jump, which more closely mirror motions that would involve tibial rotation.

## 1.4 RISK FACTORS FOR NONCONTACT ACL INJURY

Numerous biomechanical and neuromuscular studies have explored some of the risk factors for noncontact ACL injury. Factors are usually divided into those that are nonmodifiable or modifiable. Nonmodifiable factors include those that are hormonal and anatomical, such as joint laxity, femoral notch width, ligament size, and ligament alignment.[6] Modifiable factors include biomechanical and neuromuscular properties.[58]

### 1.4.1 Modifiable Risk Factors

Modifiable risk factors are an important concern because they have the possibility to be corrected in order to prevent injury. Modifiable neuromuscular risk factors include decreased relative hamstring strength and recruitment compared to quadriceps[2, 62, 69] and muscular fatigue.[66] Other neuromuscular factors include altered trunk, hip and lower extremity proprioception.[122, 123] Several biomechanical risk factors have also been examined through kinematic and kinetic analysis of athletes landing from a jump or during cutting maneuvers. These factors include low trunk, hip, and knee flexion angles, increased dorsiflexion of the ankle, lateral trunk displacement, dynamic knee valgus, increased hip internal rotation and tibial internal and external rotation.[2, 9, 37, 75, 120, 124]

### 1.4.2 Dynamic Postural Stability as a Risk Factor for Noncontact ACL Injury

Currently, there are no established postural stability predictors of primary noncontact ACL injury. There is one study that demonstrates that deficits in dynamic postural stability after an ACL injury can predict a second injury. In a prospective study following athletes after ACL reconstruction by Paterno et al., [75] a deficit in single-leg dynamic postural stability of the injured leg proved to be an excellent predictor of a re-injury. However, this study only examined dynamic postural stability as risk factor for secondary injury and indicates the need for more research to establish dynamic postural stability deficits as a risk factor for primary ACL injury.

There are several factors that demonstrate the plausibility that deficits in dynamic postural stability may be used to assess risk for primary ACL injury. Good dynamic postural stability is necessary to protect against joint injury.[108] Since neuromuscular control is a modifiable risk factor that has a great effect on dynamic joint stability and protecting the body from injury,[84] a measurement that would test neuromuscular control, such as dynamic postural stability, should be indicative of primary risk factors for lower extremity and ACL injury. While dynamic postural stability has not been established as a risk factor for primary ACL injury, studies have shown that after suffering an ACL injury, patients have deficits in dynamic postural stability.[18,106] If deficits in dynamic postural stability occur after injury, it is plausible that poor dynamic postural stability before injury may be a risk factor. In fact, one preliminary prospective study did find that female athletes with poor dynamic balance index scores were more likely to sustain ACL injury.[103]

## 1.5 DYNAMIC POSTURAL STABILITY

### 1.5.1 Postural Stability Defined

Postural stability can be defined as the ability to transfer the vertical projection of the center of gravity to the supporting base.[32] Postural stability can be assessed during static and dynamic tasks. Both static and dynamic postural stability are useful clinical assessment tools because they require the coordination of visual, vestibular, and somatosensory pathways and the efferent responses that result.[71] Static postural stability can be measured using single-limb standing tests and assessing the ground reaction forces, which have been determined to be the best indicators of steadiness.[32]

To more closely mimic the motions involved in daily living and athletic activity, measurements of dynamic postural stability are often used. Dynamic postural stability can be defined as the ability to maintain balance while transitioning from a dynamic to a static state.[32] A common method to assess dynamic postural stability uses single-leg jump landing tasks.[112] The dynamic postural stability index (DPSI) can be calculated to quantify dynamic postural stability and has been demonstrated to be a reliable and precise measurement.[112]

### 1.5.2 Static Postural Stability vs. Dynamic Postural Stability

Previous investigations have demonstrated that measurements of static postural stability may not challenge the subject enough to provide information about injury. Harrison et al.[35] measured postural sway during single-limb stance, comparing noninjured subjects to subjects that had sustained ACL injury. The results demonstrated no differences in postural sway between the injured and uninjured limbs of subjects after ACL injury, nor was there a difference between the domninant and nondominant limbs in the subjects free of injury.[35] The results suggest that standing on a single limb may not be functional enough to determine lower-leg stability or sensitive enough to provide information about risk factors for injury.[35] This illustrates the need for dynamic stability measurements to assess lower-limb postural stability because they are more challenging for the sensorimotor system and more closely resemble athletic movements.

### 1.5.3 Effects of ACL Injury on Dynamic Postural Stability

Injury to the ACL has been shown to have an effect on both static and dynamic postural stability. It has been demonstrated that ACL injury leads to deficits in dynamic postural stability as measured by Time to Stabilization.[18,106] In addition, Mohammadi et al.[60] measured differences in both static and dynamic postural stability in ACL-injured athletes compared to a control group. It was demonstrated that injured athletes had greater postural sway during the static task and higher ground reaction forces upon landing from a jump task. Paterno et al.[74] also demonstrated biomechanical limb asymmetries during jump-landing tasks in females following ACL reconstruction, as measured by changes in ground reaction forces and loading rates during landing, and force production during take-off.

The use of measurements of dynamic postural stability to assess ACL deficiency is further validated by the correlation of these measurements to more common tests used when determining ACL deficiency. Park et al.[72] demonstrated a significant correlation between Lysholm and International Knee Documentation Committee knee scores and dynamic postural stability as measured during single-leg stance using the Biodex Stability System (BSS). The effect of ACL injury on dynamic postural stability is one factor that demonstrates the plausibility that a deficit in dynamic postural stability that is present before the injury may be a risk factor.

### 1.5.4 Rotational Dynamic Postural Stability

For a dynamic postural stability test to accurately measure the risk of ACL injury, it should incorporate a rotational component. Rotation of the body before landing would place greater demands on the knee that the ACL is responsible for restraining, such as tibial rotation. In addition, a dynamic postural stability test with a rotation component is more challenging and more closely mirrors the change in direction that is one of the characteristic movements involved in ACL injury. The fact that the highest prevalence of ACL injury is seen in adolescents playing sports that involve pivoting, such as football, soccer, basketball, and team handball,[47] illustrates the importance of the rotational motion during injury.

Dynamic postural stability tasks have not been established as a risk factor for primary ACL injury, which could be attributed to only incorporating uniplanar movement. According to a systematic review by Quatman et al.,[81] ACL injuries are more likely to occur because of multiplanar rather than uniplanar mechanisms, because anterior tibial translation, valgus knee collapse, and internal or external tibial rotations combine to result in injury. Therefore, a multiplanar dynamic postural stability test would more accurately mirror the mechanisms of ACL injury, because it includes internal/external tibial rotation, and provides a greater athletic challenge.

## 1.6 STATEMENT OF THE PURPOSE

The primary purpose of this study was to develop a more challenging and realistic test of dynamic postural stability, and establish its intersession reliability and precision. The standard single-leg jump landing tests utilized to assess dynamic postural stability only incorporate uniplanar movement in the anterior-posterior and medial-lateral directions. The test developed in this study involved landing from a jump after rotation of the body to more closely mirror the mechanisms of ACL injury.

## 1.7 SPECIFIC AIMS AND HYPOTHESIS

Specific Aim: To determine the intersession reliability and precision of a newly developed dynamic postural stability test that incorporates a rotational component.

Hypothesis: It was hypothesized that the newly developed dynamic postural stability test will demonstrate excellent intersession reliability and precision.

# 2.0 REVIEW OF THE LITERATURE

Injury to the anterior cruciate ligament (ACL) is common among athletes..[40, 59, 80] Because of its high prevalence and lasting debilitating effects,[30, 47, 49, 63] many studies have evaluated the mechanisms of ACL injury and possible risk factors.[12, 27, 131] Among the factors that increase risk for ACL injury, those that are biomechanical and neuromuscular in nature are centrally important because they have the potential to be improved with training.[84, 132, 136, 58] Although not currently established as a risk factor for ACL injury, deficits in dynamic postural stability could indicate a higher risk of injury as shown in a preliminary study[103] and because they correlate well with common measurements of ACL function,[72] among other reasons. One of the main weaknesses of the current measures of dynamic postural stability is that they are uniplanar. A multiplanar test that includes a tibia rotational component, and thus more closely mirrors mechanisms of ACL injury,[63, 10, 68] would be more likely to serve as a risk factor for injury.

## 2.1 FUNCTION OF THE ANTERIOR CRUCIATE LIGAMENT

The ACL has several important functions, primarily to provide restraint against anterior loads and internal rotation forces exerted on the tibia.[122] It consists of two functional bundles that are named after the position of their insertion sites on the tibia.[70] These bundles, anteromedial

(AM) and posterolateral (PL), function during different knee flexion angles and work together to stabilize the knee from anterior and rotational loads.[122] While the PL bundle is taut during extension, the AM bundle is taut throughout the knee's range of motion and is most taut between 45° and 60° of flexion.[122] Although the contribution of each bundle varies at different flexion angles, studies have shown that both bundles are needed in order to work together to provide restraint to anterior and rotational laxity.[30, 95] The ACL provides further mechanical stability to the knee as a minor, secondary restraint to external tibial rotation and valgus stress.[23]

In addition to providing mechanical stability to the knee, the ACL has been shown to have a significant role in proprioception. Proprioception is defined as the afferent information from internal peripheral areas of the body that contributes to postural control, joint stability, and several conscious sensations.[89] It is crucial in motor control in preparing, maintaining, and restoring postural and joint stability.[88] This afferent information originates in proprioceptive mechanorecptors, many of which have been identified in the fibers of the ACL.[131] Further indication of the ACL's role in providing proprioceptive feedback is shown by deficits in proprioception following ACL injury.[20, 29, 91] Barrack et al.[7] used threshold to detection of passive motion of the knee to measure proprioception in patients with ACL deficient knees. The uninjured participants in the control group demonstrated similar mean threshold values between knees, differing by less than 2%. However, for the subjects with complete ACL tears, the mean threshold value in the injured knee was approximately 27% higher than the uninjured knee. Multivariate analysis demonstrated that this significant proprioceptive deficit was primarily due to the loss of the ACL.

Recent studies have supported these findings using different methods to measure deficits in proprioception. Jerosch et. al[43] compared proprioception in subjects with ACL rupture to those in an uninjured control group by asking the subject to reproduce specified knee flexion angles passively given by the examiner, using the difference between the angle given and the angle set by the subject as a relative measurement of proprioception. The angle of deviation was significantly higher in patients with ACL tears; 12.7° compared to 7.8° in the control group. Even with ACL reconstruction, the angle of deviation was 13.0°. Similarly, Zhou et al.[130] demonstrated a significantly higher passive reproduction error in patients with ACL reconstruction following injury: 5.59 compared to 4.34 in the control group.

### 2.1.1 The Importance of the ACL in Resisting Tibial Rotation

Among the functions of the ACL, its role in resisting tibial rotation is critical and has been demonstrated in in-vitro and cadaveric studies. Ahmed at el.[1] demonstrated the complex role of the ACL in providing rotational stability by studying the tension patterns of ACL fibers in response to tibial axial rotation. In addition, several cadaveric studies have demonstrated significant increases in internal tibial rotation upon transection of the ACL.[67] [121] [28] Andersen et al.[4] compared 14 cadaveric knees before and after ACL transection and found a small but significant increase in internal tibial rotation at lower knee flexion angles; there was a 13% decrease in the dynamic rotational resistance at 10° of knee flexion. Furthermore, Kanamori et al.[41] demonstrated in a cadaveric study that in an ACL-deficient knee, internal tibial torque significantly increased coupled anterior tibial translation by as high as 94% when compared to the uninjured knee.

The role of the ACL in providing restraint against rotation has also been supported by studies that explore the benefits of double-bundle ACL reconstruction compared to single-bundle. Single-bundle ACL reconstruction results in unfavorable outcomes, demonstrated in a meta-analysis of functional score tests that found that only 60% of patients achieved good to excellent results.[8] This has led to a search for a more successful surgical procedure, possibly double-bundle reconstruction. One of the main benefits of double-bundle reconstruction is that it better restores the ACL's function in resisting rotation.[77, 115, 116] Using 10 cadaveric knees, Yagi et al.[116] found that double-bundle reconstruction better restores the function of the ACL, especially under rotatory loads. The in-situ force of the ACL after the double-bundle reconstruction was 91% of the normal ACL, while it was only 66% after single-bundle reconstruction.[116] They further validated these findings in a later in-vivo study, in which they used the pivot shift test to compare rotatory instability between patients with double- and single-bundle reconstruction.[115] They demonstrated that the average acceleration values of the tibial motion during the pivot shift in the single-bundle reconstruction groups were significantly larger than in the double-bundle reconstruction group; patients with anteromedial single-bundle reconstruction had an average tibial acceleration of over 1000mm/s$^2$ greater than those with double-bundle reconstruction.[115] These findings illustrate that both bundles of the ACL work concurrently to provide rotational stability of the tibia.

Studies examining subjects following ACL injury have further supported the evidence of the ACL's function to resist tibial rotation. In ACL-deficient subjects, three-dimensional radiographic techniques have shown increased internal and external tibial rotation.[29, 42] Additionally, subjects with ACL deficiency demonstrate significantly increased tibial rotation range of motion during normal gait and upon pivoting.[100] Georgoulis et al.[29] found that patients in an ACL-deficient group had significantly increased tibial rotation range of motion during the initial swing phase of the gait cycle when compared to the uninjured control group. The maximum tibial rotation angles also differed greatly. In the ACL-deficient group the average value was 9.6° of internal rotation compared -0.3° of internal rotation, or 0.3° of external rotation, indicating that ACL deficiency produces rotational differences at the knee during walking.[29] These findings were also supported in a study using a task that was more demanding than walking. Ristanis et al.[86] measured rotational stability in subjects after descending stairs and then pivoting. They compared the maximum tibial rotation range of motion between the reconstructed and intact knee in patients with ACL reconstruction, and then to a control group (with intact ACLs in both knees).[86] The mean value was significantly higher in the reconstructed knee when compared to both the intact side and the control group. These values were 22.60° for the reconstructed side, 18.97° for the intact side, and 19.08° for the control. These findings demonstrate the importance of the ACL in maintaining rotational stability and warrant the need for a rotational component in a test that could determine ACL injury risk.

## 2.2 EPIDEMIOLOGY OF ANTERIOR CRUCIATE LIGAMENT INJURY

### 2.2.1 Prevalence of ACL Injury

Anterior cruciate ligament injury is dangerously common among athletes of all levels. The National Collegiate Athletics Association (NCAA) Injury Surveillance System (ISS) reported approximately 5,000 ACL injuries in 15 sports over a 16 year span (1988-1989 to 2003-2004), equating to 313 injuries per year.[40] Additionally, ACL injury is common in younger athletes. In youth soccer alone, approximately 553 ACL injuries occurred in a 5-year span from 1995 to 1999.[94] Lastly, high prevalence of injury among professional athletes has been documented as well. Over a 5-year span in the National Football League (NFL) from 1994 to

1998, 209 ACL injuries were reported,[11] and 63% percent of those injured did not return to game play until an average of approximately 11 months after surgery.[93]

Anterior cruciate ligament injury is the focus of extensive research because of its damaging consequences and high cost. Throughout the US, approximately 75,000–100,000 ACL reconstruction surgeries are performed each year, resulting in a cost of approximately one billion dollars annually.[33] For each individual, the medical costs of surgery and rehabilitation have been estimated to be $17,000-$25,000 per injury.[21] The large expense, coupled with the long-term consequences of injury,[30, 47, 49, 63] highlights the importance of understanding ACL injury in order to prevent it.

### 2.2.2 Long Term Consequences

Unfortunately, ACL injury can result in long-term consequences with debilitating effects, such as decreased activity levels, reduced knee-related quality of life, and the development of osteoarthritis. Studies have demonstrated that approximately 50% of patients with an ACL injury develop knee osteoarthritis (OA) 10-20 years later.[30, 47, 49, 63] Lohmander et al. reported that at 12 years after an ACL rupture, 75% of female soccer players had significant symptoms affecting their knee-related quality of life, and 42% had symptomatic radiographic knee osteoarthritis.[48] In another cohort study of male soccer players with ACL tears, 40% of the subjects had radiographic knee OA and 80% reported reduced activity levels 14 years after the injury.[102] Biomechanical studies have been conducted to examine the cause of long-term symptoms in ACL-deficient knees. Andriacchi et al.,[5] using a finite-element model of an ACL-deficient knee, predicted a more rapid rate of cartilage thinning throughout the knee, especially in the medial area, suggesting that osteoarthritis after ACL injury is associated with a shift in the normal load-bearing regions of the knee joint during normal function.

Additional consequences of ACL injury on the knee include a change in static and dynamic loading which leads to increased forces on cartilage and other structures of the knee joint.[5] This may cause the development of lesions, especially in the meniscus.[22, 57] Naranje et al. found that of 50 patients who underwent ACL reconstruction for chronic ACL-deficiency, 74% had menisci tears.[64] Secondary injury to the meniscus as a result of ACL injury has important implications because the status of the menisci appears to be the most important predictor of the development of osteoarthritis.[57]

In addition to long-term physical functioning deficits, ACL injury and reconstruction has been associated with psychological consequences and significant decreases in academic performance in college athletes.[26, 97] Freedman et al. followed 38 collegiate athletes with ACL injury and observed a significant drop in grade point average of 0.3 grade points during the semester of injury.[26] Because of the negative psychological and long-term physical consequences of ACL injury, it is essential to understand the mechanism of injury in order to decrease its occurrence.

## 2.3 MECHANISM OF INJURY

Many researchers have explored possible common athletic movements that cause strain on the ACL and lead to injury. These mechanisms can be categorized as either noncontact or contact. Noncontact mechanisms can be defined as injuries that occur without contact between players and result from sudden deceleration, change in direction, or landing motions in which forces at the knee are generated that apply excessive loading on the ACL, resulting in injury.[10, 24, 119] On the other hand, contact injuries occur when athletes make contact in a way that results in valgus collapse of the knee and ACL injury.[10]

### 2.3.1 Noncontact ACL Injury

Noncontact mechanisms are the most common and account for 70% of ACL injury.[10] Various types of studies, primarily in interviews with players and video analysis, have identified the most common motions that result in noncontact ACL injury.[10, 83] They include sudden deceleration during a change of direction or cutting maneuver, jump-landing in or near full extension, and pivoting with the knee extended with a planted foot.[10, 23, 44, 68] Additional mechanisms involve knee hyperextension and hyperflexion.[25, 34]

During these movements, the forces that cause strain on the ACL are knee valgus, knee varus, internal and external tibial rotation, and anterior translation force.[10, 50, 105 83] Of these forces, the anterior translation load is often a key contributing factor to injury,[10, 50, 56] which is due to the fact that the ACL provides approximately 86% of primary restraint to anterior tibial translation.[91] This anterior translation force increases as knee flexion decreases, and is greatest at knee flexion angles of 20–30º.[7, 50, 56] These results may indicate why jump-landing in or near full extension is a common mechanism of injury[10] and highlights why a jump-landing task may be a good measurement tool to determine risk of ACL injury.

However, cadaveric studies have shown that it is the combination of two or more of these forces that causes the most strain on the ACL.[7, 50] The particular combination that has the highest potential for causing injury is the addition of internal tibial torque to a knee already loaded by anterior tibial force.[50] Markolf et al.[50] found that this combined load resulted in the highest ligament force at all levels of flexion among several different applied loads, reaching 250 to 300 Newtons of force when the knee was near full extension. Since tibial rotation is a major component in the force combination that stresses the ACL the most, its role in ACL injury is critical.

### 2.3.2 Role of Tibial Rotation during Injury

Rotation is a major component of ACL injury for two central reasons. The first is that athletic motions that result in injury usually involve rotation of the lower extremity, such as plant-and-cut maneuvers, pivoting, or changes in direction.[10 68] In a meta-analysis of the incidence of ACL tears as a function of sport, Prodromos et al.[80] found that sports with the highest rates of injury were those that involved high amounts of pivoting and changes in direction, such as basketball, soccer, alpine skiing, and lacrosse. Boden et al.[10] interviewed 80 athletes following ACL injury, and found that 39 subjects reported that their injury occurred while twisting their body in the direction opposite of tibial rotation. Additionally Fauno et al.[23] conducted a similar study, surveying 105 soccer players who ruptured their ACL. They found that 63% of those injured reported that they were trying to change direction at the time of the injury.

Secondly, since the ACL functions to resist tibial rotation, forces that cause excessive rotatory strain to the ACL can lead to injury. Previously, McNair et al.[56] identified internal tibial rotation as a significant cause of ACL injury by reporting that in 53% of subjects with ACL injury, the mechanism was internal rotation of the tibia with the knee in slight flexion. Recent studies have also demonstrated the high occurrence of internal tibial rotation during injury.[10, 23, 95] These findings have been validated by several cadaveric studies that have demonstrated that the ACL is strained upon internal tibial rotation, particularly when the knee is near full extension.[1, 41, 51] Since ACL injuries tend to occur during athletic activities that require a rotational component, with increased strain placed on the ACL during tibial rotation, a multidirectional dynamic postural stability task is warranted to more closely mimic injury mechanism and determine risk factors for injury.

## 2.4 RISK FACTORS FOR NONCONTACT ACL INJURY

Postural stability can be defined as the ability to transfer the vertical projection of the center of gravity to the supporting base.[32] Although postural stability can be measured both statically and dynamically, dynamic postural stability is the preferred measurement in athletes because the sensorimotor system is more challenged and the tasks involved more closely resemble playing motions.[112] Dynamic postural stability can be defined as the ability to maintain balance while transitioning from a dynamic to a static state[32] and is most often measured during jump-landing tasks by determining either the time to stabilization (TTS) or the dynamic postural stability index (DPSI).

Increased understanding of the mechanisms of ACL injury has led to the identification of possible risk factors that can be categorized as nonmodifiable or modifiable. Modifiable factors are those that can be changed through training or other interventions, while nonmodifiable factors are those that are structural or physiological and cannot be altered with noninvasive methods.[101] Modifiable factors include neuromuscular and biomechanical factors, conditioning, footwear, playing surface, shoe-surface interactions, and weather conditions.[58] Nonmodifiable factors include those that are anatomical or hormonal, such as joint laxity, femoral notch width, ligament size, ligament alignment, and hormonal changes throughout the menstrual cycle.[6]

### 2.4.1 Modifiable Risk Factors

Determining biomechanical and neuromuscular risk factors is crucial because they are modifiable and may be improved with training. Neuromuscular control can be defined as maintaining and restoring functional joint stability through the unconscious activation of dynamic restraints in preparation for and in response to joint motion and loading.[85] To determine risk factors for ACL injury in soccer players, Alentorn-Geli et al.[2] reviewed current evidence from several studies. The neuromuscular risk factors identified were dependent upon muscle strength and recruitment, relative joint stiffness and stability, and muscular fatigue. Precise neuromuscular control is necessary for coordinated co-activation of the hamstrings and quadriceps muscles to protect the ACL.[45, 85, 113] Proper recruitment of the hamstrings provides stability to the ACL by reducing loads from quadriceps and by resisting anterior tibial translation and rotation.[45, 82, 113] Withrow et al.[113] demonstrated in-vitro that increasing hamstring muscle force during simulated jump landing significantly reduced strain on the ACL; increasing the hamstring force in cadaveric legs reduced the peak strain in the ACL by approximately 73%. Neuromuscular imbalances that lead to increased quadriceps activation and decreased hamstring activation would therefore increase strain and the risk of ACL injury.

These potentially injurious activation patterns have been found in females athletes during jump landing tasks.[14, 69, 122, 123] Zebis et al.[123] prospectively examined the neuromuscular control pattern of the quadriceps versus the hamstrings in female athletes during a standardized side-cutting maneuver. They demonstrated that the subjects who sustained ACL injury had previously been shown to have reduced EMG preactivity for the semitendinosus and increased EMG preactivity for the vastus lateralis. Additionally, both men and women have demonstrated low levels of hamstring activation during cutting maneuvers,[17] which may illustrate why cutting motions are so commonly involved in injury. The role of decreased recruitment of the hamstrings as a risk factor for injury is further supported by a prospective study by Myers et al.[62] in which female athletes who later suffered ACL injury had decreased hamstrings strength, but not decreased quadriceps strength, compared to males. Conversely, those who did not receive injuries had decreased quadriceps strength but no decrease in hamstring strength when compared to males.

Muscular fatigue can also decrease neuromuscular control, putting athletes at risk for ACL injury.[2] It has been demonstrated that both males and females decrease knee flexion angle and increase proximal tibial anterior shear force and knee varus moments during stop-jump tasks after fatigue.[15] Nyland et al.[66] also found that hamstring fatigue decreased dynamic knee control in the transverse plane. Additionally, fatigue has been shown to increase initial and peak knee abduction and internal rotation motions during jump-landings.[55]

Biomechanical risk factors have been established as well through studies using cadavers and through analytical modeling. These factors include low trunk, hip, and knee flexion angles, increased dorsiflexion of the ankle, lateral trunk displacement, dynamic knee valgus, increased hip internal rotation and tibial internal and external rotation.[2, 9, 37, 75, 120, 124] In a prospective study following 205 female athletes, Hewett et al.[37] found that female athletes who later sustained ACL injury had significantly different knee posture and loading during a jump-landing task compared to those who remained uninjured. When compared to the uninjured group, females that later endured ACL injury had 8.4° greater knee abduction angles at initial contact, a 20% higher ground reaction force peak, stance that was 16% shorter, and a peak external knee abduction moment of -45.3N·m compared to -18.4 N·m.[37] In addition to these lower extremity biomechanical factors, Zazulak et al.[122] identified increased lateral trunk displacement as a risk factor. In a prospective study, 277 collegiate athletes were tested for trunk displacement after a sudden force release. It was demonstrated that displacement at 150 milliseconds and maximum displacement were over 20% greater in athletes who later sustained ACL injury compared with those who remained uninjured.[122]

The abundance of possible neuromuscular and biomechanical risk factors has led to the development of neuromuscular and biomechanical training programs to decrease injury rates with promising results. In a meta-analysis conducted by Yoo et al.,[118] pre- and in-season neuromuscular training that emphasized plyometrics and strengthening exercises were effective at preventing ACL injury in female athletes. A recent review of prevention programs aimed to reduce injury risk in soccer players by Alentorn-Geli et al.[3] also demonstrated the success of programs aimed at improving proper biomechanical techniques. These results illustrate the need for a tool to assess neuromuscular and biomechanical risk factors for injury so proper training adjustments can be made.

### 2.4.2 Dynamic Postural Stability as a Risk Factor for ACL Injury

Research has revealed that certain neuromuscular and biomechanical factors may increase the risk of ACL injury, so measurements that incorporate these factors, such as dynamic postural stability, may serve as indicators as well. The dynamic stability of the body or a specific joint depends on neuromuscular control of the displacement of all contributing body segments during movement.[38] The major role of neuromuscular control in dynamic joint stability and protection from injury has been documented.[84, 99, 114] Therefore, measurements of dynamic postural stability may be used to determine underlying neuromuscular functioning, and have the potential to be used to determine the presence of risk factors. In fact, deficits in single-leg dynamic postural stability have been found to be a reliable measure of knee injury risk, but only as a predictor of knee re-injury.[75] Paterno et al.[75] found in a prospective study that subjects who had single-leg dynamic postural stability deficits in the involved limb, as measured by the Biodex stability system, were twice as likely to obtain a second injury.

However, there is a lack of research linking deficits in dynamic postural stability to primary ACL injury. One preliminary prospective study did find that female athletes with poor dynamic balance index scores were more likely to sustain ACL injury.[103] In this study, Vrbanic et al.[103] analyzed fifty-two female handball and volleyball athletes by measuring their static and dynamic balance index scores using the Sport KAT 2000 testing system. Seven of the athletes (13%) had sustained ACL injury when interviewed 5 years later, and these athletes demonstrated poorer dynamic balance index scores compared to the healthy population.[103] Such results, coupled with the fact that dynamic postural stability serves as an indicator for neuromuscular control, a previously established risk factor, illustrate that dynamic postural stability itself may be a risk factor.

## 2.5 DYNAMIC POSTURAL STABILITY

Time to stabilization analyzes ground reaction forces (GRF) in three directions: anterior-posterior, medial-lateral, and vertical. Time to stabilization measures dynamic postural stability by assessing the time it takes the GRF's to return to a stable range following a dynamic task or an external perturbation to the body.[88, 89] First, the range of variation of a given GRF component is defined, which is the smallest absolute range value of a GRF component during the last 10 seconds of the single-leg stance portion of a jump-landing task.[88, 89] The TTS is then measured as the time it takes for the GRF range of variation following a single-leg jump landing to resemble the GRF range of variation at the beginning of the test.[88, 89]

However, TTS has several weaknesses. First, it assesses forces from all 3 directions for each landing, so clinicians have 3 separate measures instead of one measure of dynamic postural stability as a whole.[112] Analyzing the results can therefore be tedious, since data reduction and analysis must be performed on three separate measurements.[54] Lastly, comparing TTS results between healthy and injured subjects is difficult because baseline measures may not allow for equal comparison.[54]

Thus, the dynamic postural stability index (DPSI) was developed to account for the short comings of TTS.[112] While TTS only assesses performance for the three different force directions, DPSI is a composite score that provides a common measure among the three force directions, while still providing a score for each of the three directional indices.[112] It has been shown to be more reliable and precise than TTS during a single-leg jump task, with an ICC of 0.96 and a SEM of 0.03.[112]

The validity of the DPSI as a sensitive measure of dynamic postural stability has been demonstrated in several studies that also show its association with dynamic stability deficits in populations with lower extremity pathologies, particularly ankle instability.[107, 109, 110] Wikstrom et al.[110] found that the dynamic postural stability index was significantly higher for subjects with functional ankle instability compared to healthy subjects (0.85 compared to 0.73) and indicated that DPSI can detect differences in dynamic postural stability between individuals with stable ankles and individuals with functionally unstable ankles. The ability of the DPSI to detect differences in stability between healthy subjects and those with lower extremity injury or instability may indicate that it can also be used to assess ACL function or injury risk.

### 2.5.1 ACL Injury and Dynamic Postural Stability

There currently is a lack of standardized dynamic postural stability measurements to assess ACL function. However, some studies have shown an association between poor dynamic postural stability and ACL deficiency. Colby et al. determined that TTS is reliable in detecting deficits in dynamic postural stability in those with ACL injury while performing a step-down task.[18] Additionally, Webster et al.[106] reported that female athletes following ACL reconstruction have longer TTS than healthy subjects.

It has also been shown that measurements of dynamic postural stability strongly correlate to knee functional scores that are commonly used to assess ACL deficiency, including the International Knee Documentation Committee Knee (IKDC) joint scores and the Lysholm knee scale. Both scores have well-documented reliability and quantify symptoms, activity level, and function as reported by patients.[12, 76] Park et al. found that Lysholm and IKDC are well correlated with dynamic postural stability ($r = -0.49$, $p = 0.001$ and $r = -0.52$, $p = 0.005$, respectively), as measured by a single-leg stance with the Biodex Medical Systems.[72]

Although dynamic postural stability correlates well with more common measurements of ACL function and has been used to identify stability deficits in patients with lower extremity pathology, there is a need for more research to identify dynamic postural stability as a risk factor for primary ACL injury. The main weakness of current measures of dynamic postural stability is that they are uniplanar. A multiplanar test that includes a rotational component would be more likely to identify primary risk factors for ACL injury. Wascher et al.[105] demonstrated in vitro that the greatest strain on the cruciate ligaments of the knee occur during multiplanar loading. This evidence was supported in a systematic review that reported ACL injuries are more likely to occur because of multiplanar rather than uniplanar mechanisms.[81] Therefore, the development of a multiplanar dynamic postural stability test is warranted.

## 2.6 METHOLOGICAL CONSIDERATIONS

### 2.6.1 Calculating Dynamic Postural Stability Index

The Dynamic Postural Stability Index (DPSI) is a composite of anterior-posterior, medial-lateral, and vertical ground reaction forces that was calculated according to Wikstrom et al.[112] The DPSI was determined using the first three seconds of the ground reaction forces following initial contact. Although data was collected for ten seconds, and any interval between three and ten seconds has been shown to be reliable, an interval of three seconds was used because it is most closely mimics athletic activity and is more commonly used.[109, 111, 112]

Calculation of the DPSI incorporates the stability indices in the anterior-posterior, medial-lateral, and vertical directions. The indices are mean square deviations assessing fluctuations around a zero point instead of standard deviations assessing fluctuations around a group mean.[112] The formula for the calculation is depicted in Figure 1. The medial-lateral stability index assesses fluctuations from zero along the body's frontal axis while the anterior-posterior stability index assesses fluctuations from zero along the sagittal axis. [112] The purpose of the vertical stability index is to standardize the vertical ground reaction forces along the body's vertical axis to assess fluctuation from the subject's body weight, thus normalizing vertical scores among people with different body weights.[112] While the original DPSI calculations used the square root of the number of samples as the denominator, the modified formula uses just the number of samples,[107, 109, 112] which enables calculation of the average magnitude of the ground reaction force vector around zero points in the anterior-posterior, medial-lateral, and vertical directions of the force plate.[107]

### 2.6.2 Jump-Landing Task

Two main jump-landing protocols have been used previously while calculating DPSI scores. One standardizes jump height[107, 112] and the other standardizes jump distance.[91] The first study using DPSI used a protocol in which subjects stood 70 cm away from the center of the force plate, jumped with both legs and touched a marker overhead that was approximately 50% of the subject's maximum vertical jump height, and landed on the force plate with only the test leg. They then stabilized as quickly as possible, balancing for 10 seconds with hands on their hips while looking straight ahead.[112] This study demonstrated that the DPSI has high reliability (ICC of 0.96) and high precision (SEM of 0.03).

The original jump landing protocol was modified by Sell et al.[92] to standardize the jump distance rather than the jump height and included a medial/lateral jump. This modification was used to minimize the equipment needed and to incorporate greater deceleration forces.[92] For the anterior-posterior jump task, subjects stood a distance of 40% of their body height from the edge of the force plate. They were instructed to jump forward with both legs over a 30 cm hurdle located halfway between the subject and the force plate, land on the force plate with only the test leg, stabilize as quickly as possible, and balance for 10 seconds with hands on their hips while looking forward.[91] The medial-lateral jump that was added required that the subjects stand at a distance equal to 33% of their body height away from the edge of the force plate. They were then instructed to jump laterally with both feet to clear a 15 cm hurdle, at the midpoint between the starting position and the force plate. They landed on only the test leg, stabilized as quickly as possible, placed hands on their hips, and looked straight ahead for 10 seconds. The lateral jump direction was determined by the subject's dominant foot. The DPSI for both directions were determined to have high reliability and precision: the anterior-posterior direction had an ICC of 0.86 and a SEM of 0.01 and medial-lateral direction had an ICC of 0.92 and a SEM of 0.01.[91]

## 2.7 SUMMARY

With high rates of ACL tears among athletes, many researchers have been focusing on methods of injury prevention. In order to do so, it is important to know the main functions of the ACL, which include restraint against anterior loads and internal rotation of the tibia.[117] This knowledge leads to a better understanding of the mechanisms involved in ACL injury, which primarily involve anterior tibial translation and internal rotation during sudden deceleration in cutting or pivoting maneuvers, or upon jump-landings.[7, 10]

In turn, by studying the mechanisms of ACL injury, different risk factors have been established, including modifiable neuromuscular and biomechanical factors.[2] Since dynamic postural stability depends on neuromuscular control, it is likely that it could be a risk factor for ACL injury as well. This is further supported in that measures of dynamic postural stability have a strong correlation with current methods used to test ACL function.[72] Additionally, poor dynamic postural stability scores have been associated with ACL deficiency[18, 106] and have been shown to possibly indicate risk for ACL injury in female athletes.[103] However, more research is needed to establish it as a risk factor for primary ACL injury.

In order to strengthen current measures of dynamic postural stability to more accurately demonstrate risk of ACL injury, a rotational component should be added. One of the main weaknesses of the current measurements of dynamic postural stability is that they are uniplanar. A multiplanar test, such as jump-landing tasks that include a rotational component, would more closely mimic the multiplanar and rotational mechanisms that commonly result in ACL injury,[81] making it more applicable and more likely to be a risk factor for injury.

# 3.0 METHODOLOGY

## 3.1 EXPERIMENTAL DESIGN

The purpose of this study was to develop and establish the intersession reliability and precision of a dynamic postural stability task that incorporates a tibial rotational component. Reliability is used to define the consistency of a test, while precision ensures that the measures vary minimally from the standard.[79] Dynamic postural stability was assessed using a single-leg jump landing protocol requiring participants to perform a 2-legged jump over a hurdle with a single leg landing. For the single leg jump landing protocol, subjects jumped anteriorly and rotated 90 degrees before landing. The composite Dynamic Postural Stability Index (DPSI) was calculated, as well as the stability indices in each direction.

### 3.1.1 Variables

- Dynamic Postural Stability Index (DPSI)
- Stability Indices in each direction during each measure of dynamic postural stability
    - Anterior-posterior stability index
    - Medial-lateral stability index
    - Vertical stability index

## 3.2 PARTICIPANTS

Fourteen athletes of the college club-sport level or intramural level were recruited to participate in this study. Interested subjects contacted the Neuromuscular Research Laboratory at which time the inclusion/exclusion criteria was reviewed to determine eligibility. All testing procedures were conducted at the Neuromuscular Research Laboratory. Testing lasted approximately ninety minutes.

### 3.2.1 Subject Recruitment

Subjects were recruited by a flyer distributed to the University of Pittsburgh athletic facilities and via email distribution to club and intramural teams.

### 3.2.2 Subject Consent

Each participant completed a University of Pittsburgh IRB approved informed consent form as well as had all questions answered concerning their participation in this study prior to testing.

### 3.2.3 Inclusion Criteria

- Between the ages of 18 and 25 years
- College club level or intramural athletes

### 3.2.4 Exclusion Criteria

- Lower extremity injury in the previous 2 months
- Lower extremity surgery or fracture on the dominant leg
- ACL deficient
- Prior training in balance and jump landings
- Any disorders that could affect equilibrium or neuromuscular control
- Head injury in the past 3 months
- Knowingly pregnant females

## 3.3 POWER ANALYSIS

Using NCSS Pass Software, it was determined that a sample size of 12 subjects with 2 observations per subjects will achieve 82% power to detect an intraclass correlation of 0.90 under the alternative hypothesis when the intraclass correlation under the null hypothesis is 0.60 using an F-test with a significance level of 0.05.[39] Accounting for a 10% attrition rate an additional 2 subjects were recruited. Therefore, a total of 14 subjects were needed.

**Table 1. Power Analysis**

| Power | Alpha | R0 | R1 | N |
|---|---|---|---|---|
| 0.82 | 0.05 | 0.70 | 0.90 | 19 |
| 0.82 | 0.05 | 0.60 | 0.90 | 12 |
| 0.82 | 0.05 | 0.50 | 0.90 | 9 |

*R0 = null hypothesis
*R1= alternative hypothesis

## 3.4 INSTRUMENTATION

### 3.4.1 Force Plate

A force plate (Kistler 9286A, Amherst, NY) was used to collect ground reaction forces (1200 Hz) to assess dynamic postural stability. Force plate data was passed through an amplifier and analog to digital board (DT3010, Digital Translation, Marlboro, MA) and stored on a personal computer.

### 3.4.2 Motion Analysis

Three-dimensional coordinate data was collected during the single-leg jump landings using the Vicon Motion Analysis System (Vicon Motion Systems, Englewood, CA) equipped with 8 high-speed infrared cameras to ensure the appropriate amount of rotation occurred. The motion analysis data was used to confirm that the amount of rotation occurred between the ranges of 75-105 degrees (90±15 degrees). This system is designed to capture 3-D coordinate data. Three-dimensional coordinate data were collected at 240 Hz. In the Neuromuscular Research Laboratory the accuracy of this system was determined to be 0.39mm and 0.08°.

## 3.5 TESTING PROCEDURES

Previous studies have demonstrated that similar measures of balance have strong inter- and intra-session reliability. These studies include the use of single-leg balance assessments[36, 46,

[61] and the ability of force platforms to effectively measure changes in balance.[78] In order to establish intersession reliability, the test sessions occurred 30 minutes apart.[61] This protocol follows that which was used by Muehlbauer et al[61] when establishing inter- and intra-session reliability of single-leg stance assessments in young adults. The jump protocols were based on Wikstrom et al.[126] with a modification of normalization to jump distance rather than jump height similar to Padua et al.[70, 112] This modification was used to minimize the equipment needed and to incorporate greater deceleration forces.[92]

For the jump task, the subjects started in a standing position at a distance equal to 40% of their body height from the edge of the force plate (approximately 25 inches). The subjects were given instructions to jump anteriorly over a 30cm hurdle that was placed halfway between the starting point and the force plate, rotating his/her body 90 degrees before landing on the dominant limb. Subjects were required to perform separate tasks involving medial and lateral rotation. The trial was considered successful as long as the subject rotated 90±15 degrees. Each subject rested approximately thirty seconds between each repetition, and one minute between each jump task.

Subjects were instructed to start each jump from a two-legged stance and land only on the dominant leg, which was defined as the leg the subject would use to kick a ball maximally. Subjects were instructed to jump just high enough to clear the hurdle and land with their foot completely on the force plate. The hurdle height was determined using values that were found to be reliable in a previous study.[91] Upon landing, they were instructed to stabilize as quickly as possible with their hands on their hips while looking straight ahead, remaining balanced for 10 seconds. The first three seconds after initial contact was used for data processing. Initial contact was defined as when the vertical ground reaction forces exceeds 5% of the subject's body weight. Each subject was provided a minimum of three practice trials but could continue with practice trials until they felt comfortable with the testing procedures.

To measure the ground reaction forces using the force plate, four markers were attached to the subject during each procedure: three markers on the dominant foot, which was used to measure the degree of rotation, and one marker on the sacrum, to track the height of the jump. Upon completing five successful trials in each direction, ground reaction forces were collected and used to determined stability indices and a composite index was calculated.

### 3.5.1 Discarded Trials

Trials were discarded and repeated if a subject lost balance and touched the force plate or the ground surrounding the force plate with the contralateral limb, if a short additional hop or step of the test leg occurred on landing, and if his/her hands were not placed on the hips after stabilizing following initial contact. In addition, if the subject hit the hurdle, if his/her foot did not land completely on the force plate, or if excessive swaying occurred, the trials were discarded and repeated. Lastly, the trial was discarded and repeated if the rotation was less than $75^o$ or greater than $105^o$ (outside the range of 90±15 degrees).

## 3.6 DATA REDUCTION

### 3.6.1 Dynamic Postural Stability Index

A custom MATLAB (v7.0.4, Natick, MA) script file was used to process the ground reaction force data. Data was passed through a zero-lag 4$^{th}$ order low pass Butterworth filter with a 20 Hz cutoff frequency.[91] Three successful trials in each direction were averaged and used for analysis. The variable that was analyzed was the DPSI, a composite of anterior-posterior, medial-lateral, and vertical ground reaction forces that was calculated according to Wikstrom et al.[112] The DPSI calculation is depicted in Figure 1. The DPSI was determined using the first three seconds of the ground reaction forces following initial contact. Initial contact was defined as the instant the vertical ground reaction force exceeds 5% body weight.

### 3.6.2 Motion analysis

A custom MATLAB (v7.0.4, Natick, MA) script was used to process the motion analysis data. Specifically, each trial was analyzed to determine the amount of rotation that occurred. An acceptable range of rotation was 90±15 degrees (between the ranges of 75-105 degrees).

## 3.7 STATISTICAL ANALYSIS

The precision of the rotational DPSI was determined by calculating the standard error of measurement (SEM) for the scores in each direction. The SEM calculation used for this study is depicted in Figure 2. Intersession reliability was assessed using an intraclass correlation coefficient (ICC), using the (2,k) and (2,1) models[96].

## 4.0 RESULTS

The primary purpose of this study was to determine the intersession reliability and precision of a newly developed dynamic postural stability test that incorporates a rotational component. Seven male and seven female college club or intramural level athletes participated. Single-leg jump landings were used to assess dynamic postural stability and the dynamic postural stability index (DPSI) was calculated, as well as the stability indices in each direction (anterior-posterior, medial-lateral, and vertical). The precision was determined using the standard error of measurement (SEM) for the scores in each direction. Reliability was assessed using intraclass correlation coefficients (ICC), using the (2,k) and (2,1) models.[96]

### 4.1 DEMOGRAPHICS

A total of fourteen, seven male and seven female, college club or intramural soccer athletes participated in this study. The demographics for the subjects are presented in Table 2. Individual subject demographics are included in Appendix A. To quantify activity level, the Sports-Activities Rating Scale proposed by Noyes et al.[65] was used. This scale standardizes activity level based on frequency of participation and the function of the knee during activity.[65] Since the subjects in this study all participated in soccer 1-3 days a week, they all fall under the 85-point category.

**Table 2. Subject Demographics**

| | Male (n=7) | | Female (n=7) | | Total (n=14) | |
|---|---|---|---|---|---|---|
| | Mean | SD | Mean | SD | Mean | SD |
| Age (years) | 20.9 | 1.1 | 20.9 | 1.1 | 20.9 | 1.0 |
| Height (cm) | 181.4 | 6.7 | 162.9 | 3.7 | 172.1 | 10.9 |
| Weight (kg) | 77.9 | 16.5 | 68.7 | 15.5 | 73.3 | 16.1 |
| Physical Activity | 85.0 | 0.0 | 85.0 | 0.0 | 85.0 | 0.0 |

## 4.2 DYNAMIC POSTURAL STABILITY DATA

The means and standard deviations for all of the dynamic postural stability data (anterior-posterior stability indices, medial-lateral stability indices, vertical stability indices, and DPSIs) are presented in Table 3. Individual subject scores are provided in Appendix B-E.

**Table 3. Group Dynamic Postural Stability Data**

| | Rotation Medially | | Rotation Laterally | |
|---|---|---|---|---|
| | Session 1 | Session 2 | Session 1 | Session 2 |
| MLSI | | | | |
| Group Average | 0.1397 | 0.1428 | 0.1486 | 0.1455 |
| Standard Deviation | 0.0079 | 0.0090 | 0.0170 | 0.0148 |
| APSI | | | | |
| Group Average | 0.0407 | 0.0415 | 0.0412 | 0.0433 |
| Standard Deviation | 0.0073 | 0.0081 | 0.0096 | 0.0123 |
| VSI | | | | |
| Group Average | 0.3299 | 0.3409 | 0.3381 | 0.3338 |
| Standard Deviation | 0.0339 | 0.0265 | 0.0334 | 0.0412 |
| DPSI | | | | |
| Group Average | 0.3609 | 0.3722 | 0.3719 | 0.3671 |
| Standard Deviation | 0.0322 | 0.0258 | 0.0345 | 0.0423 |

Higher scores represent worse postural stability

MLSI = Medial Lateral Stability Index

APSI = Anterior Posterior Stability Index

VSI = Vertical Stability Index

DPSI = Composite Score

## 4.3 RELIABILITY AND PRECISION OF THE ROTATIONAL DYNAMIC POSTURAL STABILITY TEST

The intersession reliability of the dynamic postural stability test was assessed using Statistical Package for the Social Sciences (SPSS) software to determine the intraclass correlation coefficient (ICC) using the (2,1) and (2,k) models. Additionally, to assess the precision of the test the standard error of measurement (SEM) was calculated using the formula in Figure 2. [81] The ICC and SEM were calculated for the stability indices (anterior-posterior, medial-lateral, and vertical) and the composite DPSI. The ICC using the (2,1) model are presented in Table 4 and the ICC using the (2,k) model are presented in Table 5.

The following scale was used to interpret the ICC values: below 0.69 = poor, 0.70 to 0.79 = fair, 0.80 to 0.89 = good, and 0.90 to 1.00 = excellent.[79, 112] Therefore, all of the values except one (MLSI for rotation medial) were fair to excellent, with the DPSI having good to excellent reliability using the (2,k) model. Overall, the reliability of the stability index in the medial-lateral direction was the poorest, while the reliability of the composite index (DPSI) was the strongest.

The SEM was relatively small for most of the dependent variables, indicating a precise measurement. The largest SEM's were observed for the VSI and DPSI during the rotation laterally, indicating these variables are less precise. For rotation in either direction (medially or laterally), the SEM was the lowest for the medial-lateral stability index and the highest for the DPSI.

**Table 4. Dependent Variables ICC (2,1) and SEM**

| | ICC | 95% CI | | SEM |
|---|---|---|---|---|
| Rotation Medially | | | | |
| MLSI | 0.670 | 0.254 | 0.790 | 0.015 |
| APSI | 0.764 | 0.410 | 0.918 | 0.016 |
| VSI | 0.792 | 0.411 | 0.931 | 0.067 |
| DPSI | 0.793 | 0.377 | 0.933 | 0.064 |
| Rotation Laterally | | | | |
| MLSI | 0.734 | 0.372 | 0.905 | 0.025 |
| APSI | 0.859 | 0.627 | 0.952 | 0.029 |
| VSI | 0.857 | 0.621 | 0.952 | 0.098 |
| DPSI | 0.863 | 0.635 | 0.953 | 0.103 |

MLSI = Medial Lateral Stability Index
APSI = Anterior Posterior Stability Index
VSI = Vertical Stability Index
DPSI = Composite Score

**Table 5. Dependent Variables ICC (2,k) and SEM**

| | ICC | 95% CI | | SEM |
|---|---|---|---|---|
| Rotation Medially | | | | |
| MLSI | 0.802 | 0.405 | 0.936 | 0.019 |
| APSI | 0.866 | 0.582 | 0.957 | 0.021 |
| VSI | 0.884 | 0.582 | 0.964 | 0.077 |
| DPSI | 0.885 | 0.547 | 0.966 | 0.086 |
| Rotation Laterally | | | | |
| MLSI | 0.846 | 0.542 | 0.950 | 0.033 |
| APSI | 0.924 | 0.770 | 0.975 | 0.040 |
| VSI | 0.923 | 0.766 | 0.975 | 0.133 |
| DPSI | 0.926 | 0.777 | 0.976 | 0.139 |

MLSI = Medial-Lateral Stability Index
APSI = Anterior-Posterior Stability Index
VSI = Vertical Stability Index
DPSI = Composite Score

# 5.0 DISCUSSION

The primary purpose of this study was to assess the reliability and precision of a dynamic postural stability test that incorporates a rotational component. The dependent variable was the dynamic postural stability index (DPSI) during the rotational single-leg jump landings. It was hypothesized that the precision and reliability would be excellent. Statistical analysis partially supported our hypothesis with the results indicating that the test was precise with "fair" to "excellent" reliability.

## 5.1 DYNAMIC POSTURAL STABILITY

Measurements of dynamic postural stability are very valuable in evaluating injury[18, 106] and determining the presence of risk factors in order to prevent injury.[52, 53, 75, 98, 104] Deficits in dynamic postural stability have not yet been established as a risk for knee injury, specifically ACL tearing, perhaps because of the methods of testing. Current tasks to measure dynamic postural stability may not be challenging enough for athletes and are uniplanar, therefore not mimicking the mechanisms of ACL injury. [63, 10, 68] This indicates the need for a new mode of measuring dynamic postural stability to address weaknesses in current measurements. This need led to the goal of the current study: to develop a more challenging method to test dynamic postural stability that is reliable and precise. Establishing the reliability of this task may enable future researchers to use the task to identify athletes at risk for ACL injury.

In the current study, dynamic postural stability was assessed using the DPSI that was measured during a single-leg hop stabilization task that included a rotational component. The group average for the DPSI was approximately 0.3700 for the four test sessions. For rotation medially, the average DPSI was 0.3609 for the first session and 0.3722 for the second session. For rotation laterally, the average DPSI was 0.3719 for the first session and 0.3671 for the second session.

It is interesting to note that, although all subjects reported that rotating laterally was more difficult, there does not appear to be any significant difference between rotations medially and laterally for the DPSI score, 0.3665 and 0.3695, respectively. This could possibly be due to the fact that, generally, each subject had more failed trials when rotating laterally. Perhaps the need to complete more trials in order obtain three successful trials allowed the subjects to improve their strategies during this task, counteracting the increased difficulty and leading to similar DPSI scores as those in the medial direction.

A comparison of these results to those of previous literature is somewhat limited because there is no literature describing a rotational dynamic postural stability test. However, our results are similar to other studies assessing dynamic postural stability during anterior jump-landings. Wikstrom et al.[112] were the first to assess dynamic postural stability using the DPSI. Their protocol required subjects to jump forward 70cm and jump vertically to 50% of their maximum vertical jump height and land on a single leg. The authors reported the following average values: 0.77(DPSI), 0.22(MLSI), 0.38(APSI), 0.62 (VSI). Brown et al.[13] conducted a study with a similar jump protocol to compare a control group to females with chronic ankle instability. The

DPSI was calculated after subjects jumped anteriorly, medially, and laterally to 50% of their maximum vertical jump height and landed on one leg. Compared to the control group, since our subjects were also healthy, the results are very similar. For the anterior jump, the values were 0.34(DPSI), 0.03(MLSI), 0.11(APSI), and 0.32 (VSI). For the lateral jump, the values were 0.33 (DPSI), 0.05(MLSI), 0.10(APSI), and 0.30(VSI). For the medial jump, the values were 0.34(DPSI), 0.05(MLSI), 0.10(APSI), and 0.32(VSI). Finally, our results are very similar to those of Sell et al.[91] who also assessed dynamic postural stability during a single-leg jump test. In this study, subjects performed jump landings in the anterior and lateral directions. The anterior jump required subjects to jump forward 40% of their height and over a 30cm hurdle and the lateral jump required subjects to jump to the side 33% of their height and over a 15cm hurdle and land on a single-leg. The authors reported the average DPSI to be 0.348 for the AP jump task and 0.316 for the ML jump task.

## 5.2 RELIABILITY

One of the primary goals of this study was to determine the reliability of the DPSI measured during a jump-landing task with a rotational component. In order for this task to be used in future research, its reliability must be established. A reliable task allows researchers to identify differences in scores as actual differences in dynamic postural stability. If the variable was not reliable, these differences in scores could simply be due to inconsistencies in measuring the variable. This is especially important if the variable is to be used in prospective studies with repeated measurements within the same subject. The results of this study concluded that the task is reliable and acceptable to use in future research.

The reliability of the DPSI calculated during the rotational jump landing task was measured using ICC values with both the (2,1) and (2,k) models. For the (2,1) model, the ICC values were 0.670 (MLSI), 0.764 (APSI), 0.792 (VSI) and 0.793 (DPSI) for rotation medially. For rotation laterally, the ICC values were 0.734 (MLSI), 0.859 (APSI), 0.857 (VSI), and 0.863 (DPSI). All of the ICC's are considered to be "fair" and "good" with the exception of the MLSI during the rotation medial which is considered to be "poor". [79, 112] For the (2,k) model, the ICC values were 0.802 (MLSI), 0.866 (APSI), 0.884 (VSI) and 0.885 (DPSI) for rotation medially. For rotation laterally the values were 0.846 (MLSI), 0.924 (APSI), 0.923 (VSI) and 0.926 (DPSI). All of the ICC's are considered to be "good" and "excellent".[79, 112] Therefore, our results demonstrate that a single-leg jump landing incorporating a rotational component is reliable.

In comparing the results of the current study to previous research, the reliability of this task is similar to that of the tasks used by Wikstrom[112] and Sell.[91] Using the (2,k) model, the ICC values of this study are 0.885 (medial rotation) and 0.926 (lateral rotation), which are very similar to the ICC values of Wikstrom[112](0.96) and Sell[91](0.86). The results of the current study are also similar to previous studies in that the DPSI scores were more reliable than the stability indices in each direction. [91, 111, 112] Therefore, this study provides further support that the DPSI composite score is more reliable than individual stability indices, and therefore a stronger measure of dynamic postural stability. These results also suggest that the rotation laterally is more reliable than the rotation medially. When the 95% confidence interval for the ICC overlaps the null hypothesis ICC value, the observed ICC is not statically significantly different from the null hypothesis at the 95% confidence level, meaning that the variable is not reliable. Using the (2,k) model, this was observed for a greater number of medial rotation variables, and for a lesser number of lateral rotation variables.

The studies by Wikstrom[112] and Sell[91] assessed dynamic postural stability during jump landing tasks in the anterior-posterior plane. However, jump landings in the anterior-posterior direction may not be an appropriate comparison for a rotational jump landing task. A more appropriate comparison would be a jump landing task in the medial-lateral direction. The rotational jump landing task used in this study is similar to a medial-lateral jump landing task in several ways. First, both tasks are more challenging than an anterior-posterior task as evidenced by the increased scores for the medial lateral stability index (MLSI). Also, both the rotational and medial-lateral tasks require subjects to land with their foot perpendicular on the force plate. Sell et al.[91] also had subjects perform the test in the medial-lateral direction, and demonstrated excellent reliability with an ICC value of 0.92 , which is similar to the findings in the current investigation.

Overall, DPSI measured during a single-leg hop stabilization test with a rotational component demonstrated “fair” to “excellent” reliability. Therefore, we believe the test is acceptable for use in future research. However, the ICC values calculated in the current investigation are not as reliable as previous studies. Perhaps this is because the tasks in the current investigation were novel and more challenging. Before completing the rotational task, the subjects completed jump landing tasks in the anterior-posterior and medial-lateral directions. Although not recorded, anecdotally each subject stated that the rotational tasks were the most difficult. Because the task was relatively novel, there was an increased need for subjects to develop strategies in order to complete the task successfully. Although we accounted for this by giving the subjects a minimum of three practice trials, there still may have been variability in how quickly each subject was able to strategize. The technique that appeared to lead to more successful landings was rotating earlier in the jump. It appeared that once subjects learned to do this, their bodies fluctuated less upon landing and they were able to achieve better rotation, closer to $90^{o}$. Another reason the task may not be as reliable is the variation in degrees of rotation. Each subject was allowed to rotate his/her body $90 \pm 15^{o}$, leading to a $30^{o}$ range of rotation. If the degree of rotation affected DPSI, this would have increased variability between sessions and among subjects. Perhaps the reliability of the task could be improved by limiting rotation to $90 \pm 10^{o}$. However, this may make the task too challenging and increase the number of failed trials.

## 5.3 PRECISION

The other primary goal of this study was to determine the precision of the task. In order for a task to be used in future research, it should be precise as well as reliable. The precision of this task was measured using the standard error of measurement (SEM). The SEM provides an index of absolute reliability. It can be used to determine the minimum difference needed between separate measures on one subject for the difference in the measures to be considered true differences. This is especially important if the task were to be used to follow progress after rehabilitation from an injury. The results of this study indicate that the task is precise and acceptable to use for future research.

For the (2,1) model, the SEM values were 0.064 for rotation medially, and 0.103 for rotation laterally. For the (2,k) model, the SEM values were 0.086 for rotation medially, and 0.139 for rotation laterally. These values are relatively small compared to the group mean, indicating a precise measurement. However, the values are fairly higher than those reported by Wikstrom[112] and Sell.[91] Wikstrom[112] found the DPSI to have an SEM of 0.03 whereas, Sell[91] found the SEM to be 0.01 for both the AP and ML jump tasks. This decreased precision may be due to the same reasons as the decreased reliability. Because the task was novel and challenging, there was an increased need for subjects to develop landing strategies in order to complete the task successfully. Therefore, a variety of landing strategies may have been adopted by the subjects in order to successfully complete the task. Kinematic and electromyography data were not collected in this investigation; therefore, we can only speculate that different landing strategies were used. Additionally, there was a wide range of allowable rotation ($30^o$), which could have led to increased variability as well.

## 5.4 LIMITATIONS

One limitation of this study is the varying athletic backgrounds of the participants. The number of years of athletic participation was not recorded, which could potentially affect DPSI scores. Anecdotally, we can state that some subjects had been playing soccer for several years, while others had only a few years of experience. Additionally, we only focused on the subject's weekly participation in soccer. Some participants were also athletes in other sports as well. It is plausible that subjects who participated in other sports that involved high amounts of jump landing, such as basketball and volleyball, had better DPSI scores. Because they had more experience in sports with jumping and rotating, these subjects may have been able to learn how to successfully complete the task more quickly, increasing variability in the scores. Although we excluded subjects with prior training in balance and jump landings, the different training programs of the subjects could have been a limitation as well. Some of the subjects participated on teams that had varying levels of agility training, which could affect their ability to control their landings and affect DPSI scores. These limitations could have affected the variability in the DPSI scores.

Another limitation is that there was a potential for a wide range of rotation. The subjects were instructed to rotate $90\pm15^{o}$; this resulted in a total range of $30^{o}$. This allowed for there to be a potential for a wide range of rotation between jumps for each subject and between subjects. Currently, it is unknown how the degree of rotation affects the DPSI. If the degree of rotation affected the DPSI score, this could have resulted in less precision and reliability.

Finally, the participants could have had varying medical histories relating to injures. Although subjects with lower extremity injury in the past two months or surgery or fracture on the dominant leg were excluded, there was still room for variability in previous injuries. For example, some subjects may have had a history of recurrent ankle sprains. Since this condition has been shown to affect dynamic postural stability,[109, 111, 112,13] the DPSI scores could have been affected, leading to decreased precision.

## 5.5 CLINICAL SIGNIFICANCE

The results of this study support that the DPSI assessed during a rotational jump landing task is a reliable and precise measurement. Since this task may be more challenging than current tests used to assess dynamic postural stability, it may be better suited for athletic populations. Having a more challenging task for athletes may enable researchers to identify differences in dynamic postural stability among athletes. The ability to detect these differences may allow the task to be used to determine the presence of risk factors for injury, especially to the ACL. Since this test is multiplanar and includes a tibia rotational component, and thus more closely mirrors mechanisms of ACL injury,[63, 10, 68] it may be used in future prospective studies to determine the presence of risk factors.

## 5.6 FUTURE DIRECTIONS

To our knowledge, this was the first study to assess the reliability and precision of a single-leg jump landing test that incorporates a rotational component. Knowing that the test is reliable and precise, future studies should determine if the test can be used to detect differences in dynamic postural stability between different populations, such as between genders. The task could also be used to increase understanding of the kinematics and muscle activation patterns during rotational landings, or to see if these patterns are different for the different rotation directions.

Future work should also explore if the DPSI, assessed using a task with a rotational component, is a risk factor for ACL injury. By adding a rotational component, we believe this task modifies current methods used to measure dynamic postural stability, making it more applicable in assessing ACL injury risk. If dynamic postural stability, measured using this task, can be established as a risk factor for ACL injury, this would be a feasible technique to identify athletes at risk for injury. Hopefully, with adjustments to training or the introduction of various neuromuscular training programs, [118] athletes could improve their dynamic postural stability and be more resistant to injury.

## 5.7 CONCLUSIONS

This study demonstrated that the dynamic postural stability index assessed during a jump landing task with a rotational component is a reliable and precise measurement. With a rotational component, the task may be more challenging and a better measurement for athletic populations. Future researchers may be able to use this test to identify athletes at risk for injury, particular to the ACL.

## LIST OF FIGURES

$$\text{DPSI} = \frac{\Sigma(0\text{-GRFx})^2 + \Sigma(0\text{-GRFy})^2 + \Sigma(\text{body weight-GRFz})^2}{\text{number of data points}} \div \text{body weight}$$

**Figure 1. Dynamic Postural Stability Index Equation**

$$SEM = s_{X\sqrt{1-r_{XX}}}$$

SEM = Standard error of measurement
$s_X$ = Grand standard deviation

$r_{XX}$ = Intraclass correlation coefficient

**Figure 2. Formula to Calculate SEM[81]**

# APPENDIX A

## [INDIVIDUAL SUBJECT DEMOGRAPHICS]

| Subject | Sex | Age | Physical Activity Level | Sport Level | Leg Dominance | Ht (cm) | Wt (kg) |
|---|---|---|---|---|---|---|---|
| 1 | Female | 21 | 85 | Club | Left | 165.0 | 70.61 |
| 2 | Female | 21 | 85 | Club | Right | 162.5 | 56.12 |
| 3 | Female | 19 | 85 | Club | Right | 162.0 | 59.25 |
| 4 | Female | 20 | 85 | Club | Right | 163.5 | 73.02 |
| 5 | Female | 22 | 85 | Club | Right | 156.5 | 58.6 |
| 6 | Female | 22 | 85 | Club | Right | 168.8 | 100.8 |
| 7 | Male | 21 | 85 | Intramural | Right | 182.5 | 85.83 |
| 8 | Female | 21 | 85 | Club | Right | 161.8 | 62.29 |
| 9 | Male | 19 | 85 | Club | Right | 180.0 | 69.85 |
| 10 | Male | 20 | 85 | Club | Left | 186.4 | 67.33 |
| 11 | Male | 22 | 85 | Intramural | Right | 193.0 | 112.61 |
| 12 | Male | 22 | 85 | Intramural | Right | 173.0 | 70.7 |
| 13 | Male | 21 | 85 | Intramural | Right | 178.5 | 70.03 |
| 14 | Male | 21 | 85 | Intramural | Right | 176.5 | 69.51 |

## APPENDIX B

## [INDIVIDUAL SUBJECT DYNAMIC POSTURAL STABILITY DATA – ROTATION MEDIAL - SESSION 1]

| Subject | MLSI | APSI | VSI | DPSI | Number of Trials | Number of Failed Trials |
|---|---|---|---|---|---|---|
| 1 | 0.152741 | 0.046457 | 0.332237 | 0.368651 | 8 | 3 |
| 2 | 0.132839 | 0.038603 | 0.319473 | 0.348243 | 8 | 3 |
| 3 | 0.142141 | 0.045796 | 0.329926 | 0.362226 | 5 | 0 |
| 4 | 0.136981 | 0.035289 | 0.312944 | 0.343443 | 5 | 0 |
| 5 | 0.143908 | 0.035831 | 0.322189 | 0.354731 | 5 | 0 |
| 6 | 0.124893 | 0.041269 | 0.295063 | 0.323081 | 5 | 0 |
| 7 | 0.151632 | 0.040592 | 0.362003 | 0.3948 | 7 | 2 |
| 8 | 0.148439 | 0.037918 | 0.342866 | 0.375642 | 7 | 1 |
| 9 | 0.142592 | 0.031962 | 0.266097 | 0.303668 | 6 | 1 |
| 10 | 0.141399 | 0.036533 | 0.348316 | 0.377705 | 6 | 1 |
| 11 | 0.134849 | 0.041832 | 0.356788 | 0.383762 | 11 | 7 |
| 12 | 0.133229 | 0.058301 | 0.368146 | 0.395865 | 5 | 0 |
| 13 | 0.134332 | 0.03079 | 0.279189 | 0.311529 | 6 | 1 |
| 14 | 0.135236 | 0.048952 | 0.383728 | 0.409859 | 5 | 0 |

## APPENDIX C

## [INDIVIDUAL SUBJECT DYNAMIC POSTURAL STABILITY DATA – ROTATION MEDIAL – SESSION 2]

| Subject | MLSI | APSI | VSI | DPSI | Number of Trials | Number of Failed Trials |
|---|---|---|---|---|---|---|
| 1 | 0.15473 | 0.045945 | 0.353101 | 0.388272 | 6 | 1 |
| 2 | 0.132326 | 0.027111 | 0.319519 | 0.346933 | 5 | 0 |
| 3 | 0.146162 | 0.041895 | 0.356264 | 0.387382 | 7 | 2 |
| 4 | 0.150789 | 0.044423 | 0.319928 | 0.356497 | 9 | 4 |
| 5 | 0.14131 | 0.03502 | 0.343004 | 0.372863 | 5 | 1 |
| 6 | 0.120851 | 0.037448 | 0.313176 | 0.337841 | 7 | 4 |
| 7 | 0.150769 | 0.038019 | 0.360356 | 0.392503 | 5 | 0 |
| 8 | 0.147929 | 0.041945 | 0.322687 | 0.357487 | 6 | 1 |
| 9 | 0.147216 | 0.033639 | 0.29438 | 0.330962 | 7 | 3 |
| 10 | 0.134503 | 0.041893 | 0.367544 | 0.393719 | 6 | 3 |
| 11 | 0.145107 | 0.041772 | 0.344812 | 0.376583 | 9 | 5 |
| 12 | 0.148366 | 0.058673 | 0.385701 | 0.417409 | 7 | 3 |
| 13 | 0.141358 | 0.038177 | 0.319222 | 0.351492 | 8 | 4 |
| 14 | 0.137777 | 0.054644 | 0.372785 | 0.401258 | 5 | 0 |

## APPENDIX D

## [INDIVIDUAL SUBJECT DYNAMIC POSTURAL STABILITY – ROTATION LATERAL – SESSION 1]

| Subject | MLSI | APSI | VSI | DPSI | Number of Trials | Number of Failed Trials |
|---|---|---|---|---|---|---|
| 1 | 0.151255 | 0.049824 | 0.361377 | 0.394969 | 8 | 3 |
| 2 | 0.140866 | 0.035926 | 0.337112 | 0.367142 | 9 | 4 |
| 3 | 0.153891 | 0.043242 | 0.358563 | 0.392686 | 8 | 2 |
| 4 | 0.148301 | 0.041767 | 0.350561 | 0.38297 | 9 | 6 |
| 5 | 0.157968 | 0.049045 | 0.358707 | 0.395069 | 16 | 12 |
| 6 | 0.142988 | 0.034188 | 0.289329 | 0.32462 | 6 | 2 |
| 7 | 0.157839 | 0.055019 | 0.367943 | 0.404466 | 6 | 2 |
| 8 | 0.138546 | 0.029892 | 0.313158 | 0.343815 | 8 | 4 |
| 9 | 0.149924 | 0.031765 | 0.289172 | 0.327496 | 11 | 7 |
| 10 | 0.140236 | 0.043294 | 0.337805 | 0.368441 | 10 | 6 |
| 11 | 0.135298 | 0.032753 | 0.310274 | 0.340227 | 15 | 10 |
| 12 | 0.150057 | 0.059115 | 0.370528 | 0.404259 | 9 | 5 |
| 13 | 0.138258 | 0.02777 | 0.29538 | 0.327528 | 10 | 5 |
| 14 | 0.175585 | 0.043089 | 0.393313 | 0.432965 | 5 | 1 |

## APPENDIX E

### [INDIVIDUAL SUBJECT DYNAMIC POSTURAL STABILITY DATA – ROTATION LATERAL – SESSION 2]

| Subject | MLSI | APSI | VSI | DPSI | Number of Trials | Number of Failed Trials |
|---|---|---|---|---|---|---|
| 1 | 0.141477 | 0.062286 | 0.357842 | 0.38997 | 6 | 1 |
| 2 | 0.134687 | 0.031308 | 0.322531 | 0.351016 | 7 | 2 |
| 3 | 0.153606 | 0.050207 | 0.39137 | 0.423517 | 5 | 0 |
| 4 | 0.14375 | 0.040765 | 0.348131 | 0.378904 | 7 | 2 |
| 5 | 0.178918 | 0.054782 | 0.376326 | 0.420397 | 11 | 8 |
| 6 | 0.125045 | 0.026841 | 0.278093 | 0.306162 | 6 | 1 |
| 7 | 0.156805 | 0.057428 | 0.373946 | 0.409635 | 6 | 1 |
| 8 | 0.138355 | 0.035861 | 0.342868 | 0.371489 | 9 | 6 |
| 9 | 0.149277 | 0.032032 | 0.271754 | 0.311859 | 6 | 2 |
| 10 | 0.127139 | 0.046575 | 0.337993 | 0.364161 | 10 | 6 |
| 11 | 0.140741 | 0.042879 | 0.295932 | 0.33056 | 7 | 3 |
| 12 | 0.148766 | 0.060408 | 0.335293 | 0.371981 | 6 | 1 |
| 13 | 0.132946 | 0.02538 | 0.267312 | 0.299957 | 5 | 1 |
| 14 | 0.165181 | 0.039486 | 0.373156 | 0.409999 | 5 | 1 |

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