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The Effects of Recurrent Lateral Ankle Sprains and Postural Control on Biomechanics during Functional Movement

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by

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The Effects of Recurrent Lateral Ankle Sprains and Postural Control on Biomechanics during Functional Movement

Timothy J. Gilleran

Study Design: Cross-sectional

Objectives: Study 1: identify relationships between physical and functional impairments and the dynamic postural stability index (DPSI) scores in participants with and without recurrent lateral ankle sprains (RLAS). Study 2: To examine whether participants with recurrent lateral ankle sprain and postural instability (RLAS-PI) are more likely than participants without RLAS-PI to have concurrent evidence of changes in joint biomechanics of the ankle, knee, hip, pelvis and trunk during jump landings.

Background: Recurrent lateral ankle sprains are common injuries which may lead to changes in postural control and joint biomechanics. The association between DPSI and clinical impairments is currently unknown. Establishing a relationship between a dynamic measure of postural stability and clinical impairments will assist clinicians in prioritizing their examination. The contributions of RLAS and postural instability to lower extremity and trunk biomechanics during functional movements are currently unclear. Understanding the biomechanics of functional movements in subjects with RLAS-PI will inform clinicians and researchers about selected postural control strategies.

Methods: In study 1, examinations of DPSI scores and clinical impairments were performed on 23 participants (5 male, 18 female, age: 26.8 ± 4.2) with RLAS and 14 participants without RLAS (8 male, 6 female, age: 27.1 ± 3.5). Jump landings were examined using data acquired by a force platform (1000 Hz). Associations of DPS and clinical measures were evaluated using bivariate correlations ($p<0.05$). Group mean differences of continuous clinical outcome measures were examined using MANCOVA; and categorical data were evaluated with chi square test ($p<0.05$). In study 2, the landing phase (initial contact to one second) of a jump onto a single limb was examined with a force platform (1000 Hz) and a 10 camera motion capture system (250 Hz) with a full body marker set. Participants included 9 with RLAS-PI (4 female, 5 male, age: 28.1 ± 4.0) and 12 controls (6 female, 5 male, age: 26.2 ± 2.7). Group mean differences in clinical measures, joint kinematics and kinetics were examined using independent t-tests ($p<0.05$).

Results: Study 1 identified weak and non-significant correlations between all DPSI scores and clinical tests. Significant group differences in questionnaires, joint stability measures and the Y Excursion Balance Test were identified, but no differences in strength, range of motion, side hop performance, and directional or composite stability indices were identified. Study 2 identified significant group differences in ankle, knee, hip, pelvis, and trunk biomechanics between RLAS-PI and control participants. Compared to controls, participants with RLAS-PI had a significant decrease in dorsiflexion excursion angles ($p = 0.034$), and increase in knee joint power ($p = 0.039$) and peak trunk flexion angles ($p = 0.038$).

Conclusion: The selected physical and functional impairment measures were not related to this measure of dynamic postural control. RLAS participants perceive significant deficits in their functional ankle stability and disability, but quantitative measures of their functional performance and dynamic postural control were unable to identify group differences. In study 2, the RLAS-PI group utilized different movement strategies to perform the jump landing task successfully. Reduced ankle joint excursions may reflect a “protective stiffening” strategy by the RLAS-PI group, but at a cost to an increasing the vertical rate of loading. As a result of this strategy, we observed proximal movement strategies with the use of increased hip and trunk movement to regain balance after the jump landing. Increases in rate of loading have been attributed to overuse injuries in running and jumping sports.

Key words: *recurrent lateral ankle sprain, postural control, biomechanics*

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Chapter 1

INTRODUCTION

Ankle injuries are common injuries in athletics, accounting for approximately 25% of all injuries occurring in running and jumping sports.[13] The majority of these injuries originate as lateral ankle sprains and have the potential to tear neural tissues within the ligaments. The acute disruption of the nervous system creates deficits in proprioception, neuromuscular control, and impairments in static postural control.[8,17,19] Approximately 40% of people who initially sprain their ankle proceed to experience recurrent lateral ankle sprains (RLAS).[11] While local impairments in ligament laxity are a common adaptation of recurrent lateral ankle sprains, it's unlikely that laxity itself is the primary cause of RLAS.[24] A constellation of local impairments (e.g. ligament laxity, ankle hypermobility, deficits in joint position sense), regional impairments (e.g. hip strength deficits and changes in neuromuscular activation of quadriceps) and centrally mediated changes (e.g. postural stability) have been identified in subjects with RLAS.[2,4,6,7,8,11,12,14,15,16,18,19,23,24] The true mechanism of RLAS is unknown, but "recurrence" is most likely linked to a number of initial local impairments that trigger regional and centrally mediated changes over time that ultimately lead to RLAS.[25]

In response to local ankle impairments, compensatory movement strategies may develop in an effort to maintain function, but may cause further stress on local structures.[25] Furthermore, these movement strategies are thought to be influenced by regional and central mediated adaptations to RLAS. For example, central mediated changes in dynamic postural control have been identified in people with RLAS. As a movement strategy, postural control requires "maintaining, achieving or restoring a state of balance during any posture or activity."[21] Recently developed dynamic postural control measures require participants to perform a jump landing onto a force platform and maintain balance for a predetermined time.[22] Studies using this metric found significant differences in ground reaction force dissipation and balance between participants with and without RLAS.[22,23] A combination of successful jump landings and significant differences in ground reaction force dissipation indicates that different postural control strategies were utilized by RLAS participants to complete the task. Examining functional movements with dynamic postural control measures provides one way to quantify these strategies, but a critical question remains. Are the changes in dynamic postural control due to centrally mediated changes in motor programming or do local and regional impairments influence the strategies as well?

Previous investigations which have examined the effects of local ankle impairments on dynamic balance and functional activities may shed some light on this question. Moderate and significant correlations between measures of weight bearing dorsiflexion range of motion and the Star Excursion Balance Test (SEBT) have been identified in participants with and without chronic ankle instability.[1,15] The SEBT is one measure of postural control in which subjects perform a series of single-limb squats using the free limb to reach maximally to touch a point along 1 of 8 designated lines on the ground.[10] A follow-up prospective investigation identified significant improvements in SEBT scores after 6 visits of manual therapy intervention to improve ankle dorsiflexion range of motion.[14] These studies provide new evidence of the effects of local impairments on dynamic balance as well as improvements in dynamic balance with focused manual therapy intervention.

However, dynamic balance, as measured by the SEBT may only challenge the ‘predictive’[21] component of a participant’s postural control. Functional and sports specific activities require a combination of ‘predictive’ and ‘reactive’ components of postural control strategies.[21] A more complex examination of dynamic postural control requires a movement that examines both strategies of postural control. The current investigation will utilize a jump landing task to challenge both predictive and reactive components of dynamic postural control in participants with and without RLAS.

Advancing previous lines of investigations, we will examine the association of clinical impairments and dynamic postural control with a jump landing task. Accurately identifying local and regional clinical impairment measures associated with dynamic postural control can further inform the research community and guide assessment and intervention in people with RLAS. This dissertation examines proposed key factors associated with postural stability, such as muscle strength, joint mobility/stability, range of motion, and functional performance, in participants with and without RLAS.

Recurrent lateral ankle sprains result in abnormal kinematics (joint motions) and kinetics (joint torques) at the ankle during various tasks; the effects on knee, hip and trunk biomechanics are mixed or unknown.[3,5,6,9,20] Linking abnormal biomechanics at the ankle, knee, hip, and trunk with postural instability following RLAS will advance our understanding of the local and regional impact of postural instability on functional movement in people with RLAS. Ultimately, linking changes in lower extremity and trunk biomechanics with functional movement deviations in participants with RLAS and postural instability will shed light on this complex pathology and focus clinical examinations and rehabilitative interventions to improve outcomes in this population.

The overall objective of this dissertation is to investigate the influences of RLAS on postural control and the biomechanics of functional movement. The central hypothesis is that postural instability from RLAS will be associated with altered biomechanics of the trunk, ankle, knee and hip joints during functional movement. This cross-sectional study utilized clinical, postural stability and motion capture testing to examine active and otherwise healthy individuals 18 to 35 years old with and without a history of RLAS. This study will help to determine important clinical and biomechanical indicators that can be used in a future prospective assessment and treatment of participants with RLAS.

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Chapter 2

Association of dynamic postural stability and clinical impairments in participants with and without recurrent lateral ankle sprains

BACKGROUND

Ankle injuries are some of the most common injuries in athletics; 75% are sprains and 85% of these sprains are lateral ankle sprains.[19, 24] Lateral ankle sprains recur at a rate as high as 80% among athletes.[24] In addition, up to 40% of subjects with lateral ankle sprains go on to experience ankle instability and subsequent disability.[19] Researchers have proposed two possible mechanisms to account for recurrent lateral ankle sprains (RLAS). First, “mechanical instability” is the development of physiological joint laxity following a severe lateral ankle sprain or recurrent lateral ankle sprains.[19,27] Second, “functional instability” is thought to occur from the disruption of neural tissues within the ankle ligaments causing deficits in the neuromuscular system that provides dynamic support to the ankle joint.[12,19] Although, local deficits in ankle proprioception, cutaneous sensation, nerve-conduction velocity, joint range of motion and strength have been reported post ankle sprain and may contribute to the high recurrence rate, research has indicated that the effects of ankle injury are not restricted to the ankle itself [2,6,13,16,19,27,28, 36, 37,45,52] regional and central affects may also contribute to RLAS.

Individuals with RLAS experience regional clinical impairments (e.g. hip muscle weakness) and impairments in postural control.[13, 37] In a systematic review, McKeon and Hertel[37] reported on static postural control and lateral ankle sprains. The authors identified 8 articles reporting that static postural control (measured by static center-of-pressure (COP) measurements on a force plate) is adversely affected in the presence of RLAS when compared to healthy controls. In evaluating the level of evidence, the authors gave these articles a Strength-of-Recommendation Taxonomy (SORT) level of evidence of 2 and recommended a grade of B, because of inconsistent results with small effect sizes and large confidence intervals.

It has been proposed that traditional static COP measurements may not be as sensitive to RLAS-related deficits as recently designed dynamic postural control measures.[48] Recent investigations have identified alterations in dynamic postural stability in subjects with RLAS.[44,45,46,48] Dynamic postural stability has been defined as "an individual's ability to maintain balance while transitioning from a dynamic to a static state".[42] Novel methodologies combine force plate data from static and "dynamic" activities that challenge the postural control system. For example, the "time to stability" concept analyzes the participant's ability to recover balance after a dynamic jump onto a force plate.[44] Stability was defined as ground reaction force (GRF) in the anterior/posterior, medial/lateral and vertical directions decayed to stay within the normal values of static baselines. According to Wikstrom et al.[48] flaws in the time-to-stabilization formula and a lack of a common measure among the three force directions were revealed over time. These investigators corrected the calculation flaws and expanded on the time to stability methodology by developing the Dynamic Postural Stability Index (DPSI). The DPSI indicates how well a subject can dissipate resultant ground reaction forces (GRF) from a jump landing.[48] The DPSI provides three separate measures of dynamic postural stability, as well as a composite postural stability score calculated by combining the three individual measures (anterior/posterior, medial/lateral and vertical directions - refer to Methods section for full description). The DPSI and separate indices scores are calculated for each jump landing such that higher scores indicate greater variability.[48,50,52] The DPSI is a more reliable (r = 0.95) and precise (SEM = 0.03) measure than calculating time to stabilization during a single-leg-hop maneuver.[48] Previous research has shown that the DPSI can differentiate postural stability after a jump landing between young individuals with and without RLAS.[50,52] Despite these improvements in methodology, little is known about dynamic postural stability in individuals with and without RLAS.

While the DPSI is reliable and precise, not all clinic sites have force plates and technology to calculate the DPSI. Clinicians regularly assess range of motion, joint stability, strength, balance and functional measures (i.e. Y Excursion Balance Test (YEBT)) in participants with chronic ankle instability, but it is unclear if these relate to dynamic postural stability. Understanding associations between dynamic postural stability and clinical examination outcomes will further inform our clinical reasoning processes to develop targeted examination and rehabilitation programs. This study examines the relationships between physical and functional impairment testing and dynamic postural control as measured by the DPSI. We hypothesized that increased ankle and hip muscle strength, dorsiflexion range of motion, YEBT, and side-to-side hop performance would be most closely associated with increased postural stability. Secondly, this study investigates group differences between clinical impairment and dynamic postural control testing between participants with and without RLAS. We posit group differences in ankle (evertor and dorsiflexor) and hip (abductor and adductor) muscle strength; dorsiflexion range of motion, YEBT, side-to-side hop, and DPSI performance.

METHODS

Participants

Women and men, 18-35 years old, with and without a history of RLAS were recruited from the local community through posted advertisements. People were eligible for the study if they had a history of “giving way” or recurrent lateral ankle sprains during a functional or sporting activity; past history of a lateral ankle sprain which required a period of protective weight bearing and/or immobilization for greater than or equal to 3 days; at least one recurrent lateral ankle sprain 6 to18 months before study participation; and performing at least 1.5 hours of cardiovascular, resistance, sport-related, or other physical activity per week without a level of pain that inhibits full participation. Individuals were excluded if they had a recent ankle injury (in the previous 12 weeks) that required a period of crutch use and/or visiting a health care provider who provided treatment (i.e. assistive device, ankle orthosis, physical therapy); history of a lower extremity fracture requiring medical intervention, immobilization and non-weight bearing; previous knee, hip or lumbar spine injury that required medical intervention (i.e. prescribed medication), period of non-weight bearing and/or loss of time in their sport/work; previous diagnosis of ankle, knee and/or hip osteoarthritis, neurologic or vestibular disorders, current inner ear or sinus infection.

Instrumentation

Lower extremity strength was measured with the MicroFET 2 digital hand held dynamometer (HHD) (HOGGAN Health Industries, Inc., Salt Lake City, UT). Joint range of motion was measured with the Baseline Bubble Inclinometer (Fabrication Enterprises Inc., White Plains, NY) and vertical jump height was measured with the Vertec device

(Sports Imports, Columbus, OH). Ground reaction forces were obtained using 1 AMTI force plate (Model #OR6-6-1, Advanced Mechanical Technology, Inc [AMTI], Watertown, Massachusetts) at a rate of 1000 Hz.

Procedures

All testing was performed at the Human Performance Center at the University of California, San Francisco Orthopaedic Institute. People interested in participating were screened for eligibility by the primary investigator over the phone. If the eligibility criteria were met, participants signed an institutionally-approved informed consent document, and were officially enrolled in the study. All clinical examination procedures were performed by a single non-blinded researcher with 23 years of orthopedic clinical experience.

Clinical Examination and Functional Testing

Questionnaires. All participants completed the Cumberland Ankle Instability Tool (CAIT)*.*[22] The CAIT is a self-report measure with 9-items in a 30-point scale for measuring perceived severity of functional ankle instability. This measure can discriminate whether a subject has had an ankle injury and assesses the severity of functional ankle instability. The CAIT does not rely on comparison to an uninvolved limb; the questions are designed to be independent of reference to the other leg.[22]

All participants also completed the Functional Ankle Disability Index (FADI) Sports subscale to measure the amount of self-reported disability.[17] The FADI Sport subscale is a self-report of the difficulty of tasks that are essential to sport. FADI Sport Scale is scored as percentages, with 100% representing no dysfunction. The RLAS participants completed for the FADI Sport for their “most affected” ankle, but control participants answered the questionnaire separately for their dominant and non-dominant lower extremities.[17] Lower extremity dominance was determined by self-report of the leg on which participants would be most comfortable landing from a jump.

The self-administered long version of the International Physical Activity Questionnaire (IPAQ) was also completed by all participants. The purpose of the questionnaire was to provide comparable data on health–related physical activity in 5 activity domains.[9] Height, weight, and leg length were measured with standard conventions.

Ankle joint mobility and stability / generalized joint laxity. Measurements of ankle joint stability and mobility were examined with the participants lying supine with the feet hanging off the end of the plinth.[1,47] The ankle joint was examined for joint translation as well as stability with the anterior drawer (AD) and talar tilt (TT) tests as described in the literature.[47] The translation classification describes the amount of motion that is felt by the examiner with each maneuver, whereas the stability classification defines the “end-point” of the motion. The translation of the ankle joint (ankle joint mobility) was documented and coded as having: excessive translation (score = 3), having normal translation (score = 2) or reduced translation (score = 1). Ankle joint stability was determined by the feel at the end of the translational movement. A ‘firm’ end feel was documented as stable (score =1) or a ‘soft’ end feel was determined to be unstable (score =0).

Prior to data collection, a small reliability study of these clinical measures was performed, comparing the results of the primary investigator and an equally experienced clinician in orthopedic physical therapy that were blinded to the participants’ previous ankle injury history. Percent agreement statistics were generated on 5 volunteers for joint stability. Inter-rater percent agreement for joint stability: AD = 60%; TT = 100%; and joint translation: AD = 20%; TT = 60%. Intra-rater percent agreement for the primary investigator: joint stability: AD = 100%; TT = 100%; and joint translation: AD = 100%; TT = 90%. The primary investigator's intra-rater reliability for joint translations confirms previous findings by Ryan et al.[47] that reported 95% agreement when examining joint translation of the ankle, but are in poor agreement with the same investigators inter-rater reliability of 85% for joint translations.

Participants' generalized joint laxity was determined by examining the following three maneuvers for the right and left extremities: hyperextension of the elbow beyond 0 degrees (neutral), hyperextension of the knee beyond 0 degrees (neutral), and apposition of the thumb to the volar aspect of the forearm. This is a modification to the Beighton scale[14] which also includes examining hyperextension of the 5th finger as well as forward bend in standing. Similar to the Beighton scale, 1 point is awarded for each positive result and the highest possible score is 6. A score of 5 or higher would indicate generalized joint laxity.

Strength testing. Ankle dorsiflexor, evertor; hip adductor and abductor muscle strength was measured with a hand held-dynamometer (HHD). The dynamometer and participant were stabilized with straps and foam wedges (Figure 1) to minimize inconsistencies in limb positioning and unintentional application of force by the tester. A "make test" was performed with the participant exerting maximal effort against the dynamometer for five seconds. Three practice trials at 50%, 75% and 100% of participant's perceived maximal effort were performed prior to testing to ensure participants would build appropriate force and achieve maximal effort.

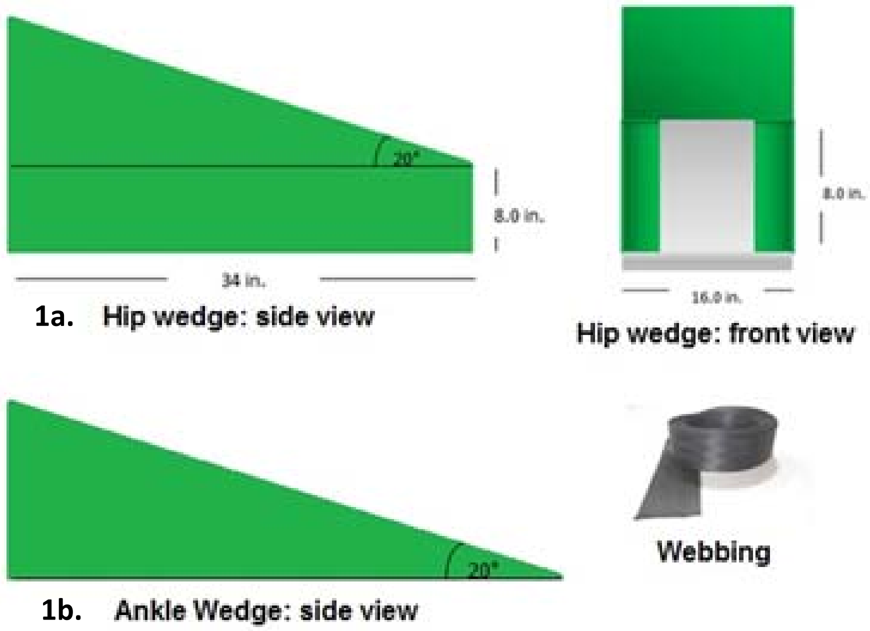

FIGURE 1. The foam wedge system used during isometric testing was designed to maximize limb stability and reproducibility of limb position. 1a) hip wedge provided a channel below the supporting surface to allow for the contralateral leg to rest. 1b) the ankle wedge allowed for the elevation of participants forefoot and positioning of the HHD on the lateral border of the foot.

Ankle dorsiflexor strength was examined using methods similar to those described by Kellen et al.[32], but the HHD dynamometer was stabilized with webbing (Figure 2). Ankle eversion strength was examined with the participant sitting in a chair (Figure 3). The lower extremities were stabilized with a towel roll between the knees and webbing secured over the distal thighs. The heel of the foot was placed on the floor with the foot in 20° of plantar flexion on a foam wedge. The HHD was secured laterally over the proximal third of the 5th metatarsal while the patient was instructed to exert force against the dynamometer for 5 seconds. The participants were cued to push against the dynamometer by everting the foot/ankle and not to externally rotate the tibia.

FIGURE 2. Strength testing for the ankle dorsiflexors

FIGURE 3. Strength testing for the ankle evertors

Hip abductor and adductor muscle strength were assessed using methods similar to those described by Ireland et al.[30] and Jaramillo et al.[31] (Figure 4 and 5).

FIGURE 4. Strength testing for the hip abductors

FIGURE 5. Strength testing for the hip adductors

All participants performed three trials bilaterally with 30s of rest between each trial and the peak force in Newtons (N) immediately recorded following each trial. A 60 second rest was taken during the change between testing positions. The peak force (N) of the trials was normalized to body mass (kg). Prior to data collection, a small reliability study of these clinical measures was performed for strength testing measures. Intraclass correlation coefficients (ICC) were established for the hip abductors: = 0.99; 95% CI = 0.89, 0.99; hip adductors ICC = 0.89; 95% CI 0.22, 0.99; ankle evertors ICC = 0.83; 95% CI 0.07, 0.98; ankle dorsiflexors ICC = 0.90; 95% CI 0.04, 0.98.

Active range of motion (AROM) testing Measurement of dorsiflexion (DF) AROM was performed in weight-bearing as outlined by Denegar et al.[11] (Figure 5 and 6). The weight-bearing measurement of dorsiflexion replicates the position the ankle/foot will take during functional testing, to enhance specific comparison.

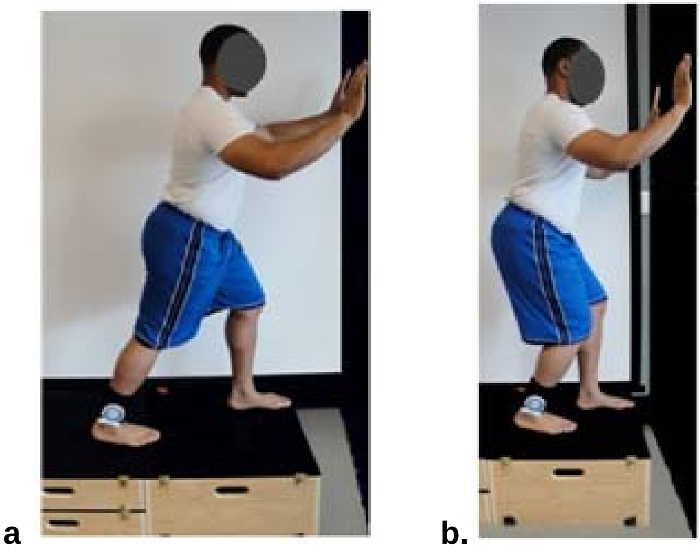

FIGURE 6. Weight bearing ankle dorsiflexion active range of motion with a bubble inclinometer fixed on the distal tibia in the a) knee extended; b) knee flexed.

The measurement of inversion was performed in a non-weight bearing position as described by Menadue et al.[38] (Figure 7).

FIGURE 7. Ankle inversion active range of motion with a standard goniometer.

Dynamic balance / functional performance testing. Balance was assessed with the YEBT (Figure8).[40] The YEBT is a reliable and valid tool for balance assessment in those with and without ankle instability.[21] Participants practiced six trials on each leg in each of the three reach directions prior to formal testing. The participants were barefoot during the test. The participant stood on one foot on the center foot plate with their toes at the starting line. While maintaining single leg stance, the participant was asked to reach with the free limb and to push the red target area on the reach indicator.

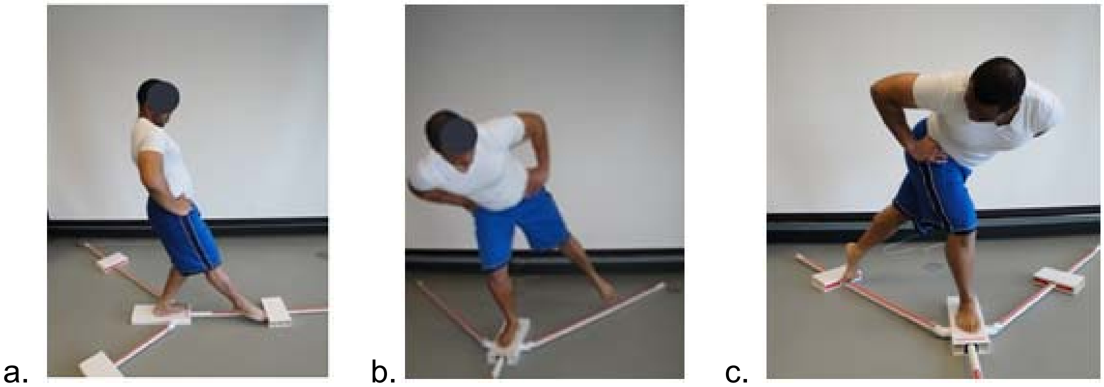

Figure 8. "Y" excursion balance test includes the following reach directions: a) anterior reach; b) posterior medial reach; c) posterior lateral reach

The testing order was three trials on a randomly selected foot reaching in the anterior direction followed by three trials standing on the opposite foot reaching in the anterior direction. This procedure was repeated for the posteromedial and the posterolateral reach directions. All testing was observed and scored by the primary investigator. Loss of balance, touching foot down or movement of stance foot over the line was documented as a missed trial. Reach distances (cm) were recorded and normalized to participant's limb length (cm) and multiplied by 100 to report percentage of limb length (Equation 1).[40]

Equation 1: $\%\ \text{of limb length} = \left[\frac{\text{reach distance (cm)}}{\text{leg length (cm)}}\right] \text{X}\ 100$

Functional performance was examined with the timed side-to-side hop test. Participants were instructed to laterally hop on a single limb over/back across 30cm distance for 10 repetitions as quickly as possible (Figure 9).[7] A repetition was discarded if the participant stepped on the line or touched his/her opposite foot to the ground. Each participant performed 3 trials and time was kept by the primary investigator.

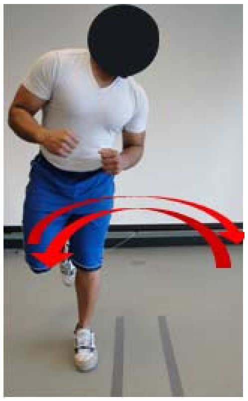

Figure 9. Side to side hop test

Dynamic Postural Stability Index. Initially, participants' maximum vertical jump height was determined over the best of three jumps with the Vertec jump device (Vertec, Sports Imports, Columbus, OH) as described by Wikstrom et al.[48] A target flag set at 50% of each participant's maximal vertical jump height was established for DPSI testing. A successful trial was defined as taking off from both feet 70cm from the center of the force platform, touching the target flag with an outstretched hand, landing on the test leg with the foot entirely on the force platform, stabilizing as quickly as possible and balancing for 3 seconds without moving the foot following the landing.[48] Three practice trials were allowed and 3 successful trials were recorded. The testing procedure was then repeated for the diagonal and lateral jump directions with 3 minute rest in between directions. The number of unsuccessful trials was documented for each jump direction.

As described by Wikstrom et al.[48], unfiltered force plate data were exported as comma delimited (CSV) files. Trials were reduced using a subroutine (Excel 2007, Microsoft Corporation, Redmond, Washington, USA) that calculated unitless scores for the dynamic postural stability index (DPSI) and three directional indices.[51] The anterior/posterior stability index (APSI), medial/lateral stability index (MLSI), and vertical stability index (VSI) correspond about the sagittal, frontal, and transverse axes of the force plate. As illustrated in Equation 2, each index examines the standard deviation of the ground reaction force fluctuations around a zero point, which are then divided by the number of data points in a 3 second trial and normalized to each participant's body mass. Higher scores indicate greater variability or less postural stability.[52] The DPSI and separate indices scores were calculated for each jump landing with the following equations.[51]

Equation 2:

$$\boldsymbol{DPSI} = \sqrt{\frac{\left[\Sigma\left(\frac{0-\mathrm{x}}{\mathrm{BW}}\right)^2+\Sigma\left(\frac{0-\mathrm{y}}{\mathrm{BW}}\right)^2+\Sigma\left(\frac{\mathrm{BW}-\mathrm{z}}{\mathrm{BW}}\right)^2\right]}{\#\text{ of data points}}}$$

- Anterior/posterior stability index (APSI) = $\sqrt{\frac{\left[\Sigma\left(\frac{0-\mathrm{x}}{\mathrm{BW}}\right)^2\right]}{\#\text{ of data points}}}$
- Medial/lateral stability index((MLSI) = $\sqrt{\frac{\left[\Sigma\left(\frac{0-\mathrm{y}}{\mathrm{BW}}\right)^2\right]}{\#\text{ of data points}}}$
- Vertical stability index (VSI) = $\sqrt{\frac{\left[\Sigma\left(\frac{\mathrm{BW}-\mathrm{z}}{\mathrm{BW}}\right)^2\right]}{\#\text{ of data points}}}$

Abbreviations: DPSI, dynamic postural stability index; BW, body weight in Newtons; x, ground reaction force in sagittal plane; y, ground reaction force in frontal plane; z, vertical ground reaction force.

Vertical rate of loading (vROL) was calculated from the vertical ground reaction force impact peak measured from initial contact onto the force plate during the loading phase of the jump landing. The vertical ground reaction force was normalized to body weight (N) and expressed as a multiple of body weight (X BW).[18] The vROL was calculated by taking the derivative of the second impact peak curve expressed in body weights per millisecond (BW/ms).

Equation 3: $$\mathrm{vROL} = \frac{\Delta\,[\mathrm{Fz(N)/BW(N)}]}{\Delta\,\mathrm{Time\ (ms)}}$$

Data Analysis

The unfiltered GRF signal was converted to a digital signal via the Vicon (Vicon Motion Systems, Inc., Lake Forest, CA) analog to digital converter. Descriptive statistics were generated for quantitative variables and frequency and percent scores for the categorical variables. All stability indices were calculated over the initial 3 seconds after landing.

Statistical Analysis

All mean stability metrics and physical and functional outcome measures were entered into a 2 tailed bivariate Pearson correlation matrix to determine association between clinical measures and DPSI. Chi square analysis was utilized to examine group differences for categorical data (i.e. joint stability scores). A paired *t*-test was utilized to examine intra-limb RLAS and control group's CAIT scores. Multivariate analyses of covariance (MANCOVA) tests were employed to control for demographic variables (i.e. gender) when comparing groups for demographic data, CAIT and FADI questionnaires, dorsiflexion AROM, ankle and hip muscle strength measures, timed side to side hop test, YEBT reach distances, DPSI, and vROL scores. All statistics were performed in SPSS statistical software (SPSS, Chicago, IL) with statistical significance defined as $p<0.05$.

RESULTS

Descriptive data

There was a significant difference in the number of women and men between the RLAS and control participants, but no significant differences in age and BMI.

Table 1. Demographic data

Group	n	Gender	Age (years)	BMI ($kg \cdot m^{-2}$)
RLAS	23	18F/5M*	26.8 (4.2)	23.8 (3.6)
Control	14	6F/8M	27.1 (3.5)	25.4 (2.8)

Abbreviations: RLAS, recurrent lateral ankle sprains; F, female; M, male
Age and BMI values are Mean (SD).

* RLAS and Healthy groups significantly different ($p<0.05$).

Questionnaires

CAIT scores demonstrated significant differences between RLAS and control participants (F =116.00, p = 0.0001). The RLAS group's self-reported "most" affected ankle scored lower on the CAIT than did the control participants. Thirteen of the twenty-three total RLAS participants had a history of bilateral ankle sprains; the contralateral ankle mean CAIT score was not significantly (t = -1.23, p = 0.252) different from their self-reported "most" affected ankle.

FADI sports scores demonstrated significant differences between RLAS and control participants (F = 6.945, p = 0.013), with the RLAS group scoring significantly lower (Table 2). The RLAS and control participants demonstrated no significant differences in their self-reported level of weekly physical activity as reported on the IPAQ ($\chi^2 = 0.536$, p = 0.464).

TABLE 2. Questionnaire data

Questionnaire	Group	Mean SD	95% CI
CAIT	RLAS	18.7* (3.3)	17.75, 20.92
	Control	30.0 (0.0)	30.00, 30.00
FADI Sport (%)	RLAS	90.6* (11.6)	83.24, 98.01
	Control	99.7 (0.8)	99.27, 100.27

Abbreviations: CAIT, Cumberland Ankle Instability Tool (unitless score); FADI, Foot and Ankle Disability Index.

CAIT: unitless score of < 27.5 = functional ankle instability; < 21.5 = severe functional ankle instability.[37]

* RLAS and control groups significantly different (p<0.05).

Physical Impairment Analysis

Multivariate analysis of covariance (MANCOVA) revealed no significant differences in AROM (DF AROM with knee extended: F = 0.302, p = 0.586; with knee flexed: F = 0.992; p = 0.326; inversion: F = 0.055; p = 0.948) and strength (dorsiflexors: F = 0.004; p = 0.948; evertors: F = 2.002, p = 0.166; abductors: F = 0.005; p = 0.943; adductors: F = 0.054, p = 0.818) between RLAS and control groups after controlling for gender.

Chi-square analysis demonstrated significant differences in anterior drawer translation ratings ($\chi^2 = 8.07$, p = 0.018) and talar tilt joint stability ($\chi^2 = 12.12$, p = 0.0001) and translation ratings ($\chi^2 = 6.03$, p = 0.049) between RLAS and control participants

(Table 3). Chi-square analyses showed no significant differences in generalized joint laxity between groups ($\chi^2 = 0.382$, $p = 0.826$).

TABLE 3. Joint stability and translation scores

Joint Stability	Condition	RLAS	Control	χ^2	p-values
Anterior Drawer Test	Stable	18	14	3.52	0.061
	Unstable	5	0		
Talar Tilt Test	Stable	10	14	12.12	0.0001
	Unstable	13	0		

Joint Translation	Condition	RLAS	Control	χ^2	p-values
Anterior Drawer Test	Limited	5	1	8.07	0.018
	Normal	7	11		
	Excessive	11	2		
Talar Tilt Test	Limited	3	3	6.03	0.049
	Normal	3	7		
	Excessive	17	6		

Abbreviations: χ^2, chi square.

Functional Impairment Analysis

Y excursion balance testing demonstrated significant decrease in the anterior reach ($F = 11.634$, $p = 0.002$) and composite score ($F = 5.108$, $p = 0.03$) of the YEBT between RLAS and control groups (Table 4). No significant differences were identified for posterior lateral and posterior medial reach distances ($p > 0.05$).

TABLE 4. "Y" excursion balance test data

Reach direction	Group	Mean (SD)	95% CI	p-value
Anterior	RLAS	67.60 (5.30)	63.59, 69.90	0.002
	Control	73.04 (5.23)	69.90, 76.20	
Posterior medial	RLAS	108.68 (8.23)	103.45, 113.91	0.110
	Control	113.79 (10.24)	107.60, 119.97	
Posterior lateral	RLAS	105.02 (9.35)	99.80, 110.97	0.152
	Control	108.71 (7.68)	104.07, 113.35	
Composite	RLAS	92.29 (6.75)	89.37, 95.20	0.030
	Control	98.04 (6.20)	94.46, 101.62	

Abbreviations: RLAS, recurrent lateral ankle sprains; SD, standard deviation; CI, confidence intervals

Means are reported as a percentage of limb length.

Dynamic Postural Stability Index

The analyses of the mean DPSI, MLSI, APSI and VSI scores demonstrated no significant differences between the RLAS and control groups (Table 5). The percentage of missed jump landings between RLAS and control participants was variable across groups and jump directions and is reported in Table 6. The side to side hop test was not significantly different between groups (F =3.310, p = 0.078).

TABLE 5. Dynamic postural stability index scores

Jump Direction	Stability Indices	Group	Mean (SD)	95% CI	p-value
Forward	APSI	RLAS	0.11 (0.01)	0.11, 0.12	0.098
		Control	0.10 (0.01)	0.09, 0.11	
	MLSI	RLAS	0.03 (0.004)	0.27, 0.30	0.432
		Control	0.03 (0.004)	0.31, 0.32	
	VSI	RLAS	0.31 (0.03)	0.29, 0.31	0.498
		Control	0.31 (0.02)	0.32, 0.34	
	DPSI	RLAS	0.33 (0.03)	0.32, 0.34	0.797
		Control	0.33 (0.01)	0.32, 0.34	
Diagonal	APSI	RLAS	0.09 (0.01)	0.09, 0.09	0.583
		Control	0.09 (0.01)	0.08, 0.09	
	MLSI	RLAS	0.07 (0.01)	0.07, 0.07	0.474
		Control	0.07 (0.01)	0.06, 0.07	
	VSI	RLAS	0.30 (0.03)	0.28, 0.31	0.154
		Control	0.31 (0.02)	0.29, 0.32	
	DPSI	RLAS	0.32 (0.03)	0.30, 0.33	0.237
		Control	0.33 (0.02)	0.32, 0.34	
Lateral	APSI	RLAS	0.05 (0.01)	0.05, 0.06	0.766
		Control	0.05 (0.01)	0.05, 0.06	
	MLSI	RLAS	0.09 (0.01)	0.09, 0.10	0.497
		Control	0.09 (0.01)	0.08, 0.10	
	VSI	RLAS	0.30 (0.03)	0.28, 0.31	0.744
		Control	0.30 (0.02)	0.29, 0.31	
	DPSI	RLAS	0.32 (0.03)	0.30, 0.33	0.867
		Control	0.33 (0.02)	0.31, 0.32	

Abbreviations: APSI, anterior/posterior stability index; MLSI, medial lateral stability index; VSI, vertical stability index; DPSI, dynamic postural stability index.

Stability indices are unitless and scores are reported as Mean (SD).

TABLE 6. Missed jump landing trials

Jump Direction	Group	0 to 5 misses	6 to 10 misses	> 10 misses
Forward	RLAS	91.3%	9.7%	0
	Control	100.0%	0	0
Diagonal	RLAS	95.7%	4.3%	0
	Control	85.7%	14.3%	0
Lateral	RLAS	77.3%	18.2%	4.5%
	Control	71.4%	28.6%	0

Abbreviations: RLAS, recurrent lateral ankle sprains

Rate of loading measures demonstrated no significant group differences for the forward (F = 3.302, p = 0.078), diagonal (F = 0.814, p = 0.373) and lateral (F = 3.727, p = 0.062) jump landings (Table 7).

TABLE 7. Vertical rate of loading measures for all jump landing directions.

Jump Landing	Group	Mean(BW/ms)	(SD)	95% CI	p-value
Forward	RLAS	0.39	(0.15)	0.33, 0.45	0.078
	Control	0.31	(0.11)	0.22, 0.38	
Diagonal	RLAS	0.32	(0.09)	0.28, 0.36	0.373
	Control	0.29	(0.11)	0.23, 0.34	
Lateral	RLAS	0.27	(0.08)	0.24, 0.30	0.062
	Control	0.24	(0.07)	0.18, 0.27	

Abbreviations: RLAS, recurrent lateral ankle sprains; SD, standard deviation; CI, confidence intervals

Rate of loading measures are expressed in body weights per millisecond (BW/ms) and reported as Mean (SD).

DPSI and Clinical Outcome Analysis

The combined RLAS and control participants' data demonstrated weak and non-significant correlations between DPSI scores and other variables: ankle AROM, ankle and hip strength; YEBT and side-to-side hop outcome measurements (Table 8).

TABLE 8. Pearson correlation table for AROM, strength, functional and DPSI measures.

AROM	Correlations	FDPSI	DDPSI	LDPSI
Ankle AROM w/ Knee Extended	r =	-.186	-.074	-.005
	p-value =	.269	.662	.975
Ankle AROM w/ Knee Flexed	r =	-.182	-.128	-.047
	p-value =	.282	.449	.784
Ankle AROM Inversion	r =	-.050	.002	-.176
	p-value =	.769	.990	.305
Strength	Correlations	FDPSI	DDPSI	LDPSI
Ankle Dorsiflexor Strength Test	r =	.020	-.101	-.067
	p-value =	.905	.553	.698
Ankle Evertor Strength Test	r =	-.045	.148	-.104
	p-value =	.793	.382	.546
Hip Abductor Strength Test	r =	-.032	.096	.078
	p-value =	.849	.573	.652
Hip Adductor Strength Test	r =	.013	-.048	-.023
	p-value =	.939	.780	.896
Function	Correlations	FDPSI	DDPSI	LDPSI
Y Excursion Balance Test - Anterior reach	r =	.186	.194	-.053
	p-value =	.272	.250	.761
Y Excursion Balance Test - Posterior Medial reach	r =	.341†	.208	.066
	p-value =	.039	.217	.700
Y Excursion Balance Test - Posterior Lateral reach	r =	.289	.126	.006
	p-value =	.082	.458	.972
Y Excursion Composite Score	r =	.325‡	.200	.019
	p-value =	.049	.236	.914
Side to Side Hop Test	r =	-.064	-.142	-.075
	p-value =	.714	.416	.674

† The scatter-plot for posterior medial reach and FDPSI scores is not normally distributed.

‡ The scatter-plot for composite and FDPSI scores is not normally distributed.

DISCUSSION

The initial hypothesis, which asserts possible significant relationships between physical and functional impairment measures and DPSI scores, was not supported by the results of this study. The secondary hypothesis was partially supported; RLAS participants were significantly different from control participants with deficits in functional reach with the YEBT, as well as ligament stability and joint translation. Furthermore, differences in self-reported functional ankle instability and disability were observed between RLAS and control participants. However, our hypotheses of between group differences were not supported for ankle evertor and hip abductor muscle strength, dorsiflexion range of motion, and functional deficits in side-to-side hop performance and dynamic postural stability.

Group Differences

Dynamic Postural Stability Index. Previous research has reported that individuals with RLAS demonstrate decreased postural stability compared to control groups, as demonstrated by longer time to stability and greater stability index scores with forward jump landings.[5,45,46,48,50,52] Contrary to this evidence, we did not find group differences in directional indices and DPSI scores for the forward jump direction. The current results do not support previous literature [5,52] that reported APSI scores are consistently higher in individuals with recurrent lateral ankle sprains. Furthermore, control and RLAS participants did not differ in MLSI and VSI scores which both agree with and contradict previous research.[5,52] The reasons behind these contradictions are most likely multi-factorial in nature, but we highlight three factors that relate to our study sample.

The criteria for entrance into this study as a participant with or without RLAS were consistent with previous research,[45,46,50,52] but our sample was older (average age 27 compared to 22 in other studies), reported high levels of activity, and showed within group differences in dynamic postural control. The self-report measures of functional ankle instability and perceived disability were significantly different between the RLAS and control groups, but the RLAS group DPSI scores did not reflect these differences. Hale and colleagues[17] recommended classifying those with chronic ankle instability based on a self-reported 20 % loss of function during sport-related activities. The mean difference in self-reported loss of function during sport-related activities between RLAS and control participants in the current study was approximately 10%. Therefore, the RLAS participants seem to be functioning at a high level during sport-related activities which may be reflected in the lack of group differences in functional activities.

The RLAS group was heterogeneous, with 12 people showing DPSI scores greater than or equal to 1 SD above the mean of the control group. The mean of the remaining 11 RLAS participants was 2 SDs *below* the mean of the control group, indicating less variability than controls. The DPSI includes sagittal and coronal GRF perturbations about a zero baseline, but the dissipation of vertical GRF's has a significant impact on the overall DPSI score. Although trends in levels of significance for vROL were observed, a lack of significant group mean differences in vROL lends support to the hypothesis of group heterogeneity. This group may have learned to compensate for ankle instability to minimize its restriction on functional and athletic activities. A sub-group analysis is beyond the scope of this current study, but it could provide further insight into explaining the lack of overall differences between control and RLAS groups as well as differences among the RLAS participants.

Finally, this study may have been underpowered to examine group differences in stability indices and DPSI scores between participants with and without RLAS. A study comparing controls to a chronic ankle instability group indicated a power of 0.80 could be accomplished with groups of 8-10 for DPSI scores with forward jump landings[50], but a similar study indicated a sample size of 26 per group was necessary for power of 0.80 with the APSI, VSI and DPSI outcome scores.[52] The current study seemed to have sufficient power for the overall DPSI outcomes, but the study was possibly underpowered for the individual stability indices scores.

Y Excursion Balance Test. This study supports previous findings identifying anterior reach differences with the Star Excursion Balance Test (SEBT) between participants with and without chronic ankle instability. The current study utilized the YEBT, a modified version of the SEBT, to examine dynamic balance. Similar to Gribble et al.[16], the RLAS participants showed a significant decrease in reach distances in the anterior reach direction as compared to the control group.

Interestingly, the group differences in anterior reach scores may highlight a variation in movement patterns between these three reach directions. According to Robinson and Gribble[43] the lower extremity movement patterns of the individual reach directions are quite different. In their examination of lower extremity kinematics of twenty subjects, the hip and knee movement explained about 78% of the variance in the maximum anterior reach distance, but less so to the posterior medial and posterior lateral reach movements. Knee flexion during the anterior reach movement relies on multiple factors: 1) adequate range of motion at the ankle enabling tibial advancement; 2) adequate strength of the quadriceps and gastroc-soleus musculature to control the knee and ankle joints. Weight-bearing DF AROM was similar between groups in the current study, but strength of muscles that control sagittal plane movement of the knee and ankle joints (i.e. quadriceps, gastroc-soleus) was not examined. It is possible that the RLAS participants did not have adequate quadriceps and/or gastroc-soleus strength to lower their center of mass and displace it forward in the sagittal plane, therefore limiting the amount of knee joint excursion and thus reach of the free limb.

The lack of reach differences in the posterior medial and posterior lateral directions between the RLAS and control groups may be explained by the similarities in hip strength. In an examination of the kinematic factors associated with performance of the SEBT, Robinson and Gribble[43] reported that hip motion contributed the greatest percentage of movement to accomplish a maximal reach in the posterior-medial and posterior lateral directions. Their stepwise regression analysis revealed that hip flexion range of motion accounted for 88.6% of the variance in posterior-medial reach and 94.5% of the variance in the posterior lateral reach distances. In the current study, it is possible that the RLAS and control participants achieved similar joint excursions at the hip; because they have similar hip muscle strength in the groups assessed.

Ankle joint mobility/stability. Talar tilt and anterior drawer examinations demonstrated significant differences in joint stability and translation ratings between RLAS and control participants (Table 3). These findings support previous investigators who utilized arthrometry to identify increased ankle joint laxity in patients with chronic ankle instability relative to uninjured controls.[29] The talar tilt test identified significant differences in stability of the calcaneal fibular ligament and excessive translation in the coronal plane. These findings indicate that the RLAS group has underlying coronal plane mechanical instability of the ankle joint.

In contrast, the anterior drawer test identified a stable ligament end feel, but excessive translation in the sagittal plane. This contradiction may be explained by the contribution of the deltoid ligament to stabilize this motion. The anterior drawer test is designed to examine the anterior talo-fibular ligament which restrains anterior glide of the talus on the tibia, but the anterior portion of the deltoid ligament also restrains this motion. Therefore, isolating the stability of the talo-fibular ligament may be difficult and contributions of the deltoid ligament could be a confounding factor in determining the results and reliability of this test.

Strength. The current investigation did not identify group mean differences in isometric strength measures of hip and ankle musculature. Unfortunately, only a few studies have examined isometric strength of hip and ankle musculature in participants with recurrent ankle sprains. In 2006, Freil et al.[13] identified isometric strength differences of the hip abductor musculature between subjects with and without unilateral chronic ankle instability. The discrepancy between our results and Freil et al.[13] may be explained by a difference in testing methods. These investigators utilized ‘break’ testing in a supine position for hip abduction and they did not normalize their results to body weight. Break testing of hip abductor muscles was previously reported in the literature to be more reliable (ICC = .91) than ‘make’ testing due to inconsistent stabilization force from the examiner, but a previous reliability study by the current investigator demonstrated improved reliability (ICC = .99) of ‘make’ testing with the use of foam wedges and webbing as previously described in the methods section.

Similar to previous studies, we identified no significant group mean differences in ankle evertor and dorsiflexor isometric strength between participants with and without recurrent lateral ankle sprains. In contrast to hand held dynamometry (HHD) testing of the hip musculature, the methodological differences in patient positioning and HHD stability during ankle testing may not have influenced the outcomes, because the dorsiflexor and evertor muscle groups develop significantly less torque than the hip musculature.

Active range of motion. Our findings support Denegar et al.[11] that also found no significant between-group differences in weight bearing measures of dorsiflexion ROM, but contradict Hoch and colleagues[26] who identified significant differences in measuring the maximal advancement of the tibia over the foot in a weight-bearing position in participants with and without chronic ankle instability. Our method replicated that of Denegar et al.[11], utilizing a bubble goniometer to measure degrees of tibial advancement over the foot. Hoch and colleagues[26] examined dorsiflexion range of motion by measuring the distance (cm) the tibia advances over the foot. The cohorts are similar, but methodological differences exist between these two measures of dorsiflexion range of motion and may help explain the discrepancy between outcomes.

Relationships between DPSI and Clinical Outcomes. Previous research has identified associations between measures of postural control and self-report measures of disability, and between postural control and clinical impairments in participants with chronic ankle instability.[29] Hubbard et al.[29] identified moderate and significant relationships between quiet standing COP measures and isometric strength of the hip abductor musculature. They also identified moderate and significant relationships between the posterior medial and posterior lateral reach distances of the SEBT and isometric strength of the hip abductor and extensor musculature. Unlike Hubbard et al.,[29] we found no significant relationships between isometric strength of the hip abductor musculature and dynamic postural stability in the combined groups of RLAS and control participants.

The SEBT is a "self directed" dynamic activity wherein the line of gravity is moved at a velocity controlled by the participant and the base of support remains unaltered. The participant may utilize the traditional "fixed support" [42] responses, which include ankle and hip balance strategies to regain balance and maintain postural control during the different reach directions. The demands on the hip and ankle musculature during this activity may be more similar to the demands placed on the musculature by an isometric test than the demands needed during the methods we used. In contrast to the SEBT measures, the DPSI utilizes a dynamic dual-task activity which places a significantly larger demand on the neuromuscular system to control posture quickly after a jump landing. The "fixed support" responses are active during the "stance" phase after the jump landing, but the "landing" phase has a significant influence on the DPSI score. Isometric strength testing only examines one component of muscle performance at a specific position in space that typically optimizes static muscle testing in contrast to the eccentric loading demands of the hip and ankle musculature during the jump landing task. Similarly to the current study, Hubbard et al.[29] found no significant correlations between dynamic strength measures (i.e. measures of power and torque with isokinetic testing) of the ankle musculature (i.e. plantar flexors, invertors, evertors and dorsiflexors) and COP or SEBT metrics. The principle of specificity seems to apply; researchers and clinicians should consider the demands placed on the neuromusculoskeletal system during the functional activity under question when specifying how to test strength. We encourage clinicians to utilize isometric strength testing when the action of the muscle group in question is as a primary stabilizer during the functional activity, and various modes (i.e. high repetitions for endurance) of isotonic testing to examine muscles groups under dynamic conditions.

Clinical Implications / Future Research

The current findings indicate that the pathoetiology of RLAS is quite complex and patients with a history of RLAS may fall anywhere along a continuum of disability. A sub-group of RLAS participants was identified whose perception of their ankle instability was quite different than their functional performance. This sub-group may be characterized as still exhibiting local impairments in functional stability at the ankle, but we hypothesize that either this sub-group has never exhibited dynamic postural control deficits in the past or may have developed coping mechanisms to maintain postural stability during dynamic activities. A study examining dynamic movement may provide further insight into this group of individuals who have adapted their postural control strategies to meet the demands of local impairments in ankle stability. Individual clinical examination procedures may have limited clinical utility in predicting outcomes on the DPSI test, but a combination of physical and functional impairments may provide further insight into dynamic postural control. Further research examining how proposed mechanisms behind RLAS interact (e.g. neuromuscular activation and postural control) with each other may be critical to further understanding the complexity of this pathoetiology.

Limitations

There are a number of limitations to this investigation, which include retrospective collection of lower extremity injury history, physical activity level and medical history. The primary investigator was not blinded to the participant's previous ankle injury history during the joint stability testing; tests with the greatest potential for bias include the anterior drawer and talar tilt tests. The physical impairment assessments were designed to minimize error and improve reliability, but the specific AROM and strength tests selected for this study have inherent limitations. The examiner relies on the participant to maximally push into ankle dorsiflexion in standing and exert force against the HHD during strength testing. The examiner did provide encouragement, but had no guarantee that each participant exerted 100% effort during these tests. Finally, the design of this study cannot conclusively determine if the noted differences occurred before or after injury.

Conclusion

The current results provide new information about the local and regional impact of RLAS. The lack of group differences in DPSI scores and clinical measures may reveal the complex nature of the pathoetiology of RLAS. The self-report measures of functional ankle instability and perceived disability were significantly different between the RLAS and control groups, but the RLAS group DPSI scores did not reflect these differences. Examination of subgroups of patients with distinctly lower stability may help to differentiate clinically useful measures. Although the current study was unable to identify significant relationships between clinical measures and DPSI scores, the results highlight the problems inherent in associating isolated impairments with complex functional movements.

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Chapter 3

Effects of recurrent lateral ankle sprains and dynamic postural instability on the biomechanics of the jump landing

BACKGROUND

Ankle injuries are some of the most common injuries in the general population with an estimated injury rate of 1 in 10,000 [30], and an estimated annual cost of 1 billion dollars.[31] Lateral ankle sprains, the most common of the ankle injuries, recur at a rate as high as 80% among athletes; 40% of those with ankle sprains experience subsequent ankle instability and disability.[11,12] Recent research has identified alterations in dynamic postural stability in this population, but questions remain about the concurrent biomechanical changes (i.e. joint angles) that uniquely contribute to both ankle joint instability and postural instability in people with recurrent lateral ankle sprains (RLAS). Developing a better understanding of local and regional biomechanical adaptations for those with RLAS and postural instability (RLAS-PI) may help to prevent recurrence in this population.

The lateral ankle sprain occurs from a hyper-inversion injury which compromises the lateral ligament structures of the talo-crural and subtalar joints and can lead to alterations in ankle joint kinematics.[12] Altered ankle joint biomechanics in participants with RLAS can lead to changes in normal loading of the ankle during functional activities.[2,4,5,24] Monaghan et al.[24] reported that participants' functionally unstable ankles were significantly more inverted pre-heel strike through the initial phase of loading during gait. The participants with functional ankle instability demonstrated significant increase in rate of inversion within the same time period. These changes in joint position during loading were also reflected in significant differences in coronal plane joint moments at the ankle. The participants with unstable ankles exhibited an evertor moment throughout stance phase while control participants developed an invertor moment over the same time period. Delahunt et al.[5] reported similar kinematic findings during gait with increased ankle inversion at pre- and post-heel strike (effect sizes ranging from .55 to .77) but no differences at the knee or hip. Initial stance phase of normal gait begins with loading of the ankle/foot in a neutral sagittal and coronal plane position, but subjects with ankle instability load their ankle/foot in an inverted position; this may lead to a latent unlocking of the subtalar and mid-tarsal joints which is essential for appropriate accommodation of ground reaction forces. Furthermore, the inverted posture of the ankle is thought to be due to the disruption of the sensorimotor system.[5,12] Deficits in the sensorimotor system could result in deficits in detecting an inverted ankle/foot position and delays in motor response of the fibularis muscles before heel strike.[21] Such evidence supports local ankle biomechanical and sensorimotor changes with RLAS during gait, but further insight into the biomechanics of the knee, hip and trunk during dynamic activities (i.e. jump landings, running, cutting activities) may help increase our understanding of the mechanisms of re-injury.

In previous literature using dynamic activities, Caulfield and Garrett[4] studied drop jump forces, and demonstrated that subjects with RLAS had increased magnitudes of time-averaged forces post-initial contact compared to a control group. Later studies by the same group documented both kinematic and kinetic data during drop jumps in individuals with RLAS as compared to control participants.[2,4,24] Individuals with RLAS had both an increase in time-averaged vertical and medial ground reaction forces post-initial contact with drop jumps. Analyses in these studies did not include examination of joint moments.

Brown et al.[2] published a comprehensive examination of lower extremity biomechanics during functional and sport-specific activities in individuals with ankle instability. They tested three groups: the “coper” group had a prior history of ankle injury but no history of mechanical instability (MI) or functional ankle instability (FI) as determined by manual ligament assessment or a history of “giving way”, respectively; the other two groups were designated as MI or FI only. The results of this study support previous findings that the FI group demonstrated greater coronal plane ankle excursion during walking, but the MI group demonstrated less ankle sagittal plane excursion than the coper group during the step down tasks. The running, drop jump and jump stop tasks showed significant group differences in increased ankle coronal plane excursion and time to peak vertical GRF during the drop jump task; and decreased sagittal plane angle at initial contact and excursion during running and jump stop tasks. Brown and colleagues[2] also examined knee kinematics with these dynamic tasks, but reported no significant differences in sagittal or coronal plane knee kinematics. In this study, running, drop jump and jump stop tasks were meant to challenge local ankle stability, but all of these tasks were primarily oriented in the sagittal plane.

In 2009, Gribble and Robinson[8] were the first to combine the examination of kinematics of the ankle, knee and hip joints during a jump landing task and a dynamic postural control test in participants with and without chronic ankle instability. They utilized the ‘time to stability’ dynamic postural control test which examines how quickly a subject returns to a pre-established baseline balance point in the sagittal and frontal planes after performing a single leg jump landing onto a force plate. Their results indicated that participants with chronic ankle instability demonstrated a significant decrease in dynamic postural stability in the sagittal plane as well as reduced knee flexion angle at impact, but no significant differences in ankle or hip flexion during the same time period. They posited that reduced knee flexion angle would have prevented the center of mass (COM) from lowering at impact, therefore contributing to greater time to stability in the sagittal plane. The authors reported group differences in reduced knee flexion angle and proposed that the compensatory landing strategy is programmed by the central nervous system, because they saw no side to side differences in knee position of participants with chronic ankle instability.

In 2012, Brown et al.[1] followed up with another study examining 4 groups: mechanically unstable, functionally unstable, copers, and controls based on ankle injury history, episodes of giving way, and joint laxity. The participants were required to jump and touch a marker set at 50% of their maximum vertical jump height and land on a force plate. The authors employed multi-directional jump landing tasks and collected lower extremity and trunk kinematics and ground reaction force data. They averaged 10 trials in each jump direction and coefficients of variation were identified for ankle, knee, hip, and trunk motion in 3 planes. The coefficients of variation make it difficult to compare with previous studies, but the authors report that individuals with ankle instability demonstrated less variability at the hip ($p<0.008$) and knee ($p<0.008$) compared to controls during single leg jump landings. Brown and colleagues[1] report that a previous ankle injury was a possible constraint on the movement system and subjects with ankle instability demonstrated less variability at the knee and hip. The authors postulated that a decrease in variability at the knee and hip would indicate central motor programming differences that decrease landing efficiency in the subjects with ankle instability.

Growing evidence shows local and regional changes in joint biomechanics in participants with ankle instability, but the cause of the alterations in movement patterns of these proximal joints is unclear. Adaptations in proximal joint kinematics might be explained by centrally mediated changes in motor programming and/or adaptations in postural control. Investigating the relationships between these factors is not the focus of this study. Rather, identifying significant variations in the biomechanics of postural control strategies will add to the growing evidence of local biomechanical changes at the ankle and proximal movement adaptations at the knee, hip and trunk in participants with and without RLAS-PI. We suspect the RLAS-PI participants will show changes in joint position and internal forces generated at the ankle, knee, hip and trunk to successfully complete a jump landing.

The purpose of this study is to investigate whether women and men with RLAS and postural instability (RLAS-PI) are more likely to have concurrent evidence of abnormal joint biomechanics of the ankle, knee, hip and trunk as compared to participants without RLAS-PI. We hypothesize that during the landing phase of jumping landing maneuvers, participants with RLAS-PI will have a significant increase in ankle and knee coronal plane peak external joint moments and joint angles that may be the predisposing factors for re-injury. Furthermore, we hypothesize that RLAS-PI participants will demonstrate a significant decrease in ankle and knee joint angles in the sagittal plane which will demonstrate a shift to more proximal compensatory strategies at the hip and trunk.

METHODOLOGY

Participants

Twenty one women and men, 18-35 years old, with and without a history of RLAS-PI were recruited through a previous study (Table 1.). Participants with RLAS-PI were eligible if they had a history of “giving way” or RLAS during a functional or sporting activity; past history of a lateral ankle sprain which required a period of protective weight bearing and/or immobilization for greater than or equal to 3 days; and at least one recurrent lateral ankle sprain 6 to 18 months before study participation. Control and RLAS-PI participants were required to be performing at least 1.5 hours of cardiovascular, resistance, sport-related, or other physical activity per week without a level of pain that inhibited full participation. All 14 control participants from the previous study were invited to participate in Study 2. RLAS-PI participants from the previous study were also invited to participate if they had forward jump landing Dynamic Postural Stability Index (DPSI) scores of greater than or equal to 1.0 standard deviation above the mean DPSI scores of the control group in the previous study.

RLAS-PI and control participants were excluded if they had a recent ankle injury (in the previous 12 weeks) that required a period of crutch use and/or visiting a health care provider who provided treatment (i.e. assistive device, ankle orthosis, physical therapy); history of a lower extremity fracture requiring medical intervention, immobilization and non-weight bearing; previous knee, hip or lumbar spine injury that required medical intervention (i.e. prescribed medication), period of non-weight bearing and/or loss of time in their sport/work; current inner ear or sinus infection.

Instrumentation

Lower extremity kinetics were measured with a force platform (AMTI measurement group, Watertown, MA). The analog signal from the force platform was sampled at a frequency of 1000 Hz converted to a digital signal via Vicon (Vicon Motion Systems, Inc., Lake Forest, CA). Upper and lower extremity kinematics were assessed by a combination of 10 marker clusters (3 to 4 reflective markers attached to a hard molded plastic shell) as well as placing 39 individual 14mm reflective markers on the following anatomical landmarks: 1st and 5th metatarsal heads, medial and lateral malleoli, medial and lateral femoral condyles, greater trochanters, iliac crests, anterior superior iliac spines, sacrum, sternum, 4 head markers (anterior, posterior, medial and lateral), acromions, 3 glenohumeral joint markers (anterior, posterior, and lateral), medial and lateral elbow and wrist, and 3rd metacarpal of each hand. The anatomical markers were attached to the skin with double-sided adhesive electrode collars and the marker cluster plates were attached to flexible Velcro-secured wraps on the upper arm, forearm, thigh, and shank and to the rearfoot of participant’s athletic shoe with duct tape. These reflective markers were identified by an infrared 10 camera motion-analysis system (VICON Motion Systems, Inc., Lake Forest, CA) at a sampling rate of 250 Hz.

Procedures

All motion-analysis took place at the University of California San Francisco Human Performance Center. Practice trials were performed for each task until the participant self-reported comfort with the task. A target flag set at 50% of each participant's maximal vertical jump height was established before testing. A successful trial was defined as taking off from both feet 70cm from the center of the force platform, touching the target flag with an outstretched hand, landing on the test leg with the foot entirely on the force platform, stabilizing as quickly as possible and balancing for 3 seconds without moving the foot following the landing.[33,34,35] Three practice trials were allowed and 3 successful trials were recorded. The testing procedure was then repeated for the diagonal and lateral jump directions with a 3 minute rest in between directions. The number of unsuccessful trials was documented for each jump direction. Participants performed three successful jump landing trials in one direction with a 30 second rest between trials. The subjects then took a 60 second break before moving onto the next jump direction. Missed trials, defined as taking a step, hopping or touching their opposite foot to the ground were recorded for analysis. Kinematics and kinetics were assessed during the jump landing maneuver. Ground reaction forces were measured during each maneuver and used to predict moments (torques) at the ankle, knee and hip joints. The motion-analysis system tracked the position of the reflective markers and provided information pertaining to 3D segment angular displacement. Data acquisition and analysis were performed by one researcher to reduce measurement error introduced by multiple researchers.

Clinical Impairment Measures

Questionnaires. All participants previously completed the Cumberland Ankle Instability Tool (CAIT) in Study 1.[13] The CAIT is a self-report measure with 9-items in a 30-point scale for measuring perceived severity of functional ankle instability. We hypothesized that the RLAS-PI participants would self-report significant functional ankle instability as compared to the control group. The control and RLAS-PI participants also previously completed the Functional Ankle Disability Index (FADI) Sports subscale.[9] We suspected that the RLAS-PI participants would self-report significant difficulty with tasks that are essential to sport. The FADI Sport subscale is scored as a percentage, with 100% representing no disability.[9]

Joint stability and mobility testing. Measurements of the ankle joint stability and mobility were examined with the participants lying supine with the feet hanging off the end of the plinth.[28] The ankle joint was examined for joint translation as well as stability with the anterior drawer and talar tilt tests as described in the literature.[28] The translation classification describes the amount of motion that is felt by the examiner with each maneuver, whereas the stability classification defines the "end-point" of the motion. The translation of the ankle joint (ankle joint mobility) was documented and coded as having: excessive translation (score = 3), having normal translation (score = 2) or reduced translation (score = 1). Ankle joint stability was determined by the feel at the end of the translational movement. A 'firm' end feel was documented as stable (score =1) or a 'soft' end feel was determined to be unstable (score =0).

Active range of motion (AROM) measures. Measurement of dorsiflexion (DF) AROM was performed in weight-bearing as outlined by Denegar et al.[6] The weight-bearing measurement of dorsiflexion replicates the position the ankle/foot will take during the jump landing and will enhance specific comparison.

Data Analysis

Reflective markers were identified manually within the VICON Nexus software. Visual 3D software (C-Motion, Rockville, MD) was used to quantify kinematics using standard anatomical conventions (i.e. relative motion between the pelvis and thigh segments).[32] Ground reaction forces were synchronized with marker coordinate data and imported into Visual 3D for kinetic and kinematic analysis. Net joint internal moments of the ankle, knee and hip were calculated using standard inverse dynamics equations.[7] A low-pass 4th-order, non-recursive Butterworth filter (cut-off frequency of 12 Hz) was applied to kinematic data. Kinematic variables of interest consisted of peak and joint excursion of ankle dorsiflexion, plantarflexion, inversion and eversion; knee and hip abduction, adduction, flexion, extension; pelvis and trunk flexion, extension and lateral flexion during the landing phase of the jump landing tasks. Kinetic variables of interest included vertical rate of loading, sagittal and frontal plane net joint external moments of the ankle, knee and hip. The landing phase was defined as initial contact (>25N) to 1000ms after the landing.

Vertical rate of loading (vROL) was calculated from the vertical ground reaction force impact peak measured from initial contact onto the force plate during the loading phase of the jump landing. The vertical ground reaction force was normalized to body weight (N) and expressed as a multiple of body weight (BW).[10] Vertical ROL was calculated by taking the derivative of the second impact peak curve expressed in body weights per millisecond (BW/ms).

Statistical Analysis

Means and standard deviations were generated for all quantitative variables. Independent t-tests compared the mean differences between groups for age, BMI, questionnaires, AROM measures, kinematic and kinetic measures. Levene's test for homogeneity was utilized to examine the variance of all quantitative measures. Chi square analysis was utilized to examine group differences in joint stability, joint translation, and the number of men and women. All statistical analyses were performed using SPSS statistical software (SPSS, Chicago, IL), with a significance level set at $p<0.05$.

RESULTS

Descriptive Data

There were no significant group differences in gender, age, BMI and amount of physical activity between the RLAS-PI and control participants (Table 9).

TABLE 9. Demographic data for the RLAS-PI and control participants.

Group	n	Gender	Age in years	Age range	BMI $kg{\cdot}m^{-2}$
RLAS-PI	9	4F/5M	28.1 (4.1)	22 - 33	24.8 (3.1)
Control	12	6F/6M	27.1 (3.4)	23 - 32	25.1 (2.9)

Abbreviations: RLAS-PI, recurrent lateral ankle sprains and postural instability ; yrs; years, BMI; body mass index; F, female; M, male.

Age and BMI values are Mean (SD).

Clinical Impairment Measures

Questionnaires. The analysis of the mean Cumberland Ankle Instability Tool (CAIT) scores demonstrated significant group differences between RLAS-PI and control participants (t =-14.629, p = 0.0001). The RLAS-PI group's self-reported "most" affected ankle scored lower on the CAIT as compared to the control participants. Regarding self-reported disability, the mean Foot Ankle Disability Index Sport (FADI Sport) scores demonstrated significant differences between RLAS-PI and control participants (t = -6.118, p = 0.0001), with the RLAS-PI group scoring significantly lower (Table 10).

TABLE 10. Questionnaire data

Questionnaire	Group	Mean SD	95% CI	p-values
CAIT	RLAS-PI	20.2 (2.1)	17.00, 23.00	0.0001
	Control	29.6 (0.8)	28.00, 30.00	
FADI Sport (%)	RLAS-PI	92.4 (3.5)	90.63, 100.00	0.0001
	Control	99.7 (0.9)	96.88, 100.00	

Abbreviations: CAIT, Cumberland Ankle Instability Tool (unitless score); FADI, Foot and Ankle Disability Index; RLAS-PI, recurrent lateral ankle sprains and postural instability; SD, standard deviation.

CAIT: score of < 27.5 = functional ankle instability; < 21.5 = severe functional ankle instability.[12]

Joint Stability and AROM Measures. Chi-square analysis demonstrated significant differences in talar tilt joint stability ($\chi^2 = 4.667$, $p = 0.031$), but no significant differences in anterior drawer stability ($\chi^2 = 1.40$, $p = 0.237$) between RLAS-PI and control groups. RLAS-PI and control participants demonstrated no significant group differences in anterior drawer ($\chi^2 = 5.763$, $p = 0.056$) and talar tilt ($\chi^2 = 2.625$, $p = 0.269$) joint translation ratings. Student's t-test revealed no significant differences in DF AROM with knee extended ($t = -1.846$, $p = 0.081$) and knee flexed positions ($t = -1.833$, $p = 0.083$) between RLAS-PI and control groups.

Biomechanical Analyses

Ankle. The analyses of ankle joint angular data (Table 11) demonstrated significant decreases in mean peak joint plantarflexion and sagittal plane ankle joint excursion values between RLAS-PI and control groups ($p < 0.05$). Further analyses of sagittal and coronal plane ankle joint peak moments and sagittal plane ankle joint powers demonstrated no significant differences between groups ($p > 0.05$).

TABLE 11. Sagittal plane ankle kinematic data

Jump	Angle	Group	Mean (SD)	95% CI	p-value
Forward	Peak PF(°)	RLAS-PI	-26.87 (5.03)	-30.74, -23.00	0.023
		Control	-31.90 (4.29)	-34.63, -29.17	
	Peak DF (°)	RLAS-PI	18.30 (5.64)	13.97, 22.64	0.593
		Control	19.45 (4.02)	16.89, 22.01	
	Excursion (°)	RLAS-PI	*45.17 (7.09)	39.73, 50.62	0.034
	0-100% LP	Control	51.35 (5.29)	47.99, 54.71	
Diagonal	Peak PF (°)	RLAS-PI	-26.72 (4.39)	-30.10, -23.35	0.024
		Control	-33.98 (3.59)	-33.26, -28.70	
	Peak DF (°)	RLAS-PI	20.03 (5.11)	16.10, 23.96	0.573
		Control	21.07 (3.18)	19.05, 23.96	
	Excursion(°)	RLAS-PI	46.75 (7.13)	41.27, 52.24	0.004
	0-100% LP	Control	55.31 (4.90)	52.21, 58.42	
Lateral	Peak PF (°)	RLAS-PI	-26.06 (4.39)	-29.43, -22.68	0.013
		Control	-31.14 (4.09)	-33.74, -28.54	
	Peak DF (°)	RLAS-PI	23.11 (3.92)	20.10, 26.12	0.593
		Control	24.15 (3.70)	21.82, 26.49	
	Excursion (°)	RLAS-PI	49.17 (6.23)	44.38, 53.96	0.021
	0-100% LP	Control	55.30 (4.91)	52.21, 58.42	

Abbreviations: RLAS-PI, recurrent lateral ankle sprains and postural instability ; SD, standard deviation; CI, confidence intervals; PF, plantarflexion; DF, dorsiflexion; LP, landing phase; (°), degree.

Knee. The effects of group membership on knee kinematic and kinetic data are presented in Table 12 and 13 respectively. The analyses of the mean peak outcome measures for peak joint angle and peak moment data demonstrated no significant differences between RLAS-PI and control groups (p > 0.05). The knee joint excursion data demonstrated significant decrease joint angle during early to late landing phase between RLAS-PI and control participants (Table 12).

TABLE 12. Knee sagittal plane knee joint excursion data

Jump Landing	Knee	Group	Means (SD)	95% CI	p-value
Forward	Excursion (°)	RLAS-PI	21.18 (4.56)	17.67, 24.69	0.046
	25-100% LP	Control	29.36 (11.9)	21.87, 36.91	
Diagonal	Excursion (°)	RLAS-PI	21.45 (7.08)	16.01, 29.30	0.256
	25-100% LP	Control	26.03 (9.95)	19.70, 32.35	
Lateral	Excursion (°)	RLAS-PI	22.00 (3.77)	19.08, 24.07	0.134
	25-100% LP	Control	26.72 (9.44)	20.72, 32.72	

Abbreviations: RLAS-PI, recurrent lateral ankle sprains and postural instability ; SD, standard deviation; CI, confidence intervals; ES, effect sizes; LP, landing phase; (°), degree

Levene's test indicated that equal variances could not be assumed with knee joint excursion values; therefore we utilized the t-statistic assuming unequal variances. The RLAS-PI group demonstrated increased peak knee power during the forward (p = 0.039) and lateral jump landings (p = 0.026) as compared to the control participants (Table 13).

TABLE 13. Knee sagittal plane kinetic data

Jump Landing	Knee	Group	Means (SD)	95% CI	p-value
Forward	Peak Power (W)	RLAS-PI	-26.05 (7.58)	-20.22, -31.88	0.039
		Control	-20.00 (5.48)	-16.51, -23.48	
Diagonal	Peak Power (W)	RLAS-PI	-23.35 (3.95)	-20.31, -26.39	0.326
		Control	-21.00 (5.67)	-17.39, -24.78	
Lateral	Peak Power (W)	RLAS-PI	-28.86 (6.28)	-24.04, -33.69	0.026
		Control	-21.96 (6.66)	-17.72, -26.19	

Abbreviations: RLAS-PI, recurrent lateral ankle sprains and postural instability ; SD, standard deviation; CI, confidence intervals; ES, effect sizes; LP, landing phase; (°), degree

Hip. Coronal plane peak hip joint angular data demonstrated significant increase in hip abduction between RLAS-PI and control groups for diagonal and lateral jump landings (Table 14). Peak hip joint angular data demonstrated a significant decrease in hip adduction during the diagonal jump landings (Table 14). We identified no significant group differences in sagittal plane hip peak angles for all three jump landing directions.

TABLE 14. Hip coronal plane kinematic data

Jump Landing	Hip	Groups	Means (SD)	95% CI	p-value
Forward	Initial Contact(°)	RLAS-PI	-11.81 (4.81)	-15.51, -8.11	0.776
		Control	-11.31 (3.04)	-13.24, -9.38	
	Peak Adduction	RLAS-PI	6.56 (3.61)	3.81, 9.85	0.767
		Control	7.12 (4.41)	4.32, 9.92	
	Peak Abduction	RLAS-PI	-15.38 (3.61)	-18.16, -12.61	0.193
		Control	-13.34 (3.29)	-15.43, -11.26	
	Peak Abduction 25-100% LP	RLAS-PI	-6.25 (6.84)	-11.78, -1.26	0.286
		Control	-3.56 (5.53)	-7.08, -0.05	
Diagonal	Initial Contact(°)	RLAS-PI	-17.73 (4.89)	-21.49, -14.00	0.489
		Control	-16.60 (2.38)	-18.11, -15.08	
	Peak Adduction	RLAS-PI	1.25 (4.15)	-1.94, 4.43	0.030
		Control	5.37 (3.95)	2.86, 7.89	
	Peak Abduction	RLAS-PI	-18.76 (4.70)	-22.37, -15.15	0.474
		Control	-17.55 (2.90)	-19.39, -15.70	
	Peak Abduction 25-100% LP	RLAS-PI	*-10.79 (5.09)	-14.70, -6.89	0.010
		Control	-4.20 (5.42)	-7.64, -0.75	
Lateral	Initial Contact(°)	RLAS-PI	-19.35 (4.44)	-22.77, -15.94	0.0001
		Control	-11.31 (3.04)	-13.24, -9.38	
	Peak Adduction	RLAS-PI	1.69 (4.11)	-1.46, 4.85	0.167
		Control	4.74 (5.26)	1.40, 8.09	
	Peak Abduction	RLAS-PI	-21.82 (2.17)	-23.49, -20.15	0.0001
		Control	-17.85 (2.11)	-19.18, -16.51	
	Peak Abduction 25-100% LP	RLAS-PI	-12.20 (3.69)	-14.70, -6.89	0.005
		Control	-5.57 (5.87)	-7.64, -0.75	

Abbreviations: RLAS-PI, recurrent lateral ankle sprains and postural instability ; SD, standard deviation; CI, confidence intervals; LP, landing phase; (°), degree

Analyses of hip joint powers indicated that equal variances could not be assumed with sagittal plane hip power values. The p-values were non-significance for peak hip power with forward (p = 0.07), diagonal (p = 0.07) and lateral (p = 0.08) jump landings (Table 15).

TABLE 15. Sagittal plane hip power data

Jump Landing	Hip	Groups	Means (SD)	95% CI	p-value
Forward	Peak Power (W)	RLAS-PI	-16.74 (10.96)	-25.17, -8.31	0.07
		Control	-10.65 (5.29)	-14.01, -7.29	
Diagonal	Peak Power (W)	RLAS-PI	-20.66 (12.43)	-30.21, -11.10	0.07
		Control	-11.49 (5.07)	-14.71, -8.27	
Lateral	Peak Power (W)	RLAS-PI	-19.49 (11.59)	-28.39, -10.58	0.08
		Control	-12.47 (5.34)	-15.86, -9.07	

Abbreviations: RLAS-PI, recurrent lateral ankle sprains and postural instability ; SD, standard deviation; CI, confidence intervals

Pelvis. The analyses demonstrated no significant differences in sagittal plane peak angular values and excursion of the pelvis between RLAS-PI and control groups (p > 0.05). A significant increase in contralateral peak pelvic elevation in the coronal plane was identified during the diagonal and lateral jump landing and a trend was identified during forward landing between RLAS and control participants (Table 16).

TABLE 16. Coronal plane kinematic data of the pelvis

Jump Landing	Pelvis	Group	Means (SD)	95% CI	p-value
Forward	Peak Oblique Angle (°)	RLAS-PI	-15.43 (5.44)	-19.62,-11.25	0.048
		Control	-11.47 (3.12)	-13.45,-9.48	
Diagonal	Peak Oblique Angle (°)	RLAS-PI	-18.56 (5.77)	-22.99,-14.12	0.013
		Control	-12.30 (2.99)	-14.20,-10.40	
Lateral	Peak Oblique Angle (°)	RLAS-PI	-21.82 (2.17)	-23.49, -20.15	0.0001
		Control	-17.85 (2.11)	-19.19, 16.51	

Abbreviations: RLAS-PI, recurrent lateral ankle sprains and postural instability; SD, standard deviation; CI, confidence intervals; (°), degree

A negative oblique angle indicates contralateral pelvic elevation towards the stance limb.

Trunk. A significant decrease in peak trunk extension was identified during the diagonal jump landing between RLAS-PI and control participants (Table 17). There were no significant differences in trunk position between the groups at initial contact (p>0.05). The forward jump landings demonstrated a significant increase in peak trunk flexion, but no significant differences in peak trunk flexion were identified with diagonal and lateral jump landings between RLAS-PI participants as compared to the control group (Table 8). There were no significant differences in sagittal plane trunk kinematics between groups during the lateral jump landings (p>0.05) (Table 17).

TABLE 17. Sagittal plane kinematic data of the trunk.

Jump Landing	Trunk	Group	Means (SD)	95% CI	p-value
Forward	Initial contact (°)	RLAS-PI	3.35 (4.46)	-0.08,6.78	0.438
		Control	4.70 (3.38)	2.55,6.84	
	Peak Flexion	RLAS-PI	-25.60 (15.77)	-37.72,-13.47	0.038
		Control	-10.85 (14.49)	-20.00,-1.70	
	Peak Extension	RLAS-PI	1.91 (4.57)	-1.60,5.42	0.077
		Control	5.38 (3.94)	2.88,7.89	
Diagonal	Initial contact	RLAS-PI	3.55 (3.82)	-5.52, 7.99	0.088
		Control	6.93 (4.56)	-4.08, 11.75	
	Peak Flexion	RLAS-PI	-21.86 (16.01)	-34.16,-9.55	0.098
		Control	-9.41 (16.37)	-19.82,0.98	
	Peak Extension	RLAS-PI	2.62 (4.21)	-0.61,5.86	0.015
		Control	7.61 (4.22)	4.93,10.29	
Lateral	Initial contact	RLAS-PI	6.68 (4.59)	3.15,10.21	0.538
		Control	8.00 (4.90)	4.89,11.12	
	Peak Flexion	RLAS-PI	-13.93 (11.56)	-22.82,-5.04	0.652
		Control	-10.61 (19.27)	-22.85,1.64	
	Peak Extension	RLAS-PI	5.80 (4.93)	2.02,9.59	0.216
		Control	8.53 (4.76)	5.50,11.56	

Abbreviations: RLAS-PI, recurrent lateral ankle sprains and postural instability ; SD, standard deviation; CI, confidence intervals; (°), degree; LP, landing phase

A significant increase in peak lateral flexion of the trunk was identified during diagonal jump landings, but forward and lateral jump landings were non-significant between RLAS-PI and control groups (Table 18). The RLAS-PI group also demonstrated significant increases in trunk excursion in the coronal plane during diagonal and lateral jump landings (Table 9). Peak lateral flexion with lateral jump landings was non-significant (p>0.05).

TABLE 18. Coronal plane kinematic data of the trunk.

Jump Landing	Trunk	Group	Means (SD)	95% CI	p-value
Forward	Initial contact(°)	RLAS-PI	-6.06 (2.45)	-7.94, -4.18	0.556
		Control	-5.13 (4.15)	-7.76, -2.49	
	Peak Lateral Flexion(°)	RLAS-PI	-14.71 (7.46)	-20.45, -8.97	0.296
		Control	-12.04 (3.80)	-14.45, -9.62	
Diagonal	Initial contact (°)	RLAS-PI	-6.13 (2.97)	-8.41, -3.84	0.390
		Control	-4.75 (3.92)	-7.24, -2.26	
	Peak Lateral Flexion(°)	RLAS-PI	-20.04 (9.23)	-27.14,-12.94	0.025
		Control	-11.41 (3.83)	-13.84, -8.97	
	Trunk Excursion(°)	RLAS-PI	16.20 (8.05)	10.02,19.39	0.007
	50-100% LP	Control	6.52 (4.13)	3.90,9.15	
Lateral	Initial contact (°)	RLAS-PI	-5.31 (3.63)	-8.11,-2.52	0.029
		Control	-1.81 (3.15)	-3.81,0.19	
	Peak Lateral Flexion(°)	RLAS-PI	-19.97 (10.48)	-28.03,-11.92	0.053
		Control	-11.75 (5.01)	-14.94,-8.57	
	Trunk Excursion(°)	RLAS-PI	18.13 (9.91)	10.50,25.75	0.023
	50-100% LP	Control	8.50 (5.50)	4.94,12.06	

Abbreviations: RLAS-PI, recurrent lateral ankle sprains and postural instability ; SD, standard deviation; CI, confidence intervals; (°), degree; LP, landing phase

Trunk angles are reported as negative for a lateral flexion over the stance limb.

Vertical Rate of Loading. Significant increases in vROL were identified for the forward (t = 2.313, p = 0.046), and lateral (t = 2.163, p = 0.043) jump landings, but no significant differences with diagonal (t = 1.108, p = 0.282) jump landings between the RLAS-PI and control groups (Table 19).

TABLE 19. Vertical rate of loading outcomes

Jump Landing	Group	Mean(BW/ms)	(SD)	95% CI	p-value
Forward	RLAS-PI	0.48	(0.17)	0.35, 0.60	0.046
	Control	0.34	(0.11)	0.26, 0.41	
Diagonal	RLAS-PI	0.41	(0.09)	0.34, 0.48	0.282
	Control	0.36	(0.13)	0.23, 0.34	
Lateral	RLAS-PI	0.37	(0.09)	0.30, 0.44	0.043
	Control	0.28	(0.11)	0.21, 0.35	

Abbreviations: RLAS-PI, recurrent lateral ankle sprains and postural instability; SD, standard deviation; CI, confidence intervals

Rate of loading measures are expressed in body weights per millisecond (BW/ms) and reported as Mean (SD).

DISCUSSION

Our data confirms that participants with RLAS-PI exhibit different movement patterns at the ankle, knee, hip, pelvis and trunk as compared to the control group during a single limb jump landing task. We observed participants with RLAS-PI limit knee and ankle joint excursion during the jump landing by increasing knee joint power, thereby limiting tibial advancement. Subsequently, the RLAS-PI participant's postural control strategy shifts to more proximal movements at the hip with greater peak hip angles and trends in increased hip power during the diagonal and lateral jump landings. In addition, significantly greater peak trunk flexion, peak lateral flexion and trunk excursion angles were identified during the forward, diagonal and lateral jump landings in the RLAS-PI group as compared to the control subjects. The RLAS-PI participant's distal "stiffening" strategy and predominant use of proximal movement strategies over more distal strategies to regain postural control after the jump landing may also be at a cost to increasing the vertical rate of loading.

Ankle / Knee

The RLAS-PI group demonstrated a decrease in peak plantarflexion at initial contact during the forward, diagonal and lateral jump landings. Additionally, the RLAS-PI group displayed a significant decrease in sagittal plane ankle joint excursion throughout the first second of all three jump landings as compared to the control group. The RLAS-PI participants may have utilized a predictive feedforward motor control strategy to minimize the amount of plantarflexion at initial contact and minimize joint excursion in the sagittal plane. The current findings support a previous report which examined ankle kinematics during drop landings in individuals with ankle instability and found reduced dorsiflexion during the landing phase.[5] The decrease in plantarflexion we observed at initial contact is also consistent with previous studies using drop jump landings in participants with mechanical ankle instability.[2] In 2008, Brown et al.[2] reported significantly less plantarflexion at initial contact in participants with mechanical ankle instability in comparison to “coper” and functionally unstable ankle groups. In contrast, Gribble and Robinson[9] examined the forward jump landing task and were unable to identify significant group differences in sagittal plane ankle kinematics between participants with and without chronic ankle instability (CAI). They delineated the CAI group according to specific inclusion criteria and scores on the disability measure, but it is unknown whether this group also had ligament laxity. We did not measure muscular activation patterns in this study, but hypothesize that the RLAS-PI group may have activated the dorsiflexor musculature through a feedforward strategy.

We label this strategy as “protective” because it would reduce the plantarflexion angle at initial contact and improve joint congruency while minimizing the stress on the lateral ankle ligaments during a vulnerable period at initial contact.

Delahunt et al.[5] examined sagittal plane ankle angles and electromyography of the tibialis anterior muscle during single leg drop jumps in subjects with functional ankle instability. They reported no significant differences in sagittal plane ankle angles at initial contact. Furthermore, Delahunt and colleagues[5] reported no significant differences in activation of the tibialis anterior muscle pre and post initial contact as compared to a control group, but it was unclear if these participants also had mechanical instability. In the future, a concurrent neuromuscular examination of the anterior tibialis musculature and joint biomechanics may provide evidence of a feedforward “protective” strategy in RLAS-PI participants with mechanical instability of the ankle joint.

The ankle joint excursion angles were significantly reduced during the early to late landing phases in the RLAS-PI as compared to the control participants (Table 11). Previous studies have identified limited talocrural joint mobility impairing ankle range of motion in subjects with chronic ankle instability as compared to control groups.[15] Additionally, impairments in ankle dorsiflexion range of motion were implicated in disordered functional performance with walking, running and dynamic balance activities.[15,16] However, weight-bearing dorsiflexion range of motion measures in the knee extended and knee flexed positions identified no significant differences between the RLAS-PI and control groups ($p = 0.326$). Limited ankle joint excursion is most likely not because of local impairments in ankle joint mobility, but possible explanations may include impairments in lower extremity strength, neuromuscular control and/or a feedforward strategy to protect the ankle from reinjury. The quadriceps and gastroc-soleus complex may play a critical role in controlling tibial advancement and subsequently ankle joint excursion during the eccentric phase of this dynamic loading activity. In the future, a more complete examination of this issue will require measures of muscle activation and eccentric strength to lend further insight into the contributions of strength and/or neuromuscular control to reduce ankle joint excursion during the landing phase of a jump.

The knee joint excursion angles were also significantly reduced during the early to late landing phases of the RLAS-PI group as compared to the control participants (Table 12). Unlike previous research[9], which identified limited knee flexion at initial contact during a jump landing in participants with CAI, we identified no significant differences in the knee angle at initial contact and peak knee flexion during the landing phase. Limiting the amount of tibial translation in the sagittal plane is consistent with a feedforward strategy of "stiffening" the ankle and subsequently also the knee joint during the landing phase of a jump. In participants with RLAS-PI, the strategies to execute this skill successfully may be influenced by a desire to protect the ankle joint while also changing kinematics and kinetics at the knee joint. This is demonstrated by reduced group mean differences in joint excursion and increased peak knee power during the forward and lateral jump landings in participants with RLAS-PI. The lack of significant differences in ankle joint power between the groups may indicate that a more proximal dynamic control strategy is being utilized to accomplish the desired "stiffening" strategy at the knee and ankle.

Previous investigations have shown soleus and peroneal muscle inhibition in subjects with RLAS.[23] Furthermore, the soleus muscle and quadriceps muscle motor-neuron pools are reciprocally linked.[17,18,20] For example, with an artificial knee effusion, the soleus is facilitated and the quadriceps is inhibited.[17,18,25] In 2007, Sedory and colleagues[29] examined arthrogenic muscle inhibition of proximal thigh musculature in participants with and without chronic ankle instability. They reported ipsilateral quadriceps facilitation and bilateral hamstring inhibition, but did not verify soleus inhibition. This supports the current findings which indicate that participants with RLAS-PI may control knee joint excursion during the jump landing by increasing knee joint power, thereby limiting tibial movement and “stiffening” the knee.

The aforementioned ‘protective’ strategy may have some unintended consequences. Significant increases in vROL for forward and lateral jump landings were identified in participants with RLAS-PI (Table 19). Limited ankle and knee joint excursion may have prevented the vertical loading to be appropriately distributed throughout the lower extremity.

Hip/Pelvis/Trunk

Similar to Gribble and Robinson[9], we identified no significant differences in sagittal plane hip kinematics during the jump landings, but significant differences in the coronal plane peak hip joint angular data were identified between RLAS-PI and control groups. The RLAS-PI participants were in greater hip abduction throughout most of the landing phase during the diagonal and lateral jump landing. Specifically, the RLAS-PI participants were in greater hip abduction at initial contact during the lateral jump landing. This strategy may allow the RLAS-PI participants more time to control the COM as it approaches the limits of stability (e.g. lateral border of the foot). In contrast to quiet standing, the single jump landing activity causes a significant increase in velocity and excursion of the COM which may overwhelm the small plantar surface area of the foot and torque generated by ankle musculature to regain balance. The head, arms and trunk together create a moment of inertia about the hip joint that is about 1/8th that of the ankle joint, therefore about 8x the moment of force is required of the ankle musculature as compared to the hip musculature to control the head, arms and trunk in a typical adult.[36] In situations where the COM is rapidly approaching the limits of the base of support the hip musculature can generate greater than 100 Nm of torque to assist in quickly moving the COM to regain balance.[36]

The current study noted trends in greater sagittal plane external peak hip moments and peak hip power during the landing phase of forward, diagonal and lateral jump landings. The combination of load accommodation and trunk excursion may explain the trend in group differences in external peak hip flexion moments during the loading phases of forward and lateral jumps. The trend in a larger external peak hip extension moment during a later period of the landing phase may indicate that RLAS-PI participant's lack precision in controlling backward displacement of the trunk. The RLAS-PI participants may have "over-corrected" and needed to control the COM now moving in the posterior direction by increasing a flexor torque about the hip. The lack of precision may be further illustrated by examination of the hip moment curves and supported statistically by Levene's test that demonstrates a significant amount of variability. The variability in flexion and extension moments may be driven in part by predominant use of hip musculature over more distal musculature to correct for trunk perturbations and regain balance after the jump landing.

The data also indicates trends in group mean differences in peak hip power in the sagittal plane during the forward, diagonal and lateral jump landings between participants with and without RLAS-PI. The RLAS-PI participants are primarily utilizing the hip extensor musculature to absorb energy in an attempt to control the upper body during the early loading phase to achieve a position of balance. The movement to a more proximal strategy to control the vertical displacement of the body may in part be driven by the distal stiffening strategy at the ankle and knee.

The current study also identified significant differences in pelvis and trunk kinematics between RLAS-PI and control participants. In the sagittal plane, the RLAS-PI participants demonstrated significantly greater peak trunk flexion and a decrease in trunk extension angles during the forward jump landings. The distal stiffening strategy may have prevented lowering the bodies COM during the initial phase of the jump landing. The possible consequence of this strategy would be an increase the momentum of the trunk in the direction of the jump landing as compared to the control group. This landing position would put a greater demand on the neuromuscular system to control the trunk. A neuromuscular delay in activation of the trunk musculature is supported by previous investigations examining the differences in trunk stability between participants with and without functional ankle instability (FAI).[22] Marshall et al.[22] identified a significant decrease in reflex times of the erector spinae after a sudden unloading of trunk flexion ($p = 0.01$). Similar to the sagittal plane differences in trunk kinematics, the current study also identified differences in peak lateral flexion and excursion angles during diagonal and lateral jump landings in RLAS-PI participants. It is currently unknown if there are differences in coronal plane neuromuscular control of the trunk between participants with and without RLAS, but it seems reasonable to assume that adjacent trunk musculature may also experience delays in activation. A delay in trunk muscle activation would require adaptive movement strategies at the hip to control the COM and maintain balance.

Clinical Implications / Future Research

The current findings indicate that RLAS-PI participants move differently when challenged to maintain postural control and balance after a functional activity. Based on the results of this study and in the context of previous research on this population clinical examination should not focus only on local joint impairments. The proposed “protective” strategy employed by RLAS-PI participants would easily be observed by a clinician through an assessment of functional movements that challenge dynamic postural control. Clinicians would benefit from similar functional movement examinations to identify suboptimal movement strategies employed by patients. This motor control examination should be followed by a focused differential examination procedures to rule in or out local ankle impairments that may influence such strategies.

In the future, further research examining the mechanisms (e.g. alterations in neuromuscular activation) behind this “protective” strategy will assist in developing new prospective studies. Prospective research focused on intervention strategies to address impairments in dynamic control will be critical to further guide examination and treatment.

Limitations

The current study has a smaller sample size which has two possible consequences; 1) causes the study to be underpowered; 2) an underpowered study results in larger variances of the estimates of the parameter (e.g. mean peak hip power) being estimated. The cross-sectional design of our study does not establish cause-and-effect relationships. Changes in trunk and lower extremity kinematics may be due to RLAS and/or postural instability, but prospective studies on a larger population with RLAS and postural instability and those without postural instability would be required to draw definitive conclusions.

Conclusion

In a controlled laboratory environment the RLAS-PI group utilized different movement strategies to perform the jump landing task successfully. The strategies to execute the jump landing may have been influenced by a desire to protect the ankle joint from reinjury. This “protective” strategy may have had some unintended consequences. First, limiting knee and ankle joint excursion may have cost the participant an increase in vertical rate of loading. Secondly, this stiffening strategy at the ankle and knee may have initially prevented lowering of the RLAS-PI participant’s COM during the landing phase, thereby challenging more proximal postural control strategies to stabilize significant trunk excursions. Finally, the RLAS-PI participant’s predominant use of proximal musculature (e.g. hip, trunk) over more distal musculature to regain postural control after the jump landing may also be at a price to increasing the vertical rate of loading.

The “protective” strategy may have some long term consequences for the RLAS-PI participants. Increases in rate of loading have been attributed to overuse injuries in running and jumping sports. Furthermore, the proposed protective strategy restricts the contributions from the ankle and knee joints to the degrees of freedom required for optimal movement variability. We hypothesize that outside the controlled laboratory environment, participants with RLAS-PI who are involved in running and jumping activities may be at a greater risk for re-injury because of the combination of restriction in degrees of freedom and postural control demand on dynamic tasks increases as they interact with the surrounding environment.

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CONCLUSION

This dissertation has investigated the effects of recurrent lateral ankle sprains (RLAS) on functional movement. The central hypothesis of this investigation is that postural instability from recurrent lateral ankle sprains will be associated with alterations in joint biomechanics during functional movement.

The first study takes a novel approach in examining which physical impairments are the best predictors of postural instability in participants with RLAS, as determined by performance on a dynamic postural control test. In addition, this study investigated group differences in clinical impairments and dynamic postural control testing between participants with and without RLAS. The second study set out to determine the effects of postural instability on lower extremity and trunk biomechanics during a jump landing.

Study 1 has shown that hip and ankle strength, ankle dorsiflexion range of motion, dynamic balance and lateral hop performance were not associated with dynamic postural stability in participants with and without recurrent lateral ankle sprains. This evidence suggests that there may not be a linear relationship between common clinical impairment measures and a dynamic measure of postural instability, but these results highlight the limitations inherent in associating isolated impairments with complex functional movements.

A lack of group differences in ankle (evertor and dorsiflexor) and hip (abductor and adductor) muscle strength and dorsiflexion range of motion, side-to-side hop, and DPSI performance was also shown between participants with and without RLAS. The self-report measures of functional ankle instability and perceived disability were significantly different between the RLAS and control groups, but the physical and functional impairment measures did not reflect these differences. A sub-group of RLAS participants was identified whose perception of their ankle instability was quite different than their functional performance. The pathoetiology of RLAS is quite complex and patients with a history of RLAS may fall anywhere along a continuum of disability.

One of the more significant findings to emerge from Study 2 is that the RLAS-PI group utilized different movement strategies to perform the jump landing task successfully. Significant decreases in ankle and knee sagittal plane joint angles were found in participants with RLAS-PI, but no coronal plane differences at the ankle and knee were identified. A stiffening strategy to protect the ankle joint from reinjury caused a shift to more proximal compensatory postural control strategies at the hip and trunk to regain balance after the jump landing. The "protective" strategy restricts the contributions from the ankle and knee joints, thereby subverting optimal movement variability. Participants with RLAS-PI who are involved in running and jumping activities may be at a greater risk for re-injury because the demand for optimal movement strategies with dynamic tasks increases as they interact with the surrounding environment.

The current findings show that dynamic postural control is quite variable among people with RLAS. The DPSI is a lab oriented examination that is not available to most clinicians, but clinicians would benefit from utilizing multiple modalities to examine postural control. The YEBT was shown to successfully identify balance deficits in patients with RLAS. Unfortunately, the 'fixed' limb design of the YEBT limits its ability to reveal impairments in postural control during transitions from a dynamic to static state. Therefore, observation of postural control strategies through dynamic functional movements, like the jump landing, will continue to benefit clinicians. The postural control strategies utilized by RLAS-PI participants in this study could have only been observed through increasing the level of difficulty of the functional activity. The strategies included a distal “stiffening” strategy at the ankle joint and proximal changes in hip and trunk movements to regain balance after the jump landing. The application of motor control principles will guide the clinician and are critical factors in understanding the relationships between emerging movement strategies and postural control. The lack of significant relationships between discreet physical impairments and dynamic postural control should not discourage clinical assessment. Study 2 demonstrated that physical impairment findings could benefit clinicians by ruling in or out contributions of the musculoskeletal system to observed changes in movement. The combination of motor control and physical impairment assessments will continue to be the best approach to building a unique clinical picture of patients with this complex pathoetiology.

Future prospective studies examining the relationships and interactions between local, regional and centrally mediated impairments would enhance our understanding of the pathoetiology behind RLAS.

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