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Laboratory Measures of Postural Control During the Star Excursion Balance Test After Acute First-Time Lateral Ankle Sprain

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Context: No researchers, to our knowledge, have investigated the immediate postinjury-movement strategies associated with acute first-time lateral ankle sprain (LAS) as quantified by center of pressure (COP) and kinematic analyses during performance of the Star Excursion Balance Test (SEBT).

Objective: To analyze the kinematic and COP patterns of a group with acute first-time LAS and a noninjured control group during performance of the SEBT.

Design: Case-control study.

Setting: University biomechanics laboratory.

Patients or Other Participants: A total of 81 participants with acute first-time LAS (53 men, 28 women; age = 23.22 ± 4.93 years, height = 1.73 ± 0.09 m, mass = 75.72 ± 13.86 kg) and 19 noninjured controls (15 men, 4 women; age = 22.53 ± 1.68 years, height = 1.74 ± 0.08 m, mass = 71.55 ± 11.31 kg).

Intervention: Participants performed the anterior (ANT), posterolateral (PL), and posteromedial (PM) reach directions of the SEBT.

Main Outcome Measure(s): We assessed 3-dimensional kinematics of the lower extremity joints and associated fractal dimension (FD) of the COP path during performance of the SEBT.

Results: The LAS group had decreased normalized reach distances in the ANT, PL, and PM directions when compared with the control group on their injured (ANT: 58.16% ± 6.86% versus 64.86% ± 5.99%; PL: 85.64% ± 10.62% versus 101.14% ± 8.39%; PM: 94.89% ± 9.26% versus 107.29 ± 6.02%) and noninjured (ANT: 60.98% ± 6.74% versus 64.76% ± 5.02%; PL: 88.95% ± 11.45% versus 102.36% ± 8.53%; PM: 97.13% ± 8.76% versus 106.62% ± 5.78%) limbs ($P <$ .01). This observation was associated with altered temporal sagittal-plane kinematic profiles throughout each reach attempt and at the point of maximum reach ($P <$ .05). This result was associated with a reduced FD of the COP path for each reach direction on the injured limb only ($P <$ .05).

Conclusions: Acute first-time LAS was associated with bilateral deficits in postural control, as evidenced by the bilateral reduction in angular displacement of the lower extremity joints and reduced reach distances and FD of the COP path on the injured limb during performance of the SEBT.

Key Words: ankle joint, biomechanics, kinematics, kinetics, postural balance

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Key Points

- Individuals with acute, first-time lateral ankle sprain injuries exhibited bilateral deficits in dynamic postural control as assessed using the reach distances achieved during the anterior, posterolateral, and posteromedial directions of the Star Excursion Balance Test.
- These deficits are underpinned by both local and global modifications in the movement patterns adopted at the point of maximum reach by the joints of the lower extremity.
- A trend toward reduced sagittal-plane range-of-motion displacement was also noted at the hip, knee, and ankle joints throughout each reach attempt in the injured group.
- These deficits were associated with an apparently reduced capacity to exploit the available base of support, as illustrated by a reduced fractal dimension of the stance-limb center-of-pressure path of the injured limb.
- Researchers need to determine if some deficits observed in the acute phase of lateral ankle sprain precede or predispose an athlete to the initial injury and to clarify whether these deficits are central to the onset of chronic injury.

I n a recent meta-analysis, we[1] elucidated that ankle sprain is an injury risk for participants of all ages during a wide variety of activity types. Decreased physical activity,[2] the potential for the development of posttraumatic ankle arthritis,[3] and medical costs[4] are immediate concerns associated with the acute ankle-joint injury, which has substantial potential for recurrence.[5]

Investigators[6,7] have hypothesized that the chronic sequelae associated with ankle-sprain injury result from the emergence of inappropriate postinjury-movement

strategies. The success or failure of these strategies depends on a process of sensorimotor reorganization, whereby structurally different components of the neurobiological system, known as *degeneracies*, combine toward a common motor output. These degeneracies in available degrees of freedom at affected joints are exploited to satisfy the demands of morphologic and task constraints.[8] An acute lateral ankle sprain (LAS) injury can be conceptualized as a morphologic constraint that challenges the human sensorimotor system to optimally organize altered peripheral sensorimotor inputs and the influence of higher brain centers.[9]

Clinicians frequently use postural-control assessments to evaluate the movement deficits associated with injury. Dynamic postural-control tasks seek to mimic the demands of physical activity by dictating movement around the supporting base.[10] The Star Excursion Balance Test (SEBT) is a dynamic postural-control task that has gained attention in clinical and research settings.[10] Whereas the primary outcome variable during SEBT performance in the clinical setting is the magnitude of the achieved reach distance, the movement patterns associated with this distance have also been evaluated in the laboratory.[11–13] With regard to the SEBT, instrumented analysis enhances the assessment of reach-distance magnitude in isolation. In particular, 3-dimensional kinematic analyses, combined with measures of force-plate stabilometry, provide insight into the causative mechanisms underpinning the test outcome, thus allowing the movement insufficiencies linked with acute injury, such as LAS, to be identified.

Analysis of center of pressure (COP) is a branch of stabilometry that has been combined with kinematic assessment in ankle-sprain research.[14] A newly applied measure called *fractal dimension* (FD) characterizes the complexity of a given COP signal by describing its shape with a discrete value ranging from 1 (*straight line*) to 2 (*line so convoluted that it fills the plane it occupies*).[15,16] A larger FD of the COP path has been associated with greater activity of the sensorimotor system in fulfilling the demands of balance. However, FD scores do not indicate on a linear scale where more or less is better or worse; an FD that is too large may reflect an inability of the sensorimotor system to synergistically modulate sensory afferents in producing an appropriate efferent response,[17] and an FD that is too small may reflect a deficit in using the base of support available[16,18] secondary to the demands of morphologic and task constraints.[19]

Previous researchers[7,20] have revealed contrasting movement patterns during dynamic postural-control tasks in groups presenting with chronic injury and full recovery in the months after an ankle sprain. Investigations[21–23] of acute LAS cohorts have typically been restricted to the evaluation of COP measures during static postural-control tasks. To our knowledge, no one has assessed the immediate postinjury-movement strategies associated with LAS using combined COP and kinematic analyses during a dynamic postural-control task. Therefore, the purpose of our study was to examine the movement-pattern characteristics of participants with acute LAS and noninjured participants serving as a control group during the performance of the SEBT using instrumented 3-dimensional kinematic and COP analyses. We hypothesized that the group with acute LAS (1) would report reduced function

secondary to injury, (2) would display bilateral impairment of dynamic balance as assessed using SEBT reach-distance scores compared with the control group, and (3) would exhibit altered kinematic and COP measures during performance of selected reach directions of the SEBT compared with the control group.

METHODS

Participants

Eighty-one participants (53 men, 28 women; age = 23.22 ± 4.93 years, height = 1.73 ± 0.09 m, mass = 75.72 ± 13.9 kg) were recruited from a university-affiliated hospital emergency department within 2 weeks of sustaining a first-time LAS (LAS group). An additional group of 19 noninjured participants (15 men, 4 women; age = 22.53 ± 1.68 years, height = 1.74 ± 0.08 m, mass = 71.55 ± 11.31 kg) with no history of LAS were recruited from the hospital catchment-area population using posters and flyers to serve as a control group. Inclusion criteria were as follows: (1) no history of LAS excluding the recent acute episode for the LAS group; (2) no other lower extremity injury in the 6 months before the study; (3) no history of ankle fracture; (4) no history of major lower limb surgery; and (5) no history of neurologic disease, vestibular or visual disturbance, or any other pathologic condition that could impair motor performance. All participants provided written informed consent, and the study was approved by the University College Dublin Human Research Ethics Committee.

Questionnaires

All participants completed the Cumberland Ankle Instability Tool (CAIT),[24] in addition to the Foot and Ankle Ability Measure for Activities of Daily Living and for Sports (FAAMadl and FAAMsports, respectively),[25] so we could quantify functional ability and patient-reported symptoms.

Procedures

Before participants performed the dynamic-balance task, we applied instrumentation for the Codamotion (Charnwood Dynamics Ltd, Leicestershire, UK) bilateral lower limb gait setup. After collecting the anthropometric measures required to calculate internal joint centers at the hip, knee, and ankle joints, we attached lower limb markers and wands as described by Monaghan et al.[26,27] A neutral-stance trial was used to align participants with the laboratory coordinate system and to function as a reference position for subsequent kinematic analysis as recommended in previously published literature.[28]

Dynamic Postural Control (SEBT Performance)

The directional components of the SEBT chosen for our study were the anterior (ANT), posterolateral (PL), and posteromedial (PM) reach directions based on the recommendations of Gribble et al.[10] Before evaluation, we instructed participants in correct SEBT procedures and allowed 4 practice trials in each direction.[29] After a short rest period, participants performed 3 consecutive trials for
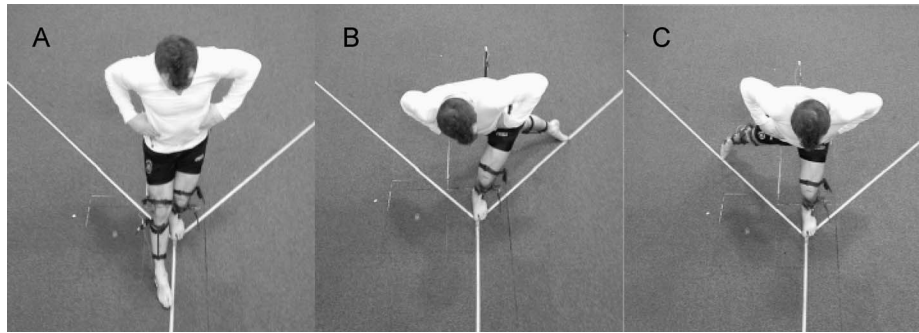
Figure 1. Laboratory setup of the Star Excursion Balance Test for the anterior (A), posterolateral (B), and posteromedial (C) reach directions.

each reach direction. The order of performance of each directional component was randomized using a random sequence of number generation. Participants began each SEBT trial standing barefoot with the left and right feet on 2 adjacent force plates. The great toe was positioned at center of an SEBT grid that was arranged on the laboratory floor extending from the force plate directly under the stance (test) limb. Reach distance was quantified using a 1.5-m measuring tape projected from the center of this grid along the relevant directional component of the SEBT. Therefore, reach distance was read from the center of this grid to the point of maximum reach, which was observed visually and recorded by the same investigator (C.D.). Trials were initiated in transition from double-limb to single-limb stance and terminated on return-to-double-limb stance. While standing on a single limb, participants were required to reach as far as possible with the nonstance limb along the predetermined reach direction, lightly touch the line with the most distal portion of the reaching foot, and return to a position of bilateral stance. Participants also were required to maintain their hands on their hips for the duration of single-limb–stance support. We determined the onset and end of each trial using a 10-N threshold of the vertical component of the ground reaction force data for the reaching (nonstance) limb. Reach distance was divided by limb length, as measured from the anterior-superior iliac spine to the ipsilateral medial malleolus and multiplied by 100 to calculate a dependent variable that represented reach distance as a percentage of limb length.[10] Trials were deemed *unsuccessful* if participants did not keep their hands on their hips, moved or lifted the stance foot, transferred weight onto the reach foot when touching the measuring tape, did not touch the tape, did not return the reach foot to the starting position, or lost their balance and were unable to maintain a unilateral-stance position during the trial. Unsuccessful trials were discarded, and additional trials were completed accordingly.

Kinematic and Kinetic Data Processing

Kinematic data acquisition for the dynamic postural-control task occurred at 1000 Hz using 3 Codamotion CX1 units; kinetic data acquisition, at 100 Hz using 2 fully integrated walkway-embedded force plates (Advanced Mechanical Technology, Inc, Watertown, MA). The Codamotion CX1 units were time synchronized with the force plates. We calculated kinematic data by comparing the angular orientations of the coordinate systems of adjacent limb segments using the angular coupling set of Euler angles to represent clinical rotations in 3 dimensions. Marker positions within a Cartesian frame were processed into rotation angles using vector algebra and trigonometry (Codamotion User Guide).

The kinetic datum of interest was COP (the location of the vertical reaction vector on the surface of a force plate) for each reach trial. The COP is a bivariate distribution jointly defined by the anterior-posterior (AP) and medial-lateral (ML) coordinates that, in a time series, defines the COP path relative to the origin of the force platform.[16] The COP data acquired from the SEBT trials were used to compute the FD of the combined AP and ML COP path using an algorithm described by Prieto et al.[16] The FD was calculated based on the full duration of unilateral stance during the SEBT reach attempt (from the initiation of the reach attempt to the return to upright bilateral stance). The AP and ML time series were passed through a fourth-order, zero-phase, Butterworth low-pass digital filter with a 5-Hz cutoff frequency. Kinematic and COP data were analyzed using the Codamotion software with the following axis conventions: x-axis is *frontal-plane motion*, y-axis is *sagittal-plane motion*, and z-axis is *transverse-plane motion*. Next, we converted the data to Excel (Microsoft Corp, Redmond, WA) file format. Temporal data were set with the number of output samples per trial at $100 + 1$ in the data-export option of the Codamotion software, which represented the complete SEBT trial as 100% for averaging and further analysis (Figure 1).

Data Analysis and Statistics

For the LAS group, the injured limb was labeled as *involved* and the noninjured limb as *uninvolved*. In all cases, the limbs in the control group were side matched to the injured group. For each control participant, we assigned 1 limb as *involved* and 1 limb as *uninvolved*, so that an equal proportion of right and left limbs was classified as *involved* and *uninvolved* in both the LAS and control groups. The average of 3 SEBT trials was calculated for all the dependent variables separately for both limbs for every participant and used for between-groups (LAS versus control) comparisons.

Participant Characteristics

Participant characteristics were compared between the LAS and control groups using multivariate analysis of variance. The dependent variables were sex, age, height,

and mass. The independent variable was group (LAS, control). We conducted preliminary assumption testing to check for normality, linearity, univariate and multivariate outliers, homogeneity of variance-covariance matrices, and multicollinearity and noted no serious violations. The α level was set a priori at .05.

Reach-Distance Scores on the SEBT

A 2-way, between-groups analysis of variance was conducted for each limb to explore differences in SEBT reach distance achieved between LAS and control participants. The independent variables were group (LAS and control) and reach direction (ANT, PL, and PM). The dependent variable was reach distance. A Bonferonni-adjusted α level of $P < .025$ (2 × limb) was used to determine significant differences for this analysis. Significant effects were evaluated post hoc via 2-tailed independent-samples t tests where appropriate. Statistical significance for post hoc analyses was established with a Bonferroni-adjusted α level of $P < .025$. We calculated associated effect sizes (η^2), with 0.01 indicating *small effect size*; 0.06, *medium effect size*; and 0.14, *large effect size*.[30]

Kinematics

To test the hypothesis that the LAS group would exhibit altered dynamic postural-control kinematic strategies compared with the control group, we calculated discrete joint angular-displacement values for the hip, knee, and ankle joints in the sagittal, transverse, and frontal planes of motion at the point of maximum reach for each reach direction. The resultant 9 joint-position dependent variables of interest were analyzed for the involved and uninvolved limbs. Delahunt et al[13] published a similar approach. A multivariate analysis of variance was undertaken for each reach direction to compare the kinematics at the point of maximum reach between the involved and uninvolved limbs of the LAS and control participants. The dependent variables were sagittal-, frontal-, and transverse-plane motion for the hip, knee, and ankle joints. The independent variables were group (LAS, control) and limb (involved, uninvolved). When a main effect for group was observed, we conducted post hoc independent-samples t tests between the involved and uninvolved limbs of the LAS and control groups for each direction. Preliminary assumption testing was conducted to check for normality, linearity, univariate and multivariate outliers, homogeneity of variance-covariance matrices, and multicollinearity, and no serious violations were noted. We calculated associated effect sizes (η^2), with 0.01 indicating *small effect size*; 0.06, *medium effect size*; and 0.14, *large effect size*.[30] The α level for this analysis was set a priori with Bonferonni adjustment at .017. The α levels for post hoc testing were adjusted for multiple tests using the Benjamini-Hochberg method of false discovery rate (FDR; <5%).[31]

Next, we plotted time-averaged profiles for hip-, knee-, and ankle-joint kinematics in the sagittal plane of motion, comparing the involved and uninvolved limbs of each group with subsequent calculation of group mean profiles for each reach direction based on findings that were different at the point of maximum reach. Between-groups differences in involved-limb and uninvolved-limb time-

averaged profiles were analyzed using independent-samples t tests for each data point. The α level for this analysis was set a priori at .05. Effect sizes were not calculated for this part of the data analysis secondary to the number of separate comparisons for each kinematic variable. This specific analysis technique has previously been used in our laboratory.[13] For conciseness, we did not report time-averaged profiles where between-groups differences did not exceed 50% of total trial length. The sagittal plane of motion was chosen in isolation for this part of the analysis secondary to the conclusions of Robinson and Gribble.[32]

Kinetics (Fractal Dimension)

To test the hypothesis that the LAS group would exhibit altered COP patterns compared with the control group, we conducted 2-way, between-groups analyses of variance for the involved and uninvolved limbs in each reach direction of the SEBT. The independent variables were group (LAS, control) and SEBT direction (ANT, PL, PM). When a significant main effect was observed for group, we undertook post hoc independent-samples t tests. Preliminary assumption testing was conducted to check for normality, linearity, univariate and multivariate outliers, homogeneity of variance-covariance matrices, and multicollinearity. The Levene test of equality error variances indicated a violation in the assumption of equality of variance for the FD of the ANT, PL, and PM reach directions. Therefore, the α level for this analysis was set a priori with Bonferroni adjustment at .0125 (.025/2). The α levels for post hoc testing were adjusted for multiple tests using a Bonferroni-adjusted α level of $P < .0125$. All statistical analyses were performed with SPSS statistical software (version 20.0; IBM Corporation, Armonk, NY).

RESULTS

Participant Characteristics and Questionnaire Results

We found no difference between the LAS and control groups for the combined dependent variables ($F_{4,93} = 1.86$, $P = .12$; Wilks $\Lambda = 0.92$; partial $\eta^2 = .07$). Regarding function, the CAIT score for the LAS group was 11.23 ± 8.09. The FAAMadl and FAAMsports scores for the LAS group were 57.66% ± 28.03% and 32.19% ± 24.55%, respectively. Participant characteristics and questionnaire scores are detailed in Table 1.

Reach-Distance Scores on the SEBT

A between-groups difference was observed at the α level of .025. Post hoc testing revealed that the LAS group achieved lower normalized reach distances for their involved (ANT: 58.16% ± 6.86% versus 64.86% ± 5.99%; PL: 85.64% ± 10.62% versus 101.14% ± 8.39%; PM: 94.89% ± 9.26% versus 107.29% ± 6.02%) and uninvolved (ANT: 60.98% ± 6.74% versus 64.76% ± 5.02%; PL: 88.95% ± 11.45% versus 102.36% ± 8.53%; PM: 97.13% ± 8.76% versus 106.62% ± 5.78%) limbs. The effect sizes for the involved limb were 0.18 in the ANT direction, 0.29 in the PL direction, and 0.27 in the PM direction. The effect sizes for the uninvolved limb were

Table 1. Participant Characteristics and Questionnaire Scores for the Lateral Ankle Sprain and Control Groups

Characteristic	Group (Mean ± SD [95% Confidence Interval])	
	Lateral Ankle Sprain	Control
Age, y	23.22 ± 4.93 (22.13, 24.31)	22.53 ± 1.68 (21.72, 23.34)
Height, m	1.73 ± 0.09 (1.71, 1.75)	1.74 ± 0.08 (1.71, 1.78)
Mass, kg	75.72 ± 13.86 (72.62, 78.83)	71.55 ± 11.31 (66.01, 77.01)
Cumberland Ankle Instability Tool	11.23 ± 8.09 (9.41, 13.06)	30.00 ± 0.00 (30.00, 30.00)
Foot and Ankle Ability Measure–Activities of Daily Living score, %	57.66 ± 28.03 (51.34, 63.98)	100.00 ± 0.00 (100.00, 100.00)
Foot and Ankle Ability Measure–Sports score, %	32.19 ± 24.55 (26.66, 37.73)	100.00 ± 0.00 (100.00, 100.00)

0.06 in the ANT direction, 0.20 in the PL direction, and 0.19 in the PM direction.

Kinematics

We observed a main effect for group in the ANT ($F_{9,154} = 20.081$, $P < .001$; Wilks $\Lambda = 0.457$; partial $\eta^2 = .543$), PL ($F_{9,151} = 4.024$, $P = .001$; Wilks $\Lambda = 0.804$; partial $\eta^2 = .196$), and PM ($F_{9,150} = 30.802$, $P < .001$; Wilks $\Lambda = 0.348$; partial $\eta^2 = .652$) reach directions. Post hoc testing with an FDR less than 5% revealed between-groups differences for several dependent variables for the involved and uninvolved limbs (Table 2).

Time-averaged sagittal-kinematic profiles were plotted based on between-groups differences at the point of maximum reach if these differences existed across more than 50% of the entire reach attempt. As such, differences were observed between the kinematic profiles in the ANT direction for the hip (uninvolved limb), knee (involved limb), and ankle (involved limb); in the PL direction for the hip (involved and uninvolved limbs) and knee (involved limb); and in the PM direction for the hip (involved and uninvolved limbs) and knee (involved and uninvolved limbs; Figures 2–11).

Kinetics (Fractal Dimension)

A main effect for group was noted for the involved limb only ($F_{2,228} = 32.809$, $P < .001$; partial $\eta^2 = .13$). Post hoc testing revealed that the LAS group had reduced COP path trajectory FD compared with the control group for all reach directions in the involved limb (Table 3).

DISCUSSION

To our knowledge, this is the first analysis to explore the movement patterns associated with acute LAS during a dynamic-balance task and the first to characterize these patterns using combined kinematic and COP profiling during specified reach directions of the SEBT in any group. Our observations confirmed our hypotheses as follows: (1) acute LAS was associated with functional impairment as revealed by the CAIT, FAAMadl, and FAAMsports questionnaire scores; (2) acute LAS manifested in a bilateral reduction in selected reach-distance scores of the SEBT, with associated large effect sizes for the involved and uninvolved limbs during performance of the PL and PM reach directions and medium and small effect sizes for the involved and uninvolved limbs in the ANT reach direction, respectively; and (3) sagittal-plane kinematic profiles revealed reduced flexion displacements at the hip, knee, and ankle during reach attempts of the SEBT task. This third observation may have been a biological substrate

of a reduction in COP path trajectory FD, which indicated a change in the postural-control strategies that the LAS participants used with their involved limb only. Discrete 3-dimensional kinematic values at the point of maximum reach confirmed the relevance of sagittal-plane motion to reach-distance scores and elucidated postural orientations specific to reach-distance performance. Statistical analysis revealed no differences between the LAS and control groups for the dependent variables of sex, age, height, or mass.

Despite unilateral injury, bilateral impairment was observed for the distance achieved in each reach direction (ie, ANT, PL, and PM). In a laboratory analysis of the SEBT, Gribble et al[12] reported decreased performance on the involved side only in a group with chronic ankle instability (CAI). They compared the sagittal-plane positions of the hip, knee, and ankle joints for the stance limb at the point of maximum reach between participants with and without CAI. In a follow-up study, regression analyses were used to determine the influence that CAI and these same kinematic variables might have had on reach-distance scores.[11] Results of these studies elucidated that sagittal-plane hip-flexion and knee-flexion displacements contributed most to the deficits observed during SEBT performance between CAI and control groups, which was in agreement with the findings of Robinson and Gribble[32] in groups with no pathologic conditions. This observation is likely due to the large muscle groups responsible for controlling these joints, which are vital for controlling both motion and stability during dynamic tasks.[10] Our investigation differed from the aforementioned papers because of its sample population (acutely injured participants); the addition of transverse-plane motion to discrete analyses; and the provision of temporal analyses of hip, knee, and ankle sagittal-plane motion to complement the discrete analyses. Finally, differences in sagittal-plane motion at the ankle joint during performance of the SEBT have not previously been reported.[11,12,33]

Our results present trends similar to those observed in groups in the chronic phase of ankle-sprain injury; a reduction in the primary determinants of test outcome (hip-flexion and knee-flexion displacement) was observed both at the point of maximum reach and throughout the reach attempt for all 3 reach directions of the SEBT on both the involved and uninvolved limbs. At the point of maximum reach, dorsiflexion range of motion (ROM) was reduced for both limbs in the PL direction and for the involved limb only in the ANT and PM directions. The reduction in dorsiflexion ROM may have been related to deficits observed more proximally at the hip and knee joints; ROM impairments in lower extremity joint motion typically are expressed elsewhere in the kinetic chain.[34]

Table 2. Discrete Kinematic Variable Values for the Hip, Knee, and Ankle at the Point of Maximum Reach During the Star Excursion Balance Test, Continued on Next Page

Star Excursion Balance Test Reach Direction	Joint	Joint Position	Involved Limb			Uninvolved Limb		
			Lateral Ankle Sprain Group, °	Control Group, °	Statistical Values	Lateral Ankle Sprain Group, °	Control Group, °	Statistical Values
Anterior	Hip	Adduction (+)/abduction (−)	14.61 ± 6.88	21.24 ± 10.43	$t_{21.24} = -2.60$, $P = .02$[a], $\eta^2 = 0.22$	18.02 ± 6.89	13.74 ± 8.55	$t_{86} = 2.27$, $P = .03$, $\eta^2 = 0.06$
		Flexion (+)/extension (−)	5.37 ± 25.91	18.69 ± 14.18	$t_{76} = -2.13$, $P = .04$, $\eta^2 = 0.06$	2.57 ± 14.05	18.58 ± 16.63	$t_{86} = -4.23$, $P < .001$[a], $\eta^2 = 0.17$
		Internal (+)/external (−) rotation	4.18 ± 10.73	3.92 ± 7.99	$t_{76} = 0.10$, $P = .92$, $\eta^2 < 0.001$	8.12 ± 11.01	4.34 ± 11.72	$t_{86} = 1.31$, $P = .20$, $\eta^2 = 0.02$
	Knee	Varus (+)/valgus (−)	−2.28 ± 4.95	−5.48 ± 4.50	$t_{76} = 2.50$, $P = .02$[a], $\eta^2 = 0.08$	−1.39 ± 6.32	−3.76 ± 9.29	$t_{86} = 1.30$, $P = .20$, $\eta^2 = 0.02$
		Flexion (+)/extension (−)	39.31 ± 15.28	58.79 ± 14.25	$t_{76} = -4.91$, $P < .001$[a], $\eta^2 = 0.24$	44.01 ± 20.37	54.16 ± 14.85	$t_{86} = 2.02$, $P = .046$, $\eta^2 = 0.05$
		Internal (+)/external (−) rotation	8.59 ± 9.15	6.13 ± 13.11	$t_{23.9} = 0.76$, $P = .45$, $\eta^2 = 0.02$	24.00 ± 14.53	8.08 ± 16.19	$t_{86} = 4.13$, $P < .001$[a], $\eta^2 = 0.17$
	Ankle	Inversion (+)/eversion (−)	−3.02 ± 7.16	−1.80 ± 24.42	$t_{19.01} = -0.21$, $P = .83$, $\eta^2 < 0.001$	−7.81 ± 8.43	−2.10 ± 11.93	$t_{86} = -2.38$, $P = .02$[a], $\eta^2 = 0.06$
		Dorsiflexion (+)/plantar flexion (−)	22.58 ± 7.17	32.21 ± 15.09	$t_{76} = -3.784$, $P < .001$[a], $\eta^2 = 0.02$	20.63 ± 16.54	27.13 ± 9.72	$t_{86} = 1.63$, $P = .61$, $\eta^2 = 0.03$
		Internal (+)/external (−) rotation	−7.60 ± 6.91	−8.00 ± 9.23	$t_{76} = 0.20$, $P = .84$, $\eta^2 < 0.001$	−11.31 ± 12.10	−5.08 ± 14.30	$t_{86} = -1.91$, $P = .06$, $\eta^2 = 0.04$
Posterolateral	Hip	Adduction (+)/abduction (−)	14.76 ± 8.21	17.91 ± 8.30	$t_{75} = -1.45$, $P = .15$, $\eta^2 = 0.03$	17.83 ± 8.82	14.38 ± 10.31	$t_{84} = 1.45$, $P = .15$, $\eta^2 = 0.02$
		Flexion (+)/extension (−)	53.88 ± 19.24	73.68 ± 15.05	$t_{75} = -4.09$, $P < .001$[a], $\eta^2 = 0.18$	50.40 ± 19.49	72.03 ± 16.30	$t_{84} = -4.41$, $P < .001$[a], $\eta^2 = 0.14$
		Internal (+)/external (−) rotation	−14.27 ± 22.34	−26.83 ± 11.30	$t_{75} = 2.35$, $P = .02$[a], $\eta^2 = 0.07$	−19.68 ± 24.89	−23.54 ± 13.29	$t_{84} = 0.65$, $P = .52$, $\eta^2 < 0.001$
	Knee	Varus (+)/valgus (−)	3.35 ± 6.11	3.29 ± 7.78	$t_{75} = 0.03$, $P = .97$, $\eta^2 < 0.001$	5.63 ± 7.88	6.44 ± 5.54	$t_{84} = -0.42$, $P = .68$, $\eta^2 < 0.001$
		Flexion (+)/extension (−)	36.96 ± 16.04	54.87 ± 11.07	$t_{75} = -4.52$, $P < .001$[a], $\eta^2 = 0.21$	39.43 ± 16.53	54.55 ± 13.10	$t_{84} = -3.69$, $P < .001$[a], $\eta^2 = 0.14$
		Internal (+)/external (−) rotation	2.32 ± 14.08	−5.31 ± 14.72	$t_{75} = 2.03$, $P = .046$, $\eta^2 = 0.05$	17.89 ± 17.10	1.84 ± 15.27	$t_{84} = 3.69$, $P < .001$[a], $\eta^2 = 0.14$

Table 2. Continued From Previous Page

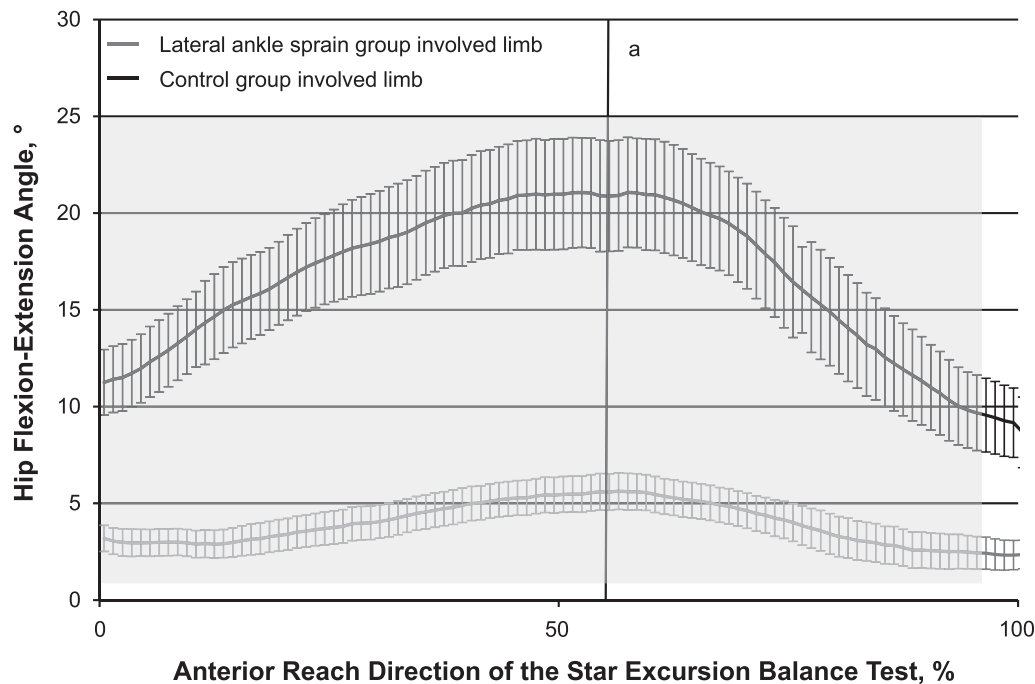| Star Excursion Balance Test Reach Direction	Joint	Joint Position	Involved Limb			Uninvolved Limb		
			Lateral Ankle Sprain Group, °	Control Group, °	Statistical Values	Lateral Ankle Sprain Group, °	Control Group, °	Statistical Values
	Ankle	Inversion (+)/eversion (−)	−7.57 ± 11.70	−11.65 ± 21.12	$t_{75} = 1.06$, $P = .29$, $\eta^2 = 0.02$	12.35 ± 8.82	−16.53 ± 19.55	$t_{84} = -2.50$, $P = .07$, $\eta^2 = 0.01$
		Dorsiflexion (+)/plantar flexion (−)	17.08 ± 8.22	24.15 ± 7.63	$t_{75} = -3.31$, $P = .001^a$, $\eta^2 = 0.13$	14.74 ± 10.98	30.76 ± 25.28	$t_{84} = -14.74$, $P = .01^a$, $\eta^2 = 0.27$
		Internal (+)/external (−) rotation	−6.68 ± 9.03	−8.24 ± 17.69	$t_{75} = 0.50$, $P = .62$, $\eta^2 < 0.001$	−10.80 ± 10.47	−7.41 ± 14.71	$t_{84} = -1.13$, $P = .26$, $\eta^2 = 0.02$
Posteromedial	Hip	Adduction (+)/abduction (−)	7.44 ± 10.86	9.01 ± 12.31	$t_{73} = -0.53$, $P = .60$, $\eta^2 < 0.001$	7.98 ± 9.14	1.83 ± 12.43	$t_{85} = 2.39$, $P = .02^a$, $\eta^2 = 0.06$
		Flexion (+)/extension (−)	45.06 ± 20.03	73.11 ± 13.81	$t_{73} = -5.65$, $P < .001^a$, $\eta^2 = 0.30$	47.47 ± 18.99	71.52 ± 11.10	$t_{85} = -5.26$, $P < .001^a$, $\eta^2 = 0.25$
		Internal (+)/external (−) rotation	3.32 ± 13.11	2.72 ± 11.813	$t_{73} = 0.18$, $P = .86$, $\eta^2 < 0.001$	8.71 ± 17.47	5.90 ± 10.65	$t_{85} = 0.67$, $P = .51$, $\eta^2 = 0.01$
	Knee	Varus (+)/valgus (−)	−2.00 ± 7.25	−7.55 ± 8.17	$t_{73} = 2.79$, $P = .007^a$, $\eta^2 = 0.10$	−1.73 ± 6.01	−2.53 ± 5.28	$t_{85} = 0.52$, $P = .60$, $\eta^2 < 0.001$
		Flexion (+)/extension (−)	44.92 ± 17.40	69.86 ± 10.79	$t_{73} = -5.86$, $P < .001^a$, $\eta^2 = 0.32$	51.34 ± 17.80	66.32 ± 8.89	$t_{85} = -3.53$, $P = .001^a$, $\eta^2 = 0.13$
		Internal (+)/external (−) rotation	25.11 ± 14.05	2.47 ± 7.92	$t_{85} = 6.655$, $P < .001^a$, $\eta^2 = 0.38$	19.95 ± 26.77	7.81 ± 13.93	$t_{85} = 1.90$, $P = .01^a$, $\eta^2 = 0.04$
	Ankle	Inversion (+)/eversion (−)	−14.58 ± 7.6	−4.05 ± 15.56	$t_{73} = -3.90$, $P < .001^a$, $\eta^2 = 0.17$	−10.50 ± 21.75	−8.04 ± 13.23	$t_{85} = -0.47$, $P = .64$, $\eta^2 < 0.001$
		Dorsiflexion (+)/plantar flexion (−)	16.16 ± 11.87	27.43 ± 9.07	$t_{73} = -3.77$, $P < .001^a$, $\eta^2 = 0.16$	15.54 ± 23.13	26.46 ± 8.32	$t_{85} = -2.02$, $P = .047$, $\eta^2 = 0.05$
		Internal (+)/external (−) rotation	−13.41 ± 7.79	−10.98 ± 8.83	$t_{73} = -1.14$, $P = .26$, $\eta^2 = 0.02$	−14.84 ± 10.33	−8.25 ± 9.53	$t_{85} = -2.50$, $P = .01^a$, $\eta^2 = 0.07$

[a] Indicates between-groups difference.

Figure 2. Hip-joint flexion-extension angle during performance of the anterior directional component of the Star Excursion Balance Test for the involved limb of the lateral ankle sprain and control groups. Flexion is represented as positive and extension as negative. Values are mean ± standard error of the mean. Shaded areas indicate statistically significant between-groups differences. [a] Indicates the point of maximum reach.

Whether the distally observed deficits preceded those further up the kinetic chain or vice versa is an important consideration. Evaluation of discrete kinematic values at the point of maximum reach revealed that the sagittal-plane ankle ROM deficit was linked with similar restrictions at the hip and knee in the involved limb. This was not the case in the uninvolved limb, where proximal restriction had no such corollary at the ankle joint in the ANT and PM directions. Therefore, in theorizing that the source of restriction was the same for both the involved and uninvolved limbs, we consider proximal ROM to be the source of distal ROM deficit, sometimes manifesting farther down the kinetic chain. However, in theorizing that the source of the deficit was different for each limb, we consider that factors
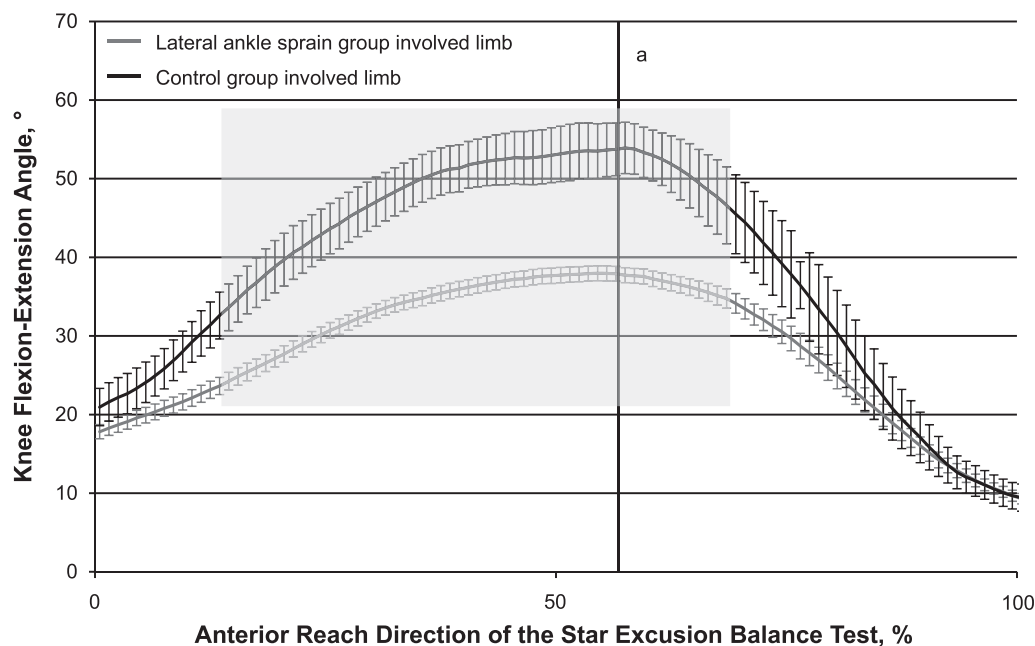

Figure 3. Knee-joint flexion-extension angle during performance of the anterior directional component of the Star Excursion Balance Test for the involved limb of the lateral ankle sprain and control groups. Flexion is represented as positive and extension as negative. Values are mean ± standard error of the mean. Shaded areas indicate statistically significant between-groups differences. [a] Indicates the point of maximum reach.
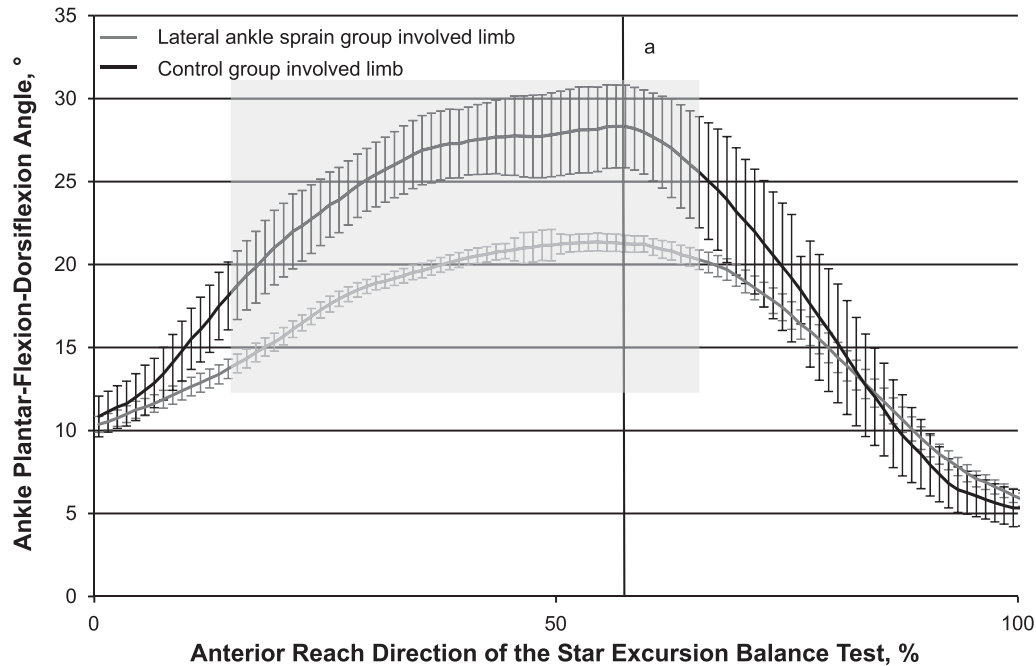
Figure 4. Ankle-joint plantar-flexion-dorsiflexion angle during performance of the anterior directional component of the Star Excursion Balance Test for the involved limb of the lateral ankle sprain and control groups. Dorsiflexion is represented as positive and plantar flexion as negative. Values are mean ± standard error of the mean. Shaded areas indicate statistically significant between-groups differences. [a] Indicates the point of maximum reach.

including swelling and pain with excessive ankle ROM restricted the proximal corollaries of knee and hip movement in the involved limb and that other factors restricted movement on the uninvolved limb. The absence of local joint symptoms associated with the acute injury in the uninvolved limb leads to a hypothesis that ankle sprain can cause spinal-level inhibition and postural-control impairment secondary to the onset of γ-motoneuron–loop dysfunction.[35] The conscious perception of swelling and pain associated with the acute LAS in our sample during the SEBT may have caused this supraspinal inhibition, impairing dynamic postural-control strategies. In summary, we believe a convergence of both peripheral and central impairment is present after acute first-time LAS; injury may result in a
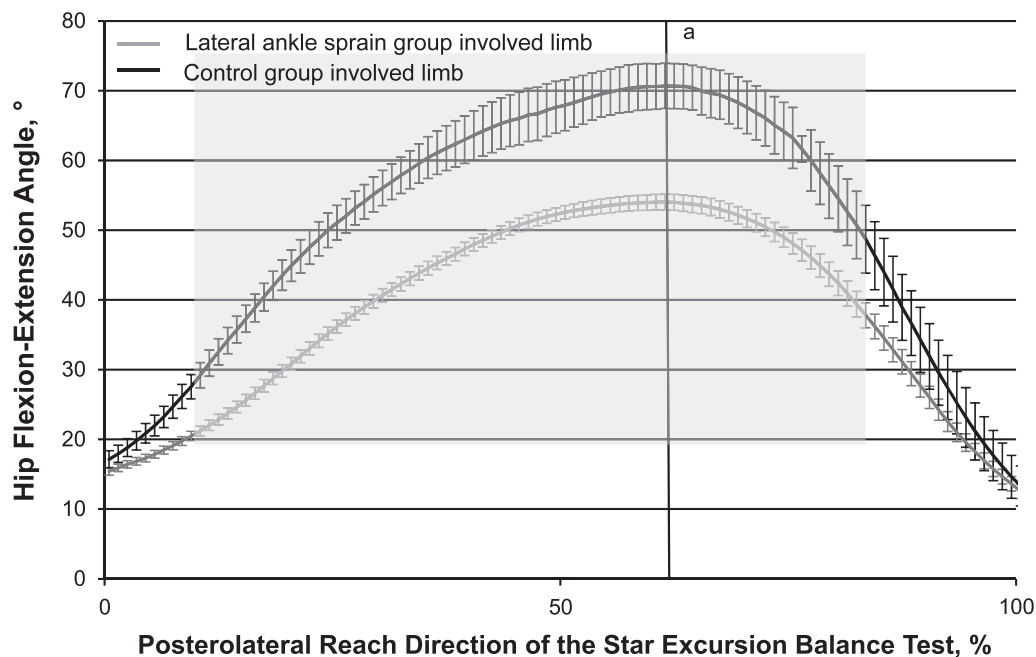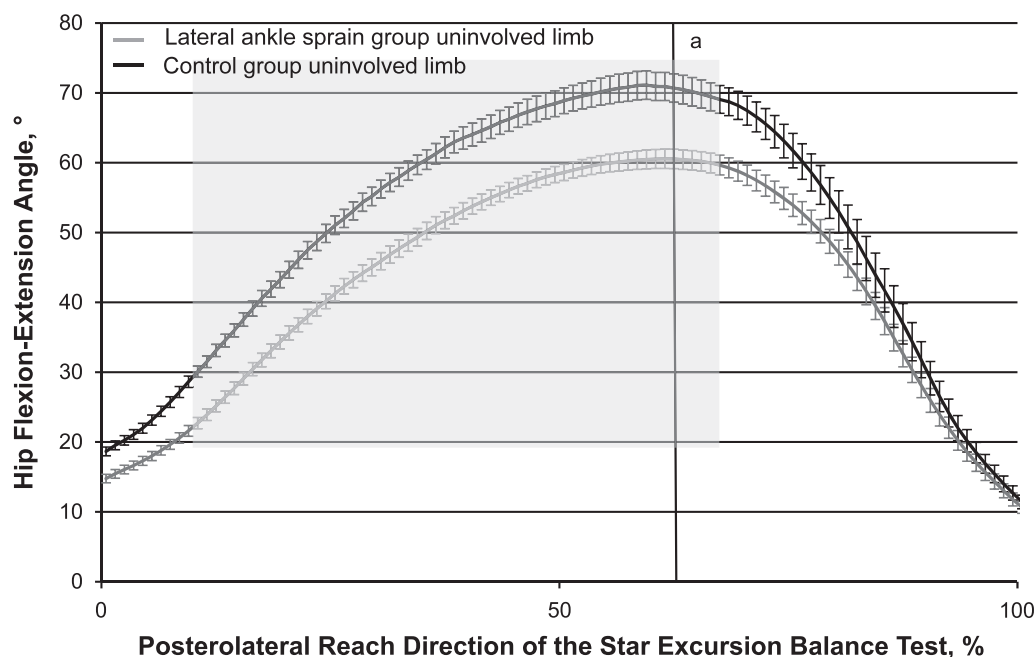

Figure 5. Hip-joint flexion-extension angle during performance of the posterolateral directional component of the Star Excursion Balance Test for the involved limb of the lateral ankle sprain and control groups. Flexion is represented as positive and extension as negative. Values are mean ± standard error of the mean. Shaded areas indicate statistically significant between-groups differences. [a] Indicates the point of maximum reach.

Figure 6. Hip-joint flexion-extension angle during performance of the posterolateral directional component of the Star Excursion Balance Test for the uninvolved limb of the lateral ankle sprain and control groups. Flexion is represented as positive and extension as negative. Values are mean ± standard error of the mean. Shaded areas indicate statistically significant between-groups differences. [a] Indicates the point of maximum reach.

motor-sensory mismatch in which a dissociation exists between actual and predicted sensory input.[36,37] This mismatch during the performance of a given motor task generates a sensory disturbance, which is expressed as local and distal anomalous movement patterns.[36] Our observations are in agreement with the results presented by Wikstrom et al,[38] who concluded in their meta-analysis that postural-control deficits are present in both the injured and noninjured limbs of patients with acute LAS.

The consistency of movement-pattern deficits in sagittal-plane–flexion displacements during the SEBT allowed simple comparison between the LAS and control groups, in whom deficits were determined by a reduction in ROM. In contrast, different discrete kinematic values for the frontal and transverse planes of motion at the point of maximum reach must be considered in view of the specific reach direction to which they are coupled and the pleiotropic nature of the neurobiological system. The
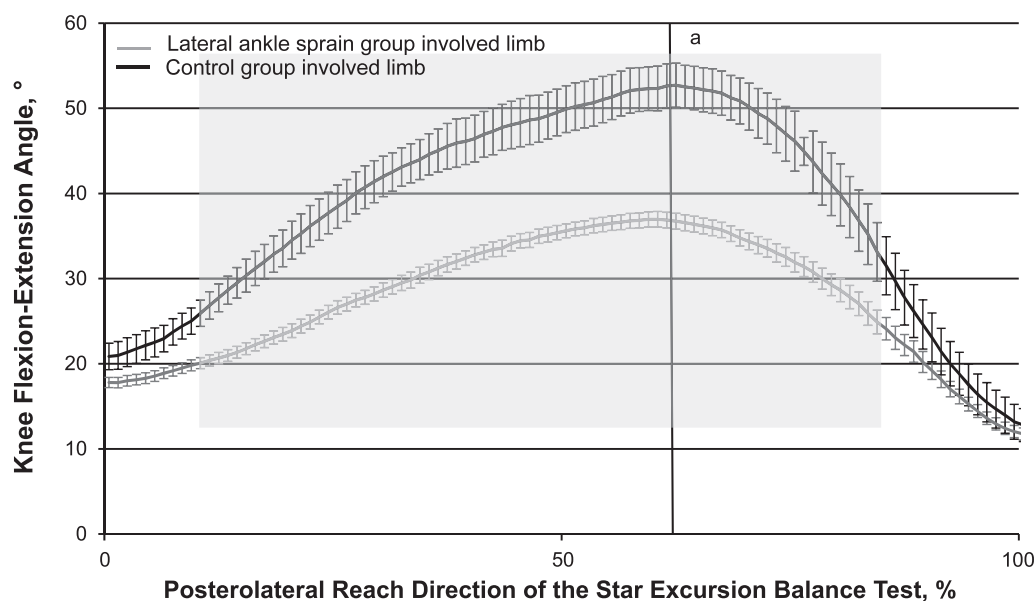

Figure 7. Knee-joint flexion-extension angle during performance of the posterolateral directional component of the Star Excursion Balance Test for the involved limb of the lateral ankle sprain and control groups. Flexion is represented as positive and extension as negative. Values are mean ± standard error of the mean. Shaded areas indicate statistically significant between-groups differences. [a] Indicates the point of maximum reach.
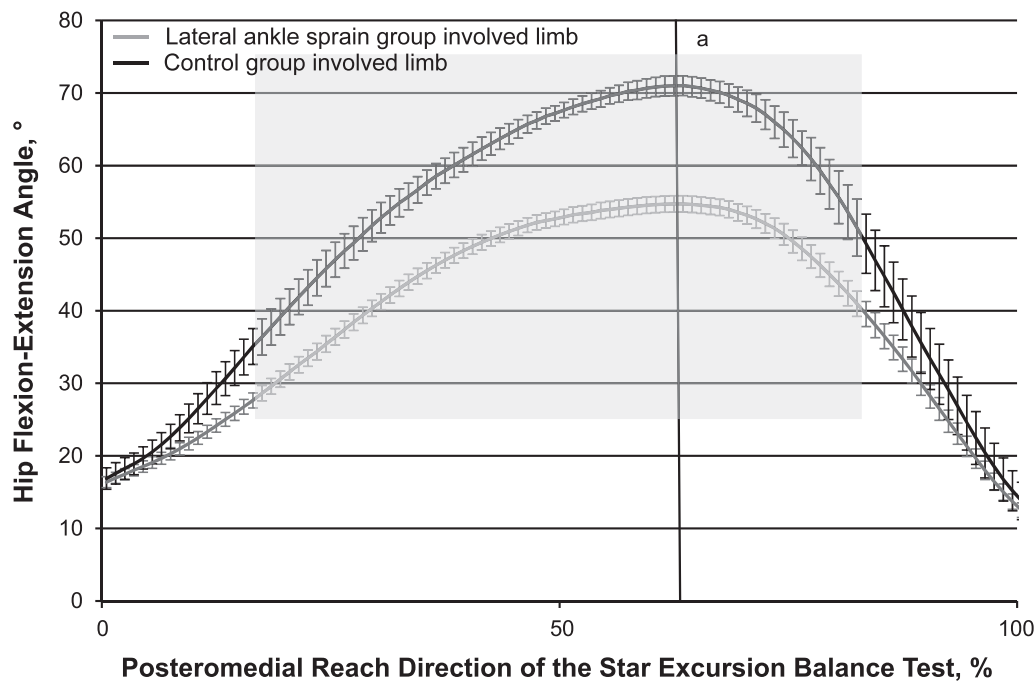
Figure 8. Hip-joint flexion-extension angle during performance of the posteromedial directional component of the Star Excursion Balance Test for the involved limb of the lateral ankle sprain and control groups. Flexion is represented as positive and extension as negative. Values are mean ± standard error of the mean. Shaded areas indicate statistically significant between-groups differences. [a] Indicates the point of maximum reach.

intricacies of the interaction between the varieties of movement are open to an interpretation that is possible only with provision of the aforementioned variables. Hence, we have sought to provide insight into these variables without theorizing about their specific importance; all components of the neurobiological kinetic chain affect each other in intricate ways, and studying them individually can disrupt their apparent interactions so much that an isolated movement may seem to behave quite differently from the way it would in its normal context. Analysis of temporal angular-displacement waveforms was performed in the same vein: to provide greater insight into
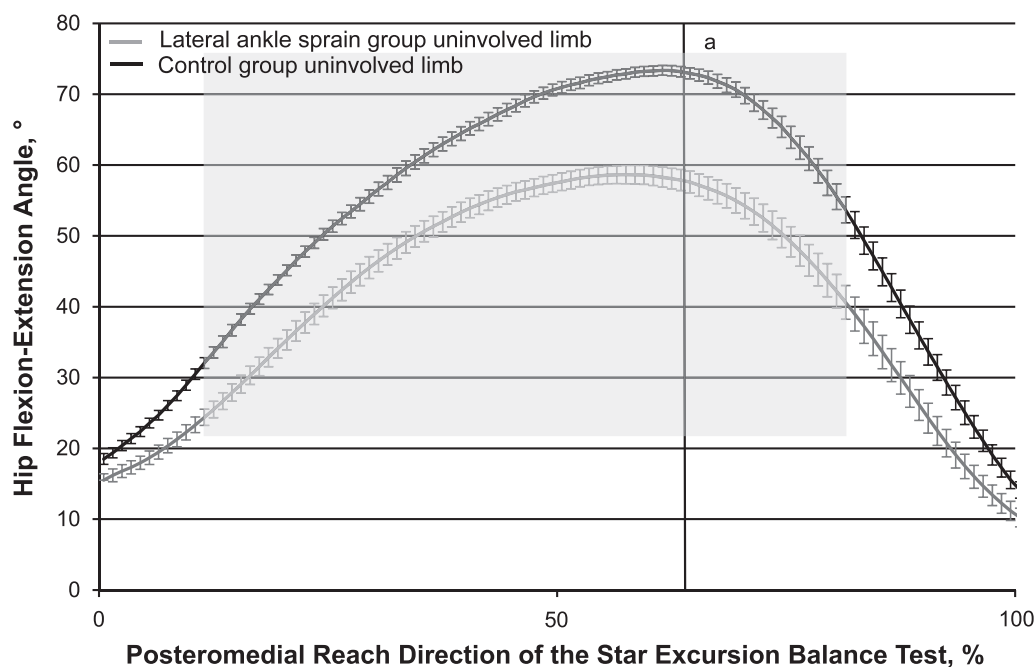

Figure 9. Hip-joint flexion-extension angle during performance of the posteromedial directional component of the Star Excursion Balance Test for the uninvolved limb of the lateral ankle sprain and control groups. Flexion is represented as positive and extension as negative. Values are mean ± standard error of the mean. Shaded areas indicate statistically significant between-groups differences. [a] Indicates the point of maximum reach.
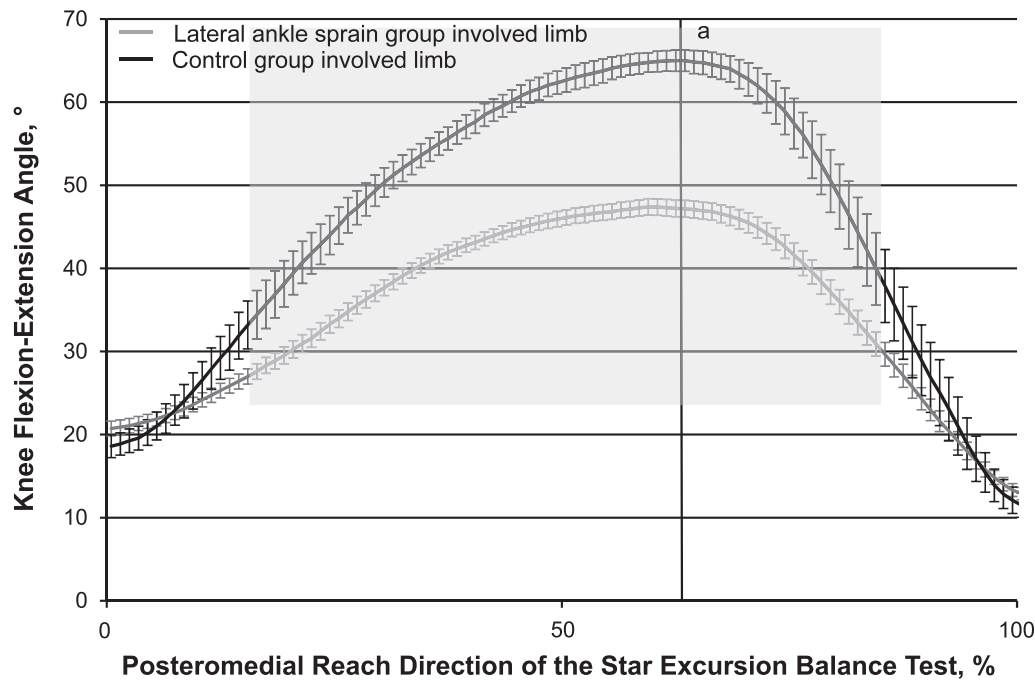
Figure 10. Knee-joint flexion-extension angle during performance of the posteromedial directional component of the Star Excursion Balance Test for the involved limb of the lateral ankle sprain and control groups. Flexion is represented as positive and extension as negative. Values are mean ± standard error of the mean. Shaded areas indicate statistically significant between-groups differences. [a] Indicates the point of maximum reach.

the movement patterns across the duration of the task. That an injury constraint produced a variety of kinematic strategy solutions to the SEBT task constraint reflects the pleiotropic nature of the neurobiological system; injury encouraged previously redundant components of the system to make compensatory adjustments to neutralize the effect of the original error.[39]

We used platform stabilometry as an additional means to classify the postural-control strategies of LAS participants during the dynamic-balance task. By calculating the FD of
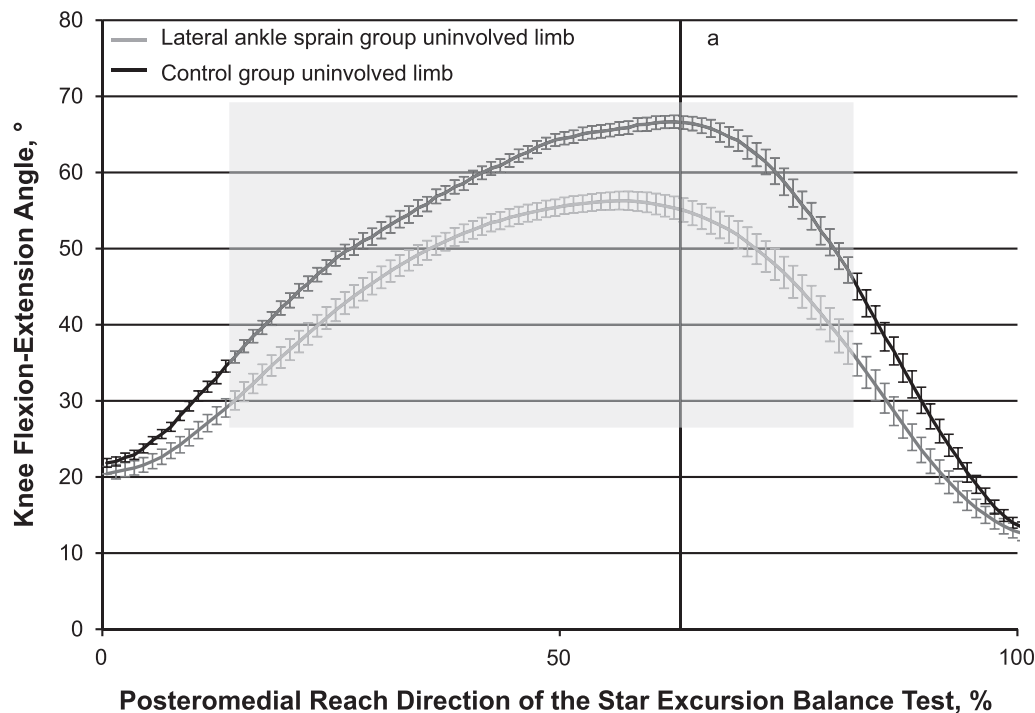

Figure 11. Knee-joint flexion-extension angle during performance of the posteromedial directional component of the Star Excursion Balance Test for the uninvolved limb of the lateral ankle sprain and control groups. Flexion is represented as positive and extension as negative. Values are mean ± standard error of the mean. Shaded areas indicate statistically significant between-groups differences. [a] Indicates the point of maximum reach.

Table 3. Lateral Ankle Sprain and Control Group Involved-Limb Fractal Dimension Scores for the Anterior, Posterolateral, and Posteromedial Reach Directions of the Star Excursion Balance Test After Post Hoc Analysis

| | Fractal Dimension | | | | | | 95% Confidence Interval of the Mean Difference | |
	Lateral Ankle Sprain Group	Control Group	t Value	Degrees of Freedom	P Value	Mean Difference	Lower	Upper
Direction								
Anterior	1.09 ± 0.21	1.23 ± 0.66	−4.558	74.966	<.001	−0.14329	−0.20591	−0.08066
Posterolateral	1.09 ± 0.22	1.25 ± 0.13	−3.790	48.443	<.001	−0.15998	−0.24484	−0.07512
Posteromedial	1.07 ± 0.21	1.28 ± 0.13	−4.997	48.865	<.001	−0.20582	−0.28860	−0.12304

the resultant ground reaction forces of the stance limb (COP path) during a reach attempt, we sought to characterize the response of the postural-control system to a volitional postural perturbation (ie, performance of selected reach directions of the SEBT) combined with injury. The FD describes the complexity of the COP path, quantifying the relationship between the activity of the postural-control system and the level of stability achieved.[16] Our results demonstrated a reduction in FD for the involved limb of the LAS group compared with the control group, which we perceive to indicate either a reduced ability to use the available base of support or the injury-confined activity of the sensorimotor system in completing the prescribed task.[18] The lack of reduction in FD for the uninvolved limb suggests that the absence of a peripheral impairment allowed enough interaction between higher and lower levels of the postural-control system to deliver a performance that, although less successful than for control participants (as demonstrated by reduced reach distances and altered kinematic profiles for this limb), was sufficient in exploiting the available base of support. With this in mind, the use of the available base of support and the activity of the sensorimotor system are not the only determinants of test outcome: hence, the importance of a complementary kinematic profile.

CONCLUSIONS

Our findings provide a comprehensive evaluation of the effects of an initial acute LAS on SEBT performance using a number of measures. Modifications in temporal and discrete kinematic measures and a reduced ability to effectively use the available base of support resulted in SEBT performance impairment. In light of these observations, clinicians must consider the early administration of bilateral rehabilitation protocols after acute ankle sprain with similar emphasis on regaining neuromuscular function in the proximal and distal segments of the kinetic chain. The potential worth of the SEBT as both an assessment tool and rehabilitation exercise should also be considered.

However, whereas our results are relevant to researchers and clinicians alike, our study had limitations. Given the study design, we do not know whether the deficits presenting in the LAS group preceded or resulted from the acute injury or whether these deficits were precursors to the chronic injury. In future longitudinal analyses, investigators should examine whether some of the deficits observed in the acute phase of ankle-sprain injury actually precede (and predispose the participants to) the initial acute injury and clarify which key deficits are central to the onset of chronic injury.

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