Abstract

Context: No research has investigated the immediate post-injury movement strategies associated with acute lateral ankle sprain (LAS), as quantified by center-of-pressure (COP) and kinematic analyses during performance of the Star Excursion Balance Test (SEBT).

Objective: Analyse the kinematic and COP patterns of a group with acute LAS and a non-injured control group during performance of the SEBT.

Design: Case-control.

Setting: University biomechanics laboratory

Participants: 81 participants with acute LAS and 19 non-injured controls.

Data collection and analysis: 3D kinematics of the lower extremity joints and associated fractal dimension (FD) of the COP path during the performance of the anterior (ANT), posterior-lateral (PL) and posterior-medial (PM) reach directions of the SEBT.

Results: The LAS group had decreased normalised reach distances in the ANT, PL and PM directions compared to control participants on their injured (ANT: 58.16 ± 6.86% *vs* 64.86 ± 5.99%; PL: 85.64 ± 10.62% *vs* 101.14 ± 8.39%; PM: 94.89 ± 9.26% *vs* 107.29 ± 6.02%) and non-injured (ANT: 60.98 ± 6.74% vs. 64.76 ± 5.02%; PL: 88.95 ± 11.45% *vs* 102.36 ± 8.53%; PM: 97.13 ± 8.76% *vs* 106.62 ± 5.78%) limbs ($p < 0.01$). This was associated with altered temporal sagittal plane kinematic profiles throughout each reach attempt, as well as at the point of maximum reach ($p < 0.05$). This was associated with a reduced FD of the COP path for each reach direction on the injured limb only ($p < 0.05$).

Conclusion: Acute LAS is associated with bilateral deficits in postural control, evidenced by reduced angular displacement of lower extremity joints and reduced reach distances and FD of the COP path during the performance of the SEBT.

Key terms: ankle joint [MEsH]; biomechanics [MEsH]; kinematics [MEsH]; kinetics [MEsH]; postural balance [MEsH].

INTRODUCTION

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

It has been hypothesized that individuals who endure the chronic sequalae associated with ankle sprain injury do so due to the emergence of inappropriate post-injury movement strategies.[6,7] The success or failure of these strategies is dependent on a process of sensorimotor re-organization, whereby structurally different components of the neurobiological system otherwise known as 'degeneracies' combine towards a common motor output. These degeneracies in available degrees of freedom at affected joints are exploited to satisfy the demands of morphological and task constraints.[8] An acute lateral ankle sprain (LAS) injury can be conceptualized as a morphological constraint that challenges the human sensorimotor system to optimally organize altered peripheral sensorimotor inputs and the influence of higher brain centers.[9]

Postural control assessments are frequently used in the clinical setting 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 notoriety in clinical and research settings.[10] Although 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 subject to evaluation via

laboratory analyses.[11-13] In the case of the SEBT, the assessment of reach distance magnitude in isolation is enhanced by instrumented analysis. In particular, 3-dimensional kinematic analyses combined with measures of force-plate stabilometry provide insight into the causative mechanisms underpinning the test outcome, thus potentiating the capacity to determine the movement insufficiencies linked with acute injury such as LAS.

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

Previous research has revealed contrasting movement patterns in groups presenting with both chronicity and full recovery in the months following an ankle sprain during dynamic postural control tasks.[7,20] Research investigations in the acute phase of LAS injury have typically been restricted to the evaluation of COP measures during static postural control tasks.[21-23] To the authors' knowledge to date, no current research exists which investigates the immediate post-injury movement strategies associated with LAS using combined COP and kinematic

analyses during a dynamic postural control task. Therefore, the aim of the current investigation was to examine the movement pattern characteristics of a group of participants with acute LAS injury compared to a non-injured control group during the performance of the SEBT using instrumental 3-D kinematic and COP analyses. It was hypothesized that the group with acute LAS would: (1) report reduced function secondary to their injury; (2) display bilateral impairment of dynamic balance as assessed using SEBT reach distance scores compared to the control group; (3) exhibit altered kinematic and COP measures during performance of selected reach directions of the SEBT compared to the control group.

MATERIALS AND METHODS

Participants

Eighty one participants (53 males and 28 females; age 23.2 ± 4.9 years; mass 75.72 ± 13.9 kg; height 1.73 ± 0.1 m) were recruited from a University-affiliated hospital Emergency Department within 2 weeks of sustaining a first-time LAS (LAS group). An additional group of nineteen uninjured participants (15 males and four females; age 22.5 ± 1.7 years; mass 71.55 ± 11.3kg; height 1.74 ± 0.1 m) with no prior history of LAS injury were recruited from the hospital catchment area population using posters and flyers to act as a control group. All participants signed an informed consent form approved by the University Human Research Ethics Committee. Inclusion criteria were as follows: (1) no previous history of LAS injury (excluding the recent acute episode for the LAS group); (2) no other lower extremity injury in the last 6 months; (3) no history of ankle fracture; (4) no previous history of major lower limb surgery; (5) no history of neurological disease, vestibular or visual disturbance or any other pathology that could impair their motor performance.

Questionnaires

All participants were required to complete the Cumberland Ankle Instability Tool (CAIT)[24] in addition to the activities of daily living and sports subscales of the Foot and Ankle Ability Measure (FAAMadl and FAAMsport)[25] with the aim of quantifying functional ability and patient-reported symptoms.

Procedures

Prior to completion of the dynamic balance task, participants were instrumented with the Codamotion (Charnwood Dynamics Ltd, Leicestershire, UK) bilateral lower limb gait set-up during laboratory assessments. Following the collection of anthropometric measures required for the calculation of internal joint centers at the hip, knee and ankle joints, lower limb markers and wands were attached, as described by Monaghan et al.[26,27] A neutral stance trial was used to align the subject 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 the current investigation included the anterior (ANT), posterior-medial (PM) and posterior-lateral (PL) reach directions, based on the recommendations of Gribble et al.[10] Prior to evaluation, participants were instructed as to correct SEBT procedures and allowed four practice trials in each direction.[29] After a short rest period, three consecutive trials were performed for each reach direction. The order of performance of each directional component was randomized using a random sequence of number generation. Participants began each individual SEBT trial standing barefoot with their left and right feet on the two (adjacent) force-plates. The big toe was positioned at the center of a SEBT grid arranged on the laboratory floor extending from the force plate directly

under the stance (test) leg. Reach distance was quantified using a 1.5m measuring tape projected from the center of this grid along the relevant directional component of the SEBT. Therefore, reach distances were read from the center of this grid to the point of maximum reach, which was visually observed and recorded by the same investigator. Trials were initiated in transition from double 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 non-stance limb along the pre-determined reach direction, lightly touch the line with the most distal portion of the reaching foot and then return to a position of bilateral stance. Participants were also required to maintain their hands on their hips for the duration of single limb stance support. The onset and end of each trial was determined using a 10N threshold of the vertical component of the ground reaction force data of the reaching (non-stance) limb. Reach distances were 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 represents reach distance as a percentage of limb length.[10] A trial was deemed unsuccessful if the participant failed to keep their hands on their hips, moved or lifted the stance (test) foot, transferred weight onto the reach foot when touching the measuring tape, failed to touch the tape, failed to return the reach foot to the starting position, or lost their balance and was 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 was made at 1000 Hz using 3 Codamotion CX1units and kinetic data at 100 Hz using 2 fully integrated AMTI (Watertown, MA) walkway embedded force-plates. The Codamotion CX1 units were time synchronized with the force-plates. Kinematic data were calculated by comparing the angular

orientations of the coordinate systems of adjacent limb segments using the angular coupling set ‘‘Euler angles’’ to represent clinical rotations in three dimensions. Marker positions within a Cartesian frame were processed into rotation angles using vector algebra and trigonometry (Codamotion User Guide, Charnwood Dynamics Ltd. Leicestershire, UK). The kinetic data of interest was center of pressure (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 antero-posterior (AP) and medio-lateral (ML) coordinates which in a time series define the COP path relative to the origin of the force platform.[16] COP data acquired from trials of the SEBT were used to compute FD of the combined AP and ML COP path using an algorithm previously published and described in the seminal paper by Prieto et al.[16] FD was calculated based on the full duration of the 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 cut-off frequency. Kinematic and COP data were analyzed using the Codamotion software, with the following axis conventions: x axis = frontal-plane motion; y = sagittal-plane motion; z = transverse-plane motion, and then converted to Microsoft Excel 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. See figure 1 for depiction of SEBT performance with laboratory setup.

Data Analysis and Statistics

For the LAS group, the injured limb was labeled as ‘‘involved’’ and the non-injured limb as ‘‘uninvolved’’. In all cases the limbs in the control group were side matched to the injured group; for each control subject, one limb was assigned as ‘‘involved’’ and one as

''uninvolved'' so that an equal proportion of right and left limbs were classified as ''involved'' and ''uninvolved'' in both the LAS and control groups.

Participant Characteristics

Participant characteristics were compared between the LAS and control groups using multivariate analysis of variance. The dependent variables were age, body mass, gender and height. The independent variable was group (LAS *vs* control). Preliminary assumption testing was conducted to check for normality, linearity, univariate and multivariate outliers, homogeneity of variance-covariance matrices and multicollinearity, with no serious violations noted. The significance level of this analysis was set a priori at $p < 0.05$.

SEBT Reach Distance Scores

Two one-way between groups analyses of variance tests were conducted for each limb (involved and uninvolved) to test the hypothesis that the LAS group would demonstrate decreased reach distances for the ANT, PL and PM reach directions of the SEBT compared to the control group on matched limbs. The independent variable was group (LAS *vs* control). The dependent variable was the average reach distance achieved in the three reach attempts for the ANT, PL and PM reach directions. Associated effect sizes (η^2) were calculated with 0.01 = small effect size, 0.06 = medium effect size and 0.14 = large effect size.[30] The significance level for this analysis was set a priori with a Bonferonni adjusted alpha level of 0.025.

The average of three trials for all reach distance, kinematic and kinetic variables for both limbs of every participant in each direction was utilized for analysis.

Kinematics

To test the hypothesis that the LAS group would exhibit altered dynamic postural control kinematic strategies compared to the control group, discrete joint angular displacement values were calculated 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 nine 'joint position' dependent variables of interest were analyzed for the involved and uninvolved limbs. A similar approach has been previously published by Delahunt et al.[13] A multivariate analysis of variance was undertaken for each reach direction to compare the kinematics at the point of maximum reach between LAS and control participants' involved and uninvolved limbs. The dependent variables were sagittal, frontal and transverse plane motion for the hip, knee and ankle joints. The independent variables were group (LAS *vs* control) and limb (involved *vs* uninvolved). When a significant effect was observed for the interaction of group and limb, post hoc tests using independent samples t-tests between involved and uninvolved limbs of the LAS and control groups for each direction was undertaken. Preliminary assumption testing was conducted to check for normality, linearity, univariate and multivariate outliers, homogeneity of variance-covariance matrices and multicollinearity, with no serious violations noted. Associated effect sizes (η^2) were calculated with 0.01 = small effect size, 0.06 = medium effect size and 0.14 = large effect size[30]. The significance level for this analysis was set a priori with a Bonferonni adjusted alpha level of 0.017. P-values for post-hoc testing were adjusted for multiple tests using the Benjamini-Hochberg method for false discovery rate (FDR) (< 5%).[31]

Following this, 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 significant findings at the point of maximum reach was performed. Between group differences in involved and uninvolved limb time-averaged profiles were tested for statistical significance using

independent-samples t-tests for each data point. The significance level for this analysis was set a priori at $p < 0.05$. 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] In the aim of reporting conciseness, those time-averaged profiles where between-group differences did not exceed fifty percent of total trial length were not reported. 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 to the control group, two-way between-groups analyses of variance were conducted for the involved and uninvolved limbs for each reach direction of the SEBT. The independent variables were SEBT direction (ANT, PL and PM) and group (LAS *vs* control). When a significant effect was observed for group, post hoc tests using independent samples t-tests was undertaken. Preliminary assumption testing was conducted to check for normality, linearity, univariate and multivariate outliers, homogeneity of variance-covariance matrices and multicollinearity. Levene's Test of Equality Error Variances revealed indicated a violation in the assumption in the equality of variance for the FD of the ANT, PL and PM reach directions. Therefore, the significance level for this analysis was set a priori with a Bonferonni adjusted alpha level of 0.0125 (0.025/2). P-values for post-hoc testing were adjusted for multiple tests using the Benjamini-Hochberg method for false discovery rate (FDR) (< 5%).[31] All statistical analyses were performed with IBM SPSS Statistics 20 (IBM Ireland Ltd, Dublin, Ireland).

RESULTS

Participant Characteristics and Questionnaire Results

There was no statistically significant difference between the LAS and control groups on the combined dependent variables, F (4, 93) = 1.86, p = 0.12; Wilks' Lambda = 0.92; partial eta squared = 0.07. Regarding function, the CAIT score for the LAS group was 11.23 ± 8.09. The FAAMadl score for the LAS group was 57.66 ± 28.03%. The FAAMsport score for the LAS group was 32.19 ± 26.66%. Participant characteristics and questionnaire score are detailed in Table 1.

SEBT Reach Distance Scores

Regarding SEBT performance, there was a significant between-group difference at the level of $p < 0.05$ with a FDR < 5% for the three reach directions. The LAS group achieved significantly lower normalized reach distances for their involved (ANT: 58.16 ± 6.86% *vs* 64.86 ± 5.99%; PL: 85.64 ± 10.62% *vs* 101.14 ± 8.39%; PM: 94.89 ± 9.26% *vs* 107.29 ± 6.02%) and uninvolved (ANT: 60.98 ± 6.74% vs. 64.76 ± 5.02%; PL: 88.95 ± 11.45% *vs* 102.36 ± 8.53%; PM: 97.13 ± 8.76% *vs* 106.62 ± 5.78%) limbs. The effect sizes for the involved limb in the ANT direction was 0.18, in the PL direction was 0.29, and in the PM direction was 0.27. The effect sizes for the uninvolved limb in the ANT direction was 0.06, in the PL direction was 0.20, and in the PM direction was 0.19.

Kinematics

There was a statistically significant interaction between group and limb for the ANT (F [9,154] = 15.611, p = 0.000, Wilks' Lambda = 0.523; partial eta squared = 0.477), PL (F [9,151] = 3.277, p = 0.001, Wilks' Lambda = 0.837; partial eta squared = 0.163) and PM (F

[9,150] = 32.476, p = 0.000, Wilks' Lambda = 0.339; partial eta squared = 0.661) reach directions. Post-hoc testing with a FDR of < 5% revealed between-group differences for a number of the dependent variables for the involved and uninvolved limbs (Table 2).

Time-averaged sagittal kinematic profiles were plotted based on between-group differences at the point of maximum reach, provided these differences existed across >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).

Fractal Dimension

The interaction effect between group and direction was not statistically significant for the involved (F [2,228] = 0.4, p = 0.672) or uninvolved (F[2,228] = 0.9, p = 0.375) limbs. There was a statistically significant main effect for group for the involved limb only (F [2,228] = 32.809, p = 0.000, partial eta squared = 0.13) Post-hoc testing at the level of $p < 0.05$ with a FDR of < 5% revealed that the LAS group had significantly reduced COP path trajectory FD compared to the control group for all reach directions on the involved limb (Table 3).

DISCUSSION

This is the first investigation to explore the movement patterns associated with acute LAS injury 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 findings confirm our hypotheses as follows: (1) acute LAS injury causes functional impairment, as revealed by CAIT, FAAMadl and FAAMsport questionnaire scores; (2) acute LAS results in a bilateral reduction in selected reach distance scores of the SEBT, with associated large effect sizes for 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; (3) sagittal plane kinematic profiles revealed a reduction in flexion displacement at the hip, knee and ankle. This finding may have been a biological substrate of a reduction in COP path trajectory fractal dimension, which indicated a change in the postural control strategies used by LAS participants on their involved limb only. Discrete 3D 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 on the dependent variables of age, sex, body mass and height.

Despite unilateral injury, bilateral impairment was observed for the distance achieved on each of the reach directions assessed (i.e. ANT, PM and PL). In a laboratory analysis of the SEBT Gribble et al.[12], reported decreased performance in a group with CAI on their involved side only. That investigation compared 2-dimensional kinematics of the sagittal-plane positions of the hip, knee and ankle joints of the stance leg at the point of maximum reach between participants with and without CAI. In a follow-up study, regression analyses were employed to determine the influence that CAI and these same kinematic variables might have had on reach distance scores.[11] Findings from these studies elucidated that sagittal plane hip and knee flexion displacements contributed most to the deficits observed during SEBT performance between CAI and control groups, which is in agreement with the findings of

Robinson and Gribble in non-pathological groups.[32] This is likely due to the large muscle groups responsible for controlling these joints which are vital for both motion and stability during dynamic tasks.[10] The current investigation differs from the aforementioned papers in its sample population (of acutely injured participants), in the addition of transverse plane motion to discrete analyses, and in that temporal analyses of hip, knee and ankle sagittal plane motion were provided 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 similar trends to those observed in groups in the chronic phase of ankle sprain injury: a reduction in the primary determinants of test outcome (hip and knee flexion displacement) was observed both at point of maximum reach and throughout the reach attempt for all three reach directions of the SEBT assessed, on both 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 are typically expressed elsewhere in the kinetic chain.[34]

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 reveals that sagittal plane ankle ROM deficit was linked with similar restrictions at the hip and knee on the involved limb. This was not the case on the uninvolved limb, where proximal restriction had no such corollary at the ankle joint (in the ANT and PM directions). Therefore, in theorizing the source of restriction to be the same for both involved and uninvolved limbs, we consider proximal ROM to be the source of distal ROM deficit,

sometimes manifesting further down the kinetic chain. However, in theorizing the source of deficit to be different for each limb, we consider that factors such as swelling and pain with excessive ankle ROM restricted proximal corollaries of knee and hip movement on the involved limb, and that other factors restricted movement on the uninvolved limb. The absence of local maladies associated with the acute injury on the uninvolved limb lends to a hypothesis that ankle sprain has the capacity to cause spinal-level inhibition and postural control impairment secondary to the onset of gamma motor neuron loop dysfunction.[35] The conscious perception of swelling and pain associated with the acute LAS in the current sample during the SEBT may have had the capacity to cause supraspinal inhibition, thus impairing dynamic postural control strategies. In summary, we believe a convergence of both peripheral and central impairment is present following acute LAS: injury may result in a motor-sensory mismatch in which there is a dissociation between actual sensory input and predicted sensory input.[36,37] This mismatch during the performance of a given motor task generates a sensory disturbance, which is expressed in the form of local and distal anomalous movement patterns.[36] Our findings are in agreement with the results presented by Wikstrom et al.[38] in their recent meta-analysis, who concluded that postural control deficits are present on both the injured (involved) and non-injured (uninvolved) limbs of patients with acute LAS.

The consistency that existed in the observation of movement pattern deficits in sagittal plane flexion displacements during the SEBT allowed simple comparison between the LAS and control groups, where deficits were determined by a reduction in ROM. In contrast, significantly 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 in view of the pleiotropic nature of the

neurobiological system. The intricacies of the interaction between the varieties of movement are open to interpretation, an interpretation that can only be allowed by the provision of the aforementioned variables. Hence we have sought to provide insight into these variables, without theorizing as to their specific importance; all components of the neurobiological kinetic chain affect each other in an intricate way, 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: in the aim of providing greater insight into 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 in an attempt at neutralizing the effect of the original error.[39] Full temporal kinematic profiles for all joints in all three dimensions presents consequences for reporting succinctness and therefore were not presented.

The use of platform stabilometry in the current investigation was performed as an additional means to classify the postural control strategies used by LAS participants during a dynamic balance task. By calculating the FD of 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 (i.e. performance of selected reach directions of the SEBT) combined with injury. 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 on the involved limb of the LAS group compared to the control group, which we perceive to either indicate a reduced

ability to utilize the base of support available, or the injury-confined activity of the sensorimotor system in completing the prescribed task.[18] That there was no reduction of FD on the uninvolved limb suggests that the absence of a peripheral impairment allowed sufficient interaction between higher and lower levels of the postural control system in the delivery of a performance which, although less successful than control participants (as demonstrated by reduced reach distances and altered kinematic profiles), was sufficient in its exploitation of the available base of support. With this in mind it is important to consider that the utilization 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.

In conclusion, the current analysis has presented a comprehensive evaluation of the effects of a first-time acute LAS injury on SEBT performance using a number of measures. Modifications in temporal and discrete kinematic measures and a reduced ability to effectively utilize the available base of support can be seen to result in SEBT performance impairment, secondary to injury-associated functional impairment. In light of these findings clinicians must consider the early administration of rehabilitation protocols following acute ankle sprain, bilaterally, with similar emphasis on regaining neuromuscular function in proximal as well as 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, while our results are relevant to researchers and clinicians alike, a number of limitations of the current study must be noted. First, due to the design of the current study, it is unknown as to whether the deficits presenting in the LAS group precede or occur as a result of their acute injury, and whether these deficits are precursors to chronicity. Future longitudinal analyses should seek to elucidate as to whether some of the deficits observed in

426 the acute phase of ankle sprain injury actually precede (and predispose) the initial acute
427 injury, and clarify which key deficits are central to the onset of chronicity.
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561 Figure legends

562 Figure 1. Laboratory setup of the Star Excursion Balance Test for the anterior, postero-lateral
563 and postero-medial reach directions.

564

565 Figure 2. Hip-joint flexion-extension angle during performance of the anterior (ANT)
566 directional component of the Star Excursion Balance Test (SEBT) for the uninvolved limb of
567 LAS and control groups. Flexion is positive; extension is negative; values are mean ± SEM.
568 Shaded area = area of statistical significance. Gradient black line = point of maximum reach.
569 Abbreviation: LAS = lateral ankle sprain.

570

571 Figure 3. Knee-joint flexion-extension angle during performance of the anterior (ANT)
572 directional component of the Star Excursion Balance Test (SEBT) for the involved limb of
573 LAS and control groups. Flexion is positive; extension is negative; values are mean ± SEM.
574 Shaded area = area of statistical significance. Gradient black line = point of maximum reach.
575 Abbreviation: LAS = lateral ankle sprain.

576

577 Figure 4. Ankle-joint dorsiflexion-plantarflexion angle during performance of the anterior
578 (ANT) directional component of the Star Excursion Balance Test (SEBT) for the involved
579 limb of LAS and control groups. Dorsiflexion is positive; plantarflexion is negative; values
580 are mean ± SEM.
581 Shaded area = area of statistical significance. Gradient black line = point of maximum reach.
582 Abbreviation: LAS = lateral ankle sprain.

583

Figure 5. Hip-joint flexion-extension angle during performance of the posterior-lateral (PL) directional component of the Star Excursion Balance Test (SEBT) for the involved limb of LAS and control groups. Flexion is positive; extension is negative; values are mean ± SEM. Shaded area = area of statistical significance. Gradient black line = point of maximum reach. Abbreviation: LAS = lateral ankle sprain.

Figure 6. Hip-joint flexion-extension angle during performance of the posterior-lateral (PL) directional component of the Star Excursion Balance Test (SEBT) for the uninvolved limb of LAS and control groups. Flexion is positive; extension is negative; values are mean ± SEM. Shaded area = area of statistical significance. Gradient black line = point of maximum reach. Abbreviation: LAS = lateral ankle sprain.

Figure 7. Knee-joint flexion-extension angle during performance of the posterior-lateral (PL) directional component of the Star Excursion Balance Test (SEBT) for the involved limb of LAS and control groups. Flexion is positive; extension is negative; values are mean ± SEM. Shaded area = area of statistical significance. Gradient black line = point of maximum reach. Abbreviation: LAS = lateral ankle sprain.

Figure 8. Hip-joint flexion-extension angle during performance of the posterior-medial (PM) directional component of the Star Excursion Balance Test (SEBT) for the involved limb of LAS and control groups. Flexion is positive; extension is negative; values are mean ± SEM. Shaded area = area of statistical significance. Gradient black line = point of maximum reach. Abbreviation: LAS = lateral ankle sprain.

Figure 9. Hip-joint flexion-extension angle during performance of the posterior-medial (PM) directional component of the Star Excursion Balance Test (SEBT) for the uninvolved limb of LAS and control groups. Flexion is positive; extension is negative; values are mean ± SEM. Shaded area = area of statistical significance. Gradient black line = point of maximum reach. Abbreviation: LAS = lateral ankle sprain.

Figure 10. Knee-joint flexion-extension angle during performance of the posterior-medial (PM) directional component of the Star Excursion Balance Test (SEBT) for the involved limb of LAS and control groups. Flexion is positive; extension is negative; values are mean ± SEM.
Shaded area = area of statistical significance. Gradient black line = point of maximum reach. Abbreviation: LAS = lateral ankle sprain.

Figure 11. Knee-joint flexion-extension angle during performance of the posterior-medial (PM) directional component of the Star Excursion Balance Test (SEBT) for the uninvolved limb of LAS and control groups. Flexion is positive; extension is negative; values are mean ± SEM.
Shaded area = area of statistical significance. Gradient black line = point of maximum reach. Abbreviation: LAS = lateral ankle sprain.