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Original Research

Bilateral spatiotemporal postural control impairments are present in participants with chronic ankle instability

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ABSTRACT

Objectives: This study evaluated center-of-pressure (COP) and time-to-boundary (TTB) measures of postural control during a Lateral Step-Down Test in participants with chronic ankle instability (CAI).
Design: Cohort study.
Setting: Biomechanics laboratory.
Participants: Physically active adults with CAI (n = 15) and matched controls (n = 15).
Main outcome measures: Traditional COP and TTB measures of postural control were computed in the medial/lateral (ML) and anterior/posterior (AP) directions.
Results: No significant results were found for the traditional COP measures ($p > 0.05$). The CAI group exhibited a lower TTB ML absolute minimum on their affected limb compared to the matched limb of the control group ($p < 0.001$). Additionally, on average the CAI group displayed significantly lower TTB ML mean of minima ($p = 0.004$) and TTB standard deviation of minima in the ML ($p < 0.001$) and AP directions ($p = 0.002$) regardless of limb.
Conclusions: Sensorimotor impairments associated with CAI negatively alter spatiotemporal postural control and may cause a maladaptive reorganization of centrally mediated motor control strategies that results in bilateral postural control deficits during the Lateral Step-Down Test. In addition, traditional COP measures did not reveal any postural control deficits suggesting that a spatiotemporal analysis should be used when assessing postural control in participants with CAI.

1. Introduction

Despite extensive research examining the mechanisms and treatment of lateral ankle sprains over the last several decades, this injury remains the most common musculoskeletal injury sustained in athletics and the general population (Doherty et al., 2014a). A low percentage of individuals (~30%) will return to high-level activity without any residual impairments following a lateral ankle sprain (McKay, Goldie, Payne, & Oakes, 2001), and consequently, the vast majority (~70%) will experience recurrent injuries (van Rijn et al., 2008), persistent pain and swelling (Hertel, 2000), decreased self-reported physical activity (Hubbard-Turner, Turner, Burcal, Song, & Wikstrom, 2018), and a continuum of sensorimotor and mechanical impairments following the initial injury (Hertel, 2008). Similarly, these factors have been suggested to contribute to the complex spectrum of long-term joint dysfunction, or chronic ankle instability (CAI), resulting in subjective feelings of ankle joint instability and/or episodes of the ankle giving way leading to recurrent injuries (Hertel, 2002; Tanen, Docherty, Van Der Pol, Simon, & Schrader, 2014).

Postural control deficits are frequently reported following an acute lateral ankle sprain (Doherty et al., 2015a; Wikstrom, Fournier, & McKeon, 2010a, b) and in individuals with CAI (Hertel & Olmsted-Kramer, 2007; Hoch, Staton, McKeon, Mattacola, & McKeon, 2012), suggesting that poor postural control is one contributing factor to the CAI paradigm. Unilateral weight-bearing

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exercises such as the Star Excursion Balance Test (SEBT) and the Lateral Step-Down Test are commonly used clinical tests to evaluate dynamic postural control and lower extremity injury potential (Claiborne, Armstrong, Gandhi, & Pincivero, 2006; Gribble, Hertel, & Plisky, 2012). Performance on the SEBT in individuals with CAI has been extensively evaluated in the literature with reports of reductions in reach distance, most notably in the anterior direction (Doherty et al., 2016a, 2016b; Hoch et al., 2012; McCann et al., 2017). The impairments in dynamic postural control often result from the underlying sensorimotor impairments associated with CAI (Hertel, 2008), but recent evidence indicates that mechanical impairments are also contributing factors to poor dynamic postural control during the SEBT (Hoch et al., 2012). Moreover, studies that evaluate other types of dynamic unilateral weight-bearing exercises in participants with CAI have also identified significant alterations to lower extremity movement mechanics during gait (Moisan, Descarreaux, & Cantin, 2017) and jump-landings (Simpson, Stewart, Macias, Chander, & Knight, 2018), as well as a proximal to distal joint movement strategy resulting in reduced dynamic postural control (Gribble & Robinson, 2009).

The Lateral Step-Down Test is a clinical measure that requires coordination of multiple lower limb joints, neuromuscular control, strength, pelvic stability, and adequate range of motion (Claiborne et al., 2006). Although this assessment has been shown to detect lower limb movement impairments in individuals with CAI (Grindstaff, Dolan, & Morton, 2017), the resultant postural control strategies exhibited while performing the Lateral Step-Down Test in individuals with CAI are currently unknown. Quantifying the rate and magnitude of center of pressure (COP) excursions is the most common method of assessing postural control, but recent evidence suggests that traditional COP measures may not adequately detect postural control deficits in participants with CAI (Hertel & Olmsted-Kramer, 2007; Hertel, Olmsted-Kramer, & Challis, 2006; Wikstrom et al., 2010b; McKeon & Hertel, 2008a, 2008b). Time-to-boundary (TTB) is a spatiotemporal analysis that estimates the time it would take the COP to reach the limits of the base of support if the COP trajectory were to continue with its instantaneous directional velocity (Hertel et al., 2006). Lower TTB indicates an individual has less time to execute a postural correction in order to preserve the COP within the boundaries of the base of support, resulting in greater postural instability. Additionally, TTB measures have been shown to be poorly correlated with traditional COP measures and research suggests that TTB measures are a more sensitive measure to detect postural control deficits in individuals with CAI (Hertel et al., 2006; Hertel & Olmsted-Kramer, 2007).

Recent studies have examined traditional COP excursions during the SEBT in healthy (Keith, Condon, Phillips, McKeon, & King, 2016) and CAI populations (Jaber et al., 2018), which enhance the understanding of the sensorimotor and mechanical constraints that contribute to poor dynamic postural control. However, a lack of consistency detecting postural control deficits using traditional COP measures in individuals with CAI (Hertel & Olmsted-Kramer, 2007; McKeon & Hertel, 2008a, 2008b; Wikstrom et al., 2010b) warrants the use of a spatiotemporal analysis such as TTB to quantify postural control during functional exercises. Examining COP excursions during the Lateral Step-Down Test, a relevant clinical assessment that has received little attention in the CAI literature (Grindstaff et al., 2017), would advance our understanding of the underlying mechanisms associated with poor postural control during unilateral weight-bearing exercises in individuals with CAI. Therefore, the purpose of this study was to assess traditional COP and TTB measures of postural control during a Lateral Step-Down Test in individuals with and without self-reported unilateral CAI. We hypothesized that individuals with CAI would demonstrate deficits in COP and TTB measures of postural control during the Lateral Step-Down Test in comparison to healthy controls.

2. Methods

2.1. Participants

Individuals with self-reported unilateral CAI ($n = 15$) and healthy controls ($n = 15$) matched based on age, mass, height, and sex that were actively participating in competitive and/or recreational sports were recruited from a university campus (Table 1). Healthy controls had no history of an ankle sprain to either ankle, while participants with CAI were required to meet all of the following criteria: (i) self-reported a history of 2 or more lateral ankle sprains with 1 of those lateral ankle sprains occurring more than 3 months prior to study participation, (ii) sustained a lateral ankle sprain that required non-weight bearing activity or immobilization for $\geq$24 h, (iii) a history of recurrent sprain, the ankle "giving way", or "feelings of instability" on the affected ankle, and (iv) scored 24 or less the Cumberland Ankle Instability Tool (CAIT) (Gribble et al., 2014). Exclusion criteria for both groups included a history of surgery or fracture to either lower extremity, any musculoskeletal injury to the lower extremity within the last 6 months, ankle sprain within the last 3 months (CAI group only), or a diagnosed musculoskeletal or neurological disorder. Participants were also excluded if they were currently receiving rehabilitative care for any lower extremity injury (including ankle sprain for CAI), or had any condition that could negatively affect their performance on the Lateral Step-Down Test.

For the CAI group, limbs were labeled as "affected" and "unaffected" based on ankle sprain history of the participants, while the "affected" and "unaffected" limbs were matched to the preferred and non-preferred limbs of the control group, respectively. Limb preference was determined by asking participants which leg they would use to kick a ball (Simpson et al., 2019). Limbs were then matched between the groups such that the "affected" and "unaffected" limb of the CAI group matched the preferred and non-preferred limbs of the control group.

Prior to participating in the study, all participants provided consent by reading and signing an informed consent document that outlined study procedures. Additionally, participants were asked to complete the CAIT questionnaire and subjectively report their total number of lateral ankle sprain occurrences. Ethical approval for all study procedures was granted from the Institutional Review Board at the authors' university prior to initiating data collection procedures.

2.2. Procedures

Participants were required to complete a total of two testing sessions. The first session was a familiarization session, which provided each participant with an explanation of testing procedures and the opportunity to practice the Lateral Step-Down Test as much as desired. The primary investigator provided the instructions for completing the Lateral Step-Down Test during the familiarization session, and following completion of the familiarization session, a single testing session was completed within two days.

Upon arrival to the laboratory for the single testing session, each participant was given 5 min to complete a self-selected warm-up. Participants then completed the Lateral Step-Down Test in the barefoot condition on a custom-built platform. An AccuGait force platform (Advanced Medical Technology, Inc., Watertown, MA, USA) was embedded and raised 25 cm above the ground to record the COP trace at 100 Hz during the Lateral Step-Down Test using

Table 1
Participants anthropometric and Cumberland Ankle Instability Tool scores (mean ± SD).

Variable	CAI ($n = 15$)	Control ($n = 15$)	*P* Value
Age (y)	21.3 ± 1.6	21.5 ± 1.5	0.730
Height (cm)	171.0 ± 11.2	169.9 ± 10.6	0.788
Mass (kg)	73.4 ± 15.2	75.5 ± 13.0	0.698
CAIT Score	18.9 ± 3.7	29.7 ± 0.6	<0.001
Total Ankle Sprains[a]	6.0 ± 3.2	0.0 ± 0.0	<0.001
Foot Length (cm) Dominant Non-Dominant	25.7 ± 2.0 25.6 ± 2.0	25.2 ± 1.9 25.3 ± 2.0	0.492 0.612
Foot Width (cm) Dominant Non-Dominant	10.4 ± 0.9 10.3 ± 0.8	10.3 ± 0.7 10.3 ± 0.7	0.674 0.891

[a] Indicates subjectively reported variable.

MotionMonitor software (Innovative Sports Training, Inc., Chicago, IL, USA). To maintain consistency between participants during the Lateral Step-Down Test, participants were instructed to place their testing foot on the force platform, keep their hands on their hips and eyes facing forward, and place their contralateral limb anterolateral to the testing limb (Grindstaff et al., 2017). Participants were then instructed to maintain full weight bearing on the testing limb, descend the contralateral limb 25 cm and make contact with their heel on a second force platform placed beneath them, without shifting 25% of their weight onto the contralateral limb, and subsequently ascend back the standing position (Fig. 1). Participants were instructed to descend/ascend at their own self-selected pace during the Lateral Step-Down Test.

Each participant completed 5 successful trials of the Lateral Step-Down Test on each limb (10 total trials) with 30 s rest between trials. The testing order (affected or unaffected limb) was counterbalanced between participants. Failed attempts were marked and trials were repeated if any of the following occurred: (i) failure to maintain balance on the testing limb, (ii) removal of either hand from the participants' hips, (iii) failure to record a vertical ground reaction force of at least 20 N with the contralateral limb, (iv) the contralateral limb touched the testing limb or the platform, or (v) if the participants shifted more than 25% of their weight to their contralateral limb, which was verified by the second force platform they were required to touch with the contralateral limb during the Lateral Step-Down Test (Fig. 1).

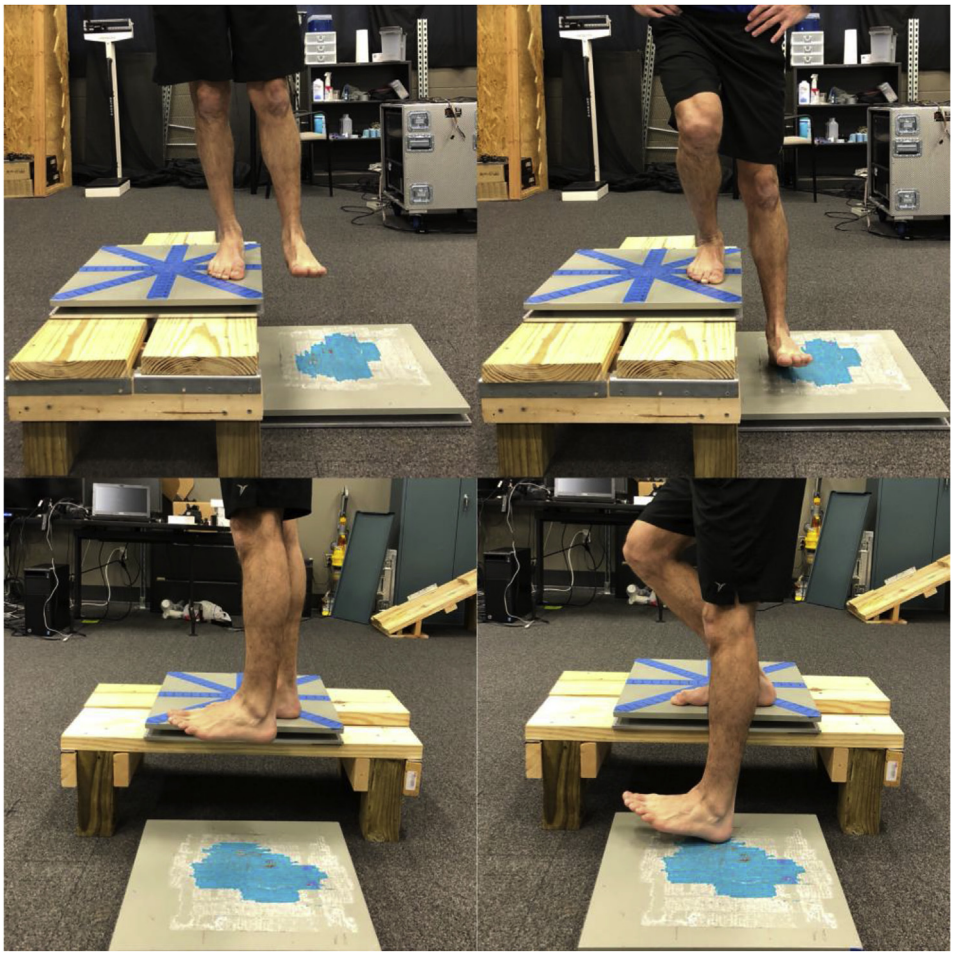

Fig. 1. Force platform arrangement and the Lateral Step-Down Test.
*Participants kept the testing foot on the force platform for the entire trial. From the starting position (left), participants lowered the contralateral limb and touched the second force platform placed 25
cm beneath them (right) and then ascended back to the starting position (left).

2.3. Data processing

2.3.1. Center of pressure

The COP trace that was recorded from the force platform was exported to an Excel (Microsoft Corporation, Redmond, WA, USA) spreadsheet and eight traditional COP measures were computed. Mean COP velocity (equation (1)) and root-mean-square (RMS) excursions (equation (2)) of the COP were calculated in the medial/lateral (ML) and anterior/posterior (AP) directions. Additionally, the range of the COP excursions (equation (3)) and percent of the available range used (equation (4)) were also calculated in the ML and AP directions, respectively.

$$\text{Mean COP Velocity (cm/s)} = \left(\frac{1}{t}\right)\sum_{i=0}^{n}\left|COP_i - COP_{i-1}\right| \quad (1)$$

$$\text{RMS Excursions (cm)} = \sqrt{\left(\frac{1}{n}\right)\sum_{i=0}^{n}\left(COP_i - COP_{avg}\right)^2} \quad (2)$$

$$\text{COP Range (cm)} = COP_{max} - COP_{min} \quad (3)$$

$$\text{Percent of Range Used (\%)} = \left(\frac{\text{COP Range [ML or AP]}}{\text{Foot Length [ML] or Width [AP]}}\right) \times 100 \quad (4)$$

2.3.2. Time-to-boundary

TTB measures were also calculated from the COP trace based on previously published guidelines (Hertel et al., 2006). Each participant's foot length and width were measured using the Arch Height Index Measurement System (JAKTOOL, Cranbury, NJ, USA). These measurements were used to model the participants' foot as a rectangle to determine their boundaries of the base of support. The raw COP data was first separated into ML and AP components and then the COP position and velocity were determined for each individual data point. Instantaneous COP positions were then used to calculate the distance to the ML and AP border of the foot, respectively. This distance was then divided by the corresponding directional velocity to calculate TTB in the ML and AP directions. These calculations were completed for every 0.01 s during each trial and in each respective direction. A typical TTB data series contains peaks (maxima) and valleys (minima). Each TTB minima represents the lowest point in time prior to a change in the direction of the COP, where the COP is closest in time to the boundaries of the base of support, and potential points of postural instability. The first and second signal derivatives were computed to identify the TTB minima for each trial and the absolute, mean, and standard deviation (SD) of the TTB minima in the ML and AP directions were analyzed (Hertel et al., 2006). The TTB absolute minimum represents the lowest valley (i.e. fastest TTB) during the entire trial, while TTB mean of minima and TTB SD of minima represents the average and variability of all the valleys (minima) identified for the entire trial, respectively. A cumulative average of the 5 successful trials on each limb was computed and used in the statistical analysis.

2.4. Statistical analysis

Mean ± SD, 95% confidence intervals, and Cohens D effect size data were computed for all dependent variables. Effect sizes (ES) were used to determine the magnitude of difference and was interpreted as small (ES < 0.40), moderate (ES = 0.40–0.80), and large (ES > 0.80) (Cohen, 1992). Independent samples *t*-tests were computed to compare anthropometric measures and CAIT scores between CAI and control groups. To compare COP and TTB measures, a series of 2 (group) x 2 (limb) mixed model analyses of variance (ANOVA) with repeated measures on the limb variable were computed. A Tukey's Least Significant Difference post hoc test was computed when significant interactions were observed. All statistical analyses were computed using SPSS Statistics (Armonk, NY, USA) and statistical significance was considered when $p \leq 0.05$.

3. Results

Results from the independent samples *t*-test revealed no significant differences between groups in age, height, mass, foot length or foot width. Significantly lower scores on the CAIT were reported for the CAI group in comparison to controls, with the CAI group subjectively reporting a significantly greater amount of lateral ankle sprain occurrences than controls. Descriptive data of the participants and scores on the CAIT questionnaire can be found in Table 1.

A significant interaction was observed for TTB ML absolute minimum ($p = 0.002$). Post hoc analysis revealed that the CAI group displayed a significantly lower TTB ML absolute minimum on the affected limb compared to the matched limb of the control group ($p < 0.001$; ES = 2.00; CAI: 0.19 ± 0.04 s vs Control: 0.31 ± 0.07 s). Significant group main effects were also observed and pairwise comparisons revealed that the CAI group on average demonstrated significantly less TTB ML mean of minima ($p = 0.004$; ES = 0.87; CAI: 0.78 ± 0.17 s vs. Control: 0.93 ± 0.18 s), TTB ML SD of minima ($p < 0.001$; ES = 1.13; CAI: 0.89 ± 0.32 s vs. Control: 1.40 ± 0.44 s) and TTB AP SD of minima ($p = 0.002$; ES = 0.94; CAI: 1.13 ± 0.48 s vs. Control: 1.60 ± 0.49 s) compared to the control group regardless of limb.

With respect to the traditional COP measures, no significant group × limb interactions, group or limb main effects for any of the eight traditional COP measures were observed ($p > 0.05$; ES = 0.01–0.55). The raw COP and TTB data can be found in Tables 2 and 3, while combined data that represents the group main effects are displayed in Fig. 2.

4. Discussion

This study was conducted to determine if the postural control impairments previously reported during unilateral weight-bearing exercises in individuals with CAI (Hertel & Olmsted-Kramer, 2007; McKeon & Hertel, 2008a, 2008b; Wikstrom et al., 2010b) would also be exhibited during a Lateral Step-Down Test as quantified by traditional COP and TTB measures of postural control. Our results revealed that the CAI group exhibited significantly lower TTB measures of postural control during the Lateral Step-Down Test when compared to healthy controls. Contrary to our hypothesis that the CAI group would demonstrate greater traditional COP measures of postural control, no significant differences between CAI and control groups were observed. Therefore, we were only able to partially confirm our initial hypothesis. To our knowledge, this was the first study to quantify postural control using both traditional COP and TTB measures during a Lateral Step-Down Test in individuals with and without self-reported unilateral CAI.

Evaluating postural control using traditional COP measures have led to inconsistent findings in the CAI literature (Wikstrom et al., 2010b; Rendos et al., 2017), but some studies have shown reduced postural sway as a compensatory mechanism for ankle stability deficits while performing functional exercises (dos Santos, Gorges, & Rios, 2014; Rios, Gorges, & dos Santos, 2015). However,

Table 2
Center of pressure (COP) measures (mean ± SD) for the CAI and control groups on the Lateral Step-Down Test.

Variable	Group		*P* Value (ES)		95% Confidence Interval of the Difference	
	CAI	Control	Group	Limb	Group (Lower, Upper)	Limb (Lower, Upper)
COP RMS ML (cm) affected limb unaffected limb	0.82 ± 0.18 0.82 ± 0.13	0.75 ± 0.16 0.84 ± 0.29	0.678 (0.10)	.374 (0.21)	−0.09, 0.13	−0.15, 0.06
COP RMS AP (cm) affected limb unaffected limb	1.85 ± 0.55 2.05 ± 0.65	1.86 ± 0.74 1.95 ± 0.65	0.798 (0.06)	.361 (0.22)	−0.33, 0.42	−0.46, 0.17
COP ML velocity (cm/s) affected limb unaffected Limb	4.24 ± 0.90 4.32 ± 0.52	4.02 ± 0.86 4.89 ± 1.21	0.413 (0.17)	.069 (0.55)	−0.61, 0.26	−0.99, 0.04
COP AP velocity (cm/s) affected limb unaffected limb	7.94 ± 1.59 8.16 ± 1.55	7.69 ± 1.72 8.34 ± 1.97	0.936 (0.21)	.291 (0.25)	−0.94, 1.02	−1.26, 0.39
COP ML range (cm) affected limb unaffected limb	3.21 ± 0.69 3.21 ± 0.53	2.84 ± 0.58 3.30 ± 0.97	0.445 (0.18)	.231 (0.31)	−0.23, 0.51	−0.61, 0.15
COP AP range (cm) affected limb unaffected limb	7.33 ± 2.21 7.81 ± 2.36	6.71 ± 1.89 7.36 ± 1.92	0.387 (0.28)	.231 (0.26)	−0.72, 1.80	−1.52, 0.382
ML ranged used (%) affected limb unaffected limb	30.84 ± 6.67 31.46 ± 4.53	27.55 ± 4.94 31.84 ± 7.42	0.356 (0.24)	.124 (0.41)	−1.73, 4.65	−5.62, 0.72
AP range used (%) affected limb unaffected limb	28.69 ± 8.89 30.86 ± 8.98	26.85 ± 8.34 29.42 ± 8.25	0.515 (0.20)	.229 (0.28)	−3.50, 6.74	−6.32, 1.58

Table 3
Time-to-boundary (TTB) measures (mean ± SD) for the CAI and control groups on the Lateral Step-Down Test.

Variable	Group		*P* Value (ES)		95% Confidence Interval of the Difference	
	CAI	Control	Group	Limb	Group (Lower, Upper)	Limb (Lower, Upper)
TTB ML absolute minimum (s) affected limb unaffected limb	0.19 ± 0.04[b] 0.19 ± 0.05	0.31 ± 0.07 0.22 ± 0.07	0.004 (1.09)	0.005 (0.73)	−0.11, −0.04	0.02, 0.07
TTB AP absolute minimum (s) affected limb unaffected limb	0.29 ± 0.10 0.30 ± 0.12	0.36 ± 0.09 0.31 ± 0.12	0.217 (0.33)	0.363 (0.19)	−0.09, 0.02	−0.03, 0.07
TTB ML mean of minima (s) affected limb unaffected Limb	0.79 ± 0.19 0.77 ± 0.15	0.96 ± 0.14[a] 0.90 ± 0.21[a]	0.004 (0.87)	0.288 (0.24)	−0.25, −0.05	−0.04, 0.13
TTB AP mean of minima (s) affected limb unaffected limb	1.04 ± 0.25 1.13 ± 0.26	1.20 ± 0.29 1.18 ± 0.37	0.251 (0.31)	0.585 (0.11)	−0.28, 0.08	−0.17, 0.10
TTB ML SD of minima (s) affected limb unaffected limb	0.85 ± 0.27 0.94 ± 0.43	1.40 ± 0.45[a] 1.40 ± 0.43[a]	<0.001 (1.13)	0.600 (0.09)	−0.74, −0.26	−0.21, 0.13
TTB AP SD of minima (s) affected limb unaffected limb	0.93 ± 0.33 1.33 ± 0.64	1.63 ± 0.43[a] 1.56 ± 0.55[a]	0.002 (0.94)	0.174 (0.29)	−0.74, −0.19	−0.43, 0.08

[a] Denotes significantly different than CAI group ($p < 0.05$).
[b] Denotes significantly different than the matched limb of the control group ($p < 0.05$).

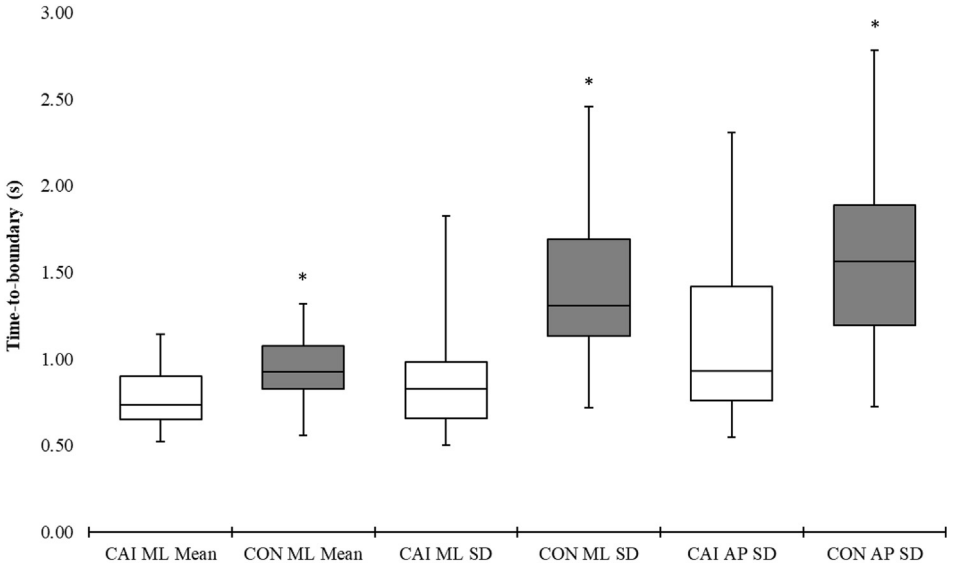

Fig. 2. Box and whisker plot comparisons (middle line = median; top/bottom boxes = 2nd/3rd quartiles; error bars = min/max values) of cumulative means for TTB minima between the CAI and control groups. * indicates significant difference between CAI and control groups ($p < 0.05$).

these findings were not supported in the current investigation as we did not observe any significant interactions or main effects for any of the eight traditional COP measures reported (Table 2). Significant increases proximal muscle activation (Rios et al., 2015) and reductions in postural sway (dos Santos et al., 2014) while kicking a ball in a single-leg stance have been reported in individuals with CAI. Furthermore, proximal joint movement strategies have also been observed in participants with CAI during various unilateral weight-bearing exercises including the SEBT (de La Motte, Arnold, & Ross, 2015), jump-landings (Brown, Bowser, & Simpson, 2012; Doherty et al., 2016a, 2016b), and change of direction tasks (Kim, Son, Seeley, & Hopkins, 2017; Son, Kim, Seeley, & Hopkins, 2017). Although lower limb kinematics or muscle activity are not reported in this study, perhaps the CAI group utilized a proximal to distal joint movement and muscular recruitment postural control strategy to complete the Lateral Step-Down Test. This movement strategy would shift reliance away from the affected ankle to the proximal joints as a compensatory mechanism in attempt to

maintain minimal postural sway and could possibly explanation the lack of between group differences in COP measures.

However, significantly lower TTB measures in the CAI group were observed during the Lateral Step-Down Test (Table 3; Fig. 2). Previous studies including a spatiotemporal analysis of TTB have identified deficits in postural control more consistently in individuals with CAI (Hertel & Olmsted-Kramer, 2007; Wikstrom et al., 2010b; Pope et al., 2011). Our findings support previous research that have suggested TTB measures of postural control are a more sensitive measure to identify postural control deficits than traditional COP measures in individuals with CAI (Hertel & Olmsted-Kramer, 2007; Wikstrom et al., 2010b; McKeon & Hertel, 2008a, 2008b). TTB is a unique spatiotemporal analysis that measures postural control in which the magnitude of COP excursions in relation to the boundaries of the base of support are analyzed (Hertel et al., 2006). As a result, this yields potential points of postural instability during the respective trials, whereas traditional COP measures only consider the average rate and magnitude of all COP excursions. As such, the significantly lower TTB ML absolute minimum (Table 3; ES = 2.00) and TB ML mean of minima (Table 3; ES = 0.87) observed in the CAI group would indicate that while performing the Lateral Step-Down Test postural equilibrium was maintained with the COP approaching the ML limits of stability at a much faster rate compared to controls. Perhaps this finding identifies a potential underlying factor contributing to repetitive episodes of the ankle 'giving way' during functional activity as the CAI group demonstrated a reduced ability to regulate the COP excursions in relation to the ML limits of stability. In addition, TTB measures of postural control identified deficits in dynamic postural control between the CAI and control groups while traditional COP measures were not significantly different between groups. This also further highlights the importance of conducting a comprehensive assessment inclusive of a spatiotemporal analysis when evaluating dynamic postural control in participants with CAI.

An additional finding in this study was a significant reduction in the TTB SD of minima in both the ML (ES = 1.13) and AP (ES = 0.94) directions on both limbs in the CAI group (Fig. 2). This finding has also been supported in the literature as reductions in the TTB SD of minima have also been reported during unilateral static postural control (Hertel & Olmsted-Kramer, 2007; McKeon & Hertel, 2008a, 2008b). It has been suggested that reductions in the variability of TTB measures indicates increased sensorimotor system constraints (Hertel et al., 2006; Hertel & Olmsted-Kramer, 2007). Consequently, damaged sensory afferents that manifest from chronic ankle joint injury can reduce the available somatosensory feedback and diminish the ability of the postural control system to effectively and efficiently generate postural corrections to maintain postural equilibrium during unilateral weight-bearing (Doherty et al., 2014b; Hertel & Olmsted-Kramer, 2007; McKeon & Hertel, 2008a, 2008b). Furthermore, reductions in neuromuscular control (Jaber et al., 2018), ankle dorsiflexion range of motion (Grindstaff et al., 2017; Hoch et al., 2012), and joint kinematic (Brown et al., 2012) and neuromuscular control variability (Koldenhoven, Feger, Fraser, & Hertel, 2018) have been observed in individuals with CAI during various functional exercises. Reductions in the variability of the ML and AP TTB minima likely reflects the sensorimotor impairments associated with CAI resulting in postural control strategies that are less efficient when performing the Lateral Step-Down Test.

It should also be considered that with the exception of a significant interaction for TTB ML absolute minimum, significant group main effects for three of six reported TTB measures were observed with large effect sizes (ES = 0.87–1.13; Fig. 2). That is, the CAI group on average exhibited significantly lower TTB measures of postural control during the Lateral Step-Down Test on both limbs. Recent literature supports the hypothesis that an acute lateral ankle sprain impairs sensorimotor function resulting in a maladaptive reorganization of centrally mediated motor control strategies that impairs static and dynamic postural control on both the injured and non-injured limbs (Doherty et al., 2014b, 2015a; Wikstrom et al., 2010a). Although the development of longitudinal postural control deficits on the contralateral limb following an acute lateral ankle sprain is not well-understood, poor static and dynamic postural control on the injured and non-injured limbs 6 months following an acute lateral ankle sprain (Doherty et al., 2015b) and in individuals with CAI (Doherty et al., 2016a, 2016b; Hertel & Olmsted-Kramer, 2007) have been observed. In combination with the results from the present study, these aforementioned findings would suggest that alterations to centrally mediated postural control and movement strategies occur through various stages after the initial lateral ankle sprain occurs. This highlights a potential underlying mechanism that is potentially an associated factor with chronic joint instability, which has clinical implications for rehabilitation programs intended to improve sensorimotor impairments and reduce the likelihood of developing CAI after an acute lateral ankle sprain.

This study did have limitations that should be mentioned. First, only COP measures of postural control were reported. Lower extremity kinematics and neuromuscular activity data would further elucidate altered postural control and movement strategies in individuals with CAI during the Lateral Step-Down Test and could further substantiate the clinical implications of our findings. An additional limitation was that only CAI and healthy matched control groups were compared. Not all individuals that suffer an acute lateral ankle sprain develop CAI, and thus, are deemed as ankle sprain copers. Future studies should consider including an ankle sprain coper group when examining postural control to determine differences between these three groups.

5. Conclusion

This study found that individuals with CAI displayed deficits in TTB measures of postural control on both limbs during the Lateral Step-Down Test compared to controls. These findings indicate constraints on the sensorimotor systems as a result of chronic ankle joint injury alters centrally mediated spatiotemporal postural control strategies during functional movements, which may also highlight an underlying mechanism linked to the development of CAI. Moreover, TTB measures appear to also identify postural control deficits during functional movements, as opposed to traditional COP measures, and should be evaluated in subsequent studies that quantify postural control in individuals with and without CAI.

6. Ethical statement

The study protocol was approved by the authors Institutional Review Board (IRB-18-023) in accordance with the recommendations of the Declaration of Helsinki. The authors do not have any affiliations, or financial involvement, to declare with any company or organization in the content or equipment discussed in this manuscript.

Conflicts of interest

The authors declare no conflicts of interest. There was no grant aid, or manufacturers' aid, received to complete this study.

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