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Neuromuscular control in individuals with chronic ankle instability: A comparison of unexpected and expected ankle inversion perturbations during a single leg drop-landing

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ABSTRACT

While neuromuscular control deficits during inversion perturbations in chronic ankle instability (CAI) cohorts are well documented in the literature, anticipatory motor control strategies to inversion perturbations in CAI are largely unknown. The purpose of this study was to examine neuromuscular control and ankle kinematics in individuals with CAI ($n = 15$) and matched controls ($n = 15$) during unexpected and expected single leg drop-landings onto a tilted surface rotated 20° in the frontal plane. Muscle activity from 200 ms pre- to post-landing was recorded from the tibialis anterior (TA), medial gastrocnemius (MG), peroneus longus (PL) and peroneus brevis (PB). Mean muscle activity, co-contraction index (CCI), and peroneal latency was analyzed. Ankle inversion angle at initial contact, time to maximum inversion angle, maximum inversion angle and velocity were also assessed. Significantly longer PL latency, less time to maximum inversion and greater maximum inversion angle was found in CAI compared to controls. Regarding landing condition, significantly greater maximum inversion angle, less inversion at initial contact, longer PB latency, less TA activity and frontal plane CCI during the post-landing phase was found during the unexpected perturbation. Prolonged PL latency and altered ankle kinematics suggests reduced frontal plane ankle stabilization in CAI. However, similar motor control strategies were utilized in both groups during the ankle inversion perturbations.

1. Introduction

Chronic ankle instability (CAI), which commonly develops following lateral ankle ligament trauma, is a pathological condition characterized by repetitive bouts of ankle instability causing the ankle to give way leading to recurrent lateral ankle sprains (Delahunt et al., 2010; Hertel, 2002). Damage to the mechanoreceptors located within the lateral ankle ligaments, and possibly the muscle spindles, has been shown to negatively alter proprioceptive and neuromuscular function (Freeman, 1965; Hertel, 2008; Munn, Sullivan, & Schneiders, 2010). As a result, reductions in neuromuscular control of the lateral ankle musculature, particularly in the

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peroneus longus and peroneus brevis, has been identified to be one causative factor that contributes to the recurrent lateral ankle sprain paradigm in individuals that develop CAI (Hopkins, Brown, Christensen, & Palmieri-Smith, 2009; Sierra-Guzmán, Jiménez, & Abián-Vicén, 2018).

Extensive research has been conducted using various methodological approaches and injury simulations to assess neuromuscular control to sudden inversion in individuals with a history of a lateral ankle sprain and CAI (Ha, Fong, & Chan, 2015). While previous investigations provide valuable insight to the potential underlying pathology that contributes to recurrent lateral ankle sprains and the development of chronic ankle joint instability, only a limited number of investigations have controlled for anticipatory responses to ankle inversion perturbations in CAI cohorts (Gutierrez et al., 2012; Levin et al., 2015). Anticipatory mechanisms to potentially injurious and destabilizing perturbations can confound biomechanical and neuromuscular responses, prohibiting a reliable and valid assessment of real time injury mechanisms and the potential sensorimotor deficits that arise from the constraints of CAI (Dicus & Seegmiller, 2012; Gutierrez et al., 2012). Specifically, increased preparatory and reactive neuromuscular control of the lateral ankle musculature and altered ankle joint kinematics has been shown in anticipation to inversion perturbations (Dicus & Seegmiller, 2012; Gehring, Wissler, Lohrer, Nauck, & Gollhofer, 2014; Gruneberg, Nieuwenhuijzen, & Duysens, 2003; Simpson et al., 2018b). This suggests alterations to movement dynamics arise when there is knowledge of a potentially injurious and destabilizing perturbation. Therefore, implementing experimental protocols that control for anticipatory responses are warranted to understand the mechanisms of injury and identify motor control strategies that increase the propensity of a lateral ankle sprain (Simpson et al., 2018b).

Individuals with CAI have been shown to exhibit altered preparatory and reactive neuromuscular control during single leg jump-landings (Caulfield, Crammond, O'Sullivan, Reynolds, & Ward, 2004; Delahunt, Monaghan, & Caulfield, 2006; Simpson et al., 2018a). Prior studies have shown individuals with CAI demonstrate significant reductions in preparatory muscle activity of the peroneus longus and peroneus brevis on the affected ankle during single leg jump-landings (Caulfield et al., 2004; Delahunt et al., 2006; Kunugi, Masunari, Yoshida, & Miyakawa, 2017). These reductions in preparatory neuromuscular control of the primary ankle evertors have been linked to greater subtalar inversion angle and ankle frontal plane variability during the preparatory phase of a jump-landings (Delahunt et al., 2006; Kipp & Palmieri-Smith, 2012). This provides evidence that sensorimotor impairments associated with CAI alter centrally mediated motor control strategies causing reductions in ankle neuromuscular control in preparation for ground contact. Consequently, these maladaptive landing mechanics likely coincide with reduced dynamic ankle joint stabilization and an increased risk of aberrant ankle positioning when initial contact with the ground is unexpected during dynamic movements.

Although few studies highlight the potential anticipatory motor control strategies to ankle inversion perturbations in individuals with CAI during bilateral jump-landings (Gutierrez et al., 2012; Levin et al., 2015), extrapolating results from these studies to a single leg jump-landing that initiates the lateral ankle sprain mechanism is difficult (Terada & Gribble, 2015). Investigating unexpected and expected ankle inversion perturbations during a single leg landings would further elucidate the motor control strategies that are associated with recurrent injury in CAI. Using a recently published protocol that has been shown to closely mimic the unexpected lateral ankle sprain mechanism (Simpson et al., 2018b), this study assessed neuromuscular control and discrete ankle kinematic parameters in individuals with and without CAI during unexpected and expected single leg drop-landings on an inverted surface. It was hypothesized the CAI group would demonstrate reduced neuromuscular control and altered ankle kinematics compared to healthy controls during unexpected and expected single leg drop-landings on the tilted surface.

2. Methods

2.1. Participants

An *a priori* power analysis (G-Power software, Düsseldorf, Germany) was computed to determine sample size using a mixed model analysis of variance (ANOVA) with the following input parameters: $\beta = 0.80$, effect size = 0.50, and $\alpha = 0.05$. This indicated that 13 participants in each group and a critical F of 4.25 would be needed. As such, individuals with self-reported CAI ($n = 15$) and healthy matched controls ($n = 15$) based on age, mass, and gender with no history of any musculoskeletal injuries to the lower extremity were recruited from a sample of convenience on a university campus and completed the study procedures. All participants were currently participating in competitive and/or recreational athletics, and participants were placed in the CAI group based on the following criteria: (i) history of at least two lateral ankle sprains with one of those lateral ankle sprains occurring within the previous 12 months; (ii) sustained a lateral ankle sprain that required non-weight bearing activity and/or immobilization for ≥ 24 h; (iii) experienced the affected ankle "giving way" or "feelings of instability"; (iv) a score of 24 or less 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 acute musculoskeletal injury to the lower extremity within the previous 3 months, or a diagnosed musculoskeletal and/or neurological disease/disorder. All participants read and signed an informed consent document outlining potential risks and procedures of the study prior to participation. Ethical approval for the study was obtained from the Institutional Review Board at the authors' university prior to collecting data.

2.2. Instrumentation

Flat and inverted platforms were constructed to allow a force platform (AMTI AccuGait, Watertown, MA, USA) sampling at 1,000 Hz to be embedded within the top of each platform. The inversion platform was rotated 20° in the frontal plane to produce an ankle inversion perturbation of upon landing from a height of 30 cm in the unilateral stance (Fig. 1). Both the flat and inverted

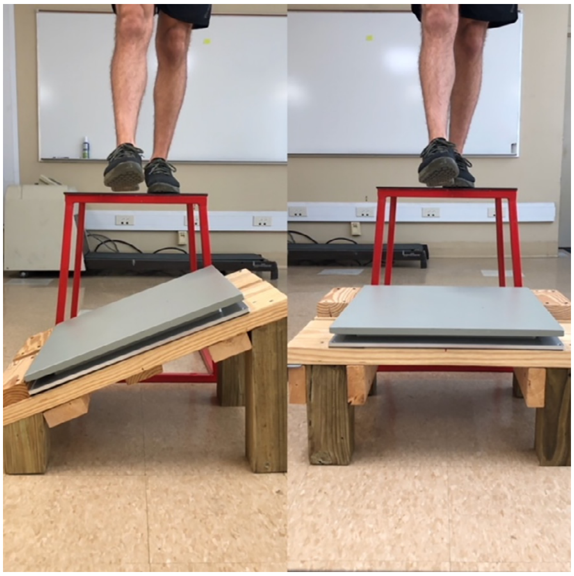

Fig. 1. The inverted (left) and flat (right) platforms with force platform arrangement that was used to simulate a lateral ankle sprain during a single leg drop-landing.

platforms were constructed to maintain a consistent drop-landing height of 30 cm from the center of the force platform and grip tape was applied to the top of the force platform to prevent the participants' foot from slipping during the drop-landing task. The platform design was derived from recently published studies using unilateral landings on an inverted surface (Simpson et al., 2018b) and an inversion perturbation of 20° was chosen for participant safety, especially those with CAI, as lateral ankle sprains can occur when the subtalar joint exceeds 30° of inversion (Terada & Gribble, 2015).

A wireless 8-channel surface electromyography (EMG) system (Noraxon, Scottsdale, AZ, USA) sampling at 1500 Hz was used to record muscle activity during the drop-landing task. Surface electrodes were placed with an inter-electrode distance of less than 2 cm over the most prominent part of the muscle belly of the tibialis anterior (TA), medial gastrocnemius (MG), peroneus longus (PL), and peroneus brevis (PB). Prior to electrode placement, each site was shaved, abraded, and thoroughly cleaned with isopropyl alcohol.

Ankle kinematic data was collected at 100 Hz using a 3-dimentional motion capture system equipped with 12 infra-red Bonita 10 cameras (Vicon, Oxford, UK). Retro-reflective marker clusters were attached to the participant's posterior pelvis and bilaterally on the thigh, shank, and dorsal foot using double sided tape and nylon therapeutic wraps to further reduce marker movement artifact.

2.3. Protocol

Participants first completed a familiarization session, which provided each participant with detailed information regarding study procedures. In addition, participants completed the CAIT questionnaire and were permitted to practice the single leg drop-landing task onto the flat surface as many times as desired during this session. Although participants were made aware, both verbally and in the written consent document, that an inversion platform would be used without their knowledge during their testing session, participants were restricted from visually seeing the inverted platform during this session to further reduce anticipation to the inversion perturbation.

Less than a week later, participants returned to the laboratory in a low top athletic shoe of their choice to complete their testing session. Each testing session began with participants performing practice trials (5–10 trials) onto the flat platform to establish a normal drop-landing pattern. The single leg drop-landing task consisted of participants standing on the non-testing limb with their testing limb relaxed over the edge of a box that was raised 30 cm above the center of the force platform embedded on the flat platform. Participants were instructed to step forward and land on the platform with their testing limb only and subsequently take another 30 cm step down and land on the ground with their non-testing limb. This task was very similar to walking down a flight of stairs. During all drop-landing conditions, participants were reminded to keep their eyes facing forward and were required to wear dribbling goggles (Spalding, Bowling Green, KY, USA) to create visual obstruction of the participants' feet and the landing surface. Participants then completed a total of five normal drop-landing trials onto the flat surface that were recorded with 30 s rest periods between each drop-landing trial. Following completion of the five normal drop-landing trials, participants were faced away from the testing space, and they listened to music being played on noise cancelling headphones for 60 s to take away the knowledge of the subsequent landing on either the flat or inverted surface.

Participants then completed a maximum of 10 more trials of the drop-landing task onto the flat surface with a 60 s breaks between trials while facing away from the testing space and listening to music being played on noise-cancellation headphones. However, the inverted platform was switched with the flat platform without the participants' knowledge on a random trial, which was randomized using Excel (Microsoft Corporation, Redmond, WA, USA), and was considered the unexpected (UE) ankle inversion perturbation. Immediately following the UE trial, each participant subjectively reported on a scale of 1–10 if they were expecting the inverted platform during the UE trial. To further reduce anticipation to the UE ankle inversion perturbation, trial numbers 1 and 10 were excluded. Following the UE trial, the inverted platform was re-adjusted and participants were given a 60 s break before completing the drop-landing task onto the inverted platform again. However, this time the investigator gave participants the verbal instruction that they will be “landing on the inverted platform” and this trial was treated as the expected (EXP) ankle inversion perturbation.

2.4. Data analysis

2.4.1. Electromyography

Raw EMG signals for each trial were amplified by a gain of 1000, filtered using a 10–500 Hz band-pass filter, smoothed and full wave rectified with a root mean square algorithm in the MotionMonitor software. EMG amplitudes were averaged for two distinct time periods: (i) 200 ms pre-landing and (ii) 200 ms post-landing. Average EMG amplitudes during these two time periods were then normalized to each participants highest 100 ms average of a 3 s maximum voluntary isometric contraction (MVIC) for each muscle. Pre-landing was identified as the 200 ms before initial contact (when the vertical ground reaction force exceeded 15 N), while post-landing was identified as the first 200 ms after initial contact. This 400 ms time window was selected to be analyzed as lateral ankle sprains occur within the first 200 ms of initial ground contact (Kristianslund, Bahr, & Krosshaug, 2011; Terada & Gribble, 2015). Co-contraction index (CCI) was also calculated for pre- and post-landing from in the sagittal and frontal plane using Eq. (1) (Suda, Amorim, & Sacco Ide, 2009). Muscle pairs for sagittal plane CCI were the TA and MG, while muscle pairs for frontal plane CCI were the combined average of the PL and PB and the TA.

$$CCI = \frac{EMG_{Minimum}}{(EMG_{Minimum} + EMG_{Maximum})/2} \tag{1}$$

Latency of the PL and PB was determined from the rectified EMG signal as the time in ms from when the vertical component of the ground reaction force exceeded 15 N, which coincided with the initiation of the inversion perturbation, to the point where muscle activity exceeded 5 standard deviations (SD) above the averaged 200 ms pre-landing muscle activity (Fig. 2). While previous studies have used 2 SD (Hopkins, McLoda, & McCaw, 2007; Midgley et al., 2007) and 10 SD (Knight & Weimar, 2011a, 2012b) thresholds, 2 SD may be too sensitive and 10 SD may be too high of a threshold to determine the onset of muscle activity. Therefore, we analyzed PL and PB latency using a 5 SD threshold to be consistent with previous literature examining latency during dynamic inversion perturbations (Knight & Weimar, 2011a, 2011b).

2.4.2. Kinematics

All kinematic, muscle activity and force platform data was collected simultaneously and time synchronized at 1000 Hz using the MotionMonitor software (Innovative Sports Training Inc., Chicago, IL, USA). Ankle kinematics were calculated in the MotionMonitor software using the Grood-Suntay angle orientation method (Grood & Suntay, 1983). Foot and ankle joint centers were defined in the software by placing the measurement sensor on the lateral and medial malleoli and the distal second phalanx. Knee joint centers were defined by placing the measurement sensor on the medial and lateral femoral condyles, while hip joint centers were defined by

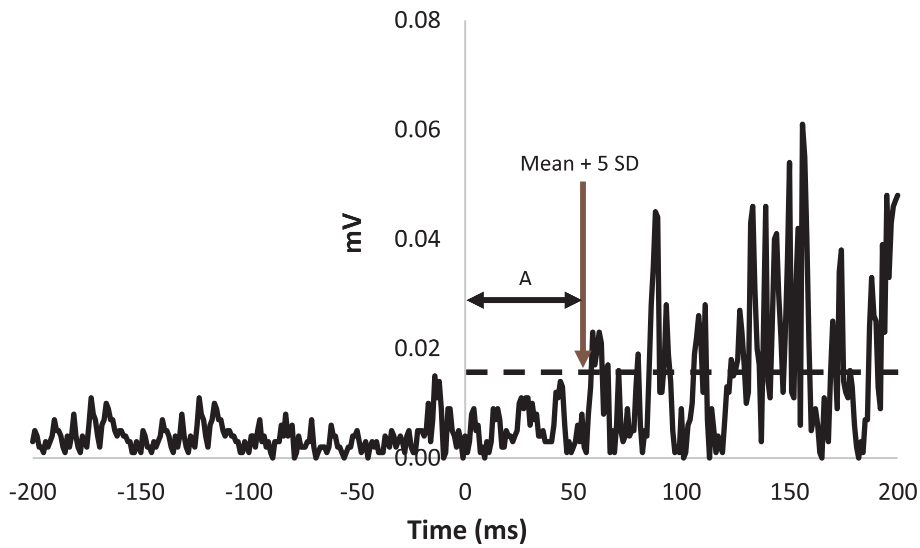

Fig. 2. Determining latency (A) of the peroneus longus and peroneus brevis from the rectified EMG signal. *Criteria for latency (A), measured in milliseconds (ms), was determined as the point at which the post-landing muscle activity went 5 standard deviations above average pre-landing muscle activity (−200 to 0 ms) as indicated by the dashed line during the post-landing period (0–200 ms).

placing the measurement sensor on the anterior superior iliac spine and the L5/S1 joint (Simpson et al., 2018b). Ankle and knee joint centers were calculated using the centroid method, while hip joint centers were calculated using the Davis Method (Davis, Ounpuu, Tyburski, & Gage, 1991) in the MotionMonitor software.

The raw ankle kinematic data was filtered with a low-pass third-order Butterworth filter with a cutoff frequency of 15 Hz. The distal shank served as the frame of reference for all discrete ankle kinematic variables. Maximum inversion velocity, maximum ankle inversion angle, inversion angle at initial contact and time to maximum inversion angle were computed for UE and EXP trials. Maximum inversion velocity (°/s) and maximum inversion angle (°) was defined as the maximum inversion velocity and angle during the post-initial contact period (Simpson et al., 2018b), while time to maximum inversion angle in milliseconds (ms) was defined as the total time to complete the inversion perturbation during the post-initial contact period (Knight & Weimar, 2011b, 2012a).

2.5. Statistical analysis

Descriptive and dependent measures were calculated as mean ± SD. Independent samples two tailed *t*-tests were computed to compare CAIT scores and descriptive data between CAI and control groups. Dependent measures were analyzed using a series of 2 (condition) × 2 (group) mixed model ANOVA with condition (UE vs. EXP) serving as the repeated measure. Tukey's post hoc tests were performed when significant interactions were found. Cohen's D effect size data was also calculated for all discrete ankle kinematic and muscle activity variables as the difference in means divided by the pooled SD and considered as small ($d < 0.40$), moderate ($d = 0.40$–0.80), and large ($d > 0.80$) (Cohen, 1992). All statistical analyses were performed using a statistical software package (SPSS Statistics, Armonk, NY, USA) and the level of statistical significance was set at 0.05.

3. Results

3.1. Participant characteristics

Descriptive and CAIT scores from the participants can be found in Table 1. No statistical differences between groups were found for the participants' age ($p = 0.730$), height ($p = 0.788$), or mass ($p = 0.698$). Individuals with CAI reported significantly lower CAIT scores ($p < 0.001$) compared to the control group and subjectively reported a significantly greater total number of lateral ankle sprain occurrences ($p < 0.001$).

3.2. Muscle activity

Tables 2 and 3 display muscle activity data from the UE and EXP trials. Results revealed no significant condition by group interactions for latency of the PL and PB, or for any of the pre- and post-initial contact muscle activity variables ($p > 0.05$). A significant group main effect for PL latency was observed, with the CAI group exhibiting significantly longer PL latency compared to the control group ($p < 0.001$; $d = 1.20$). Significant condition main effects were also observed for PL and PB latency, with significantly reduced PL ($p = 0.004$; $d = 0.90$) and PB ($p = 0.011$; $d = 0.66$) latency during EXP when compared to UE (Table 3). Regarding post-landing muscle activity, significant condition main effects were found for TA and frontal plane CCI. Significantly greater TA activity ($p = 0.009$; $d = 0.40$) and frontal plane CCI ($p < 0.001$; $d = 0.97$) were found for the post-landing time period during the EXP trial in comparison to the UE trial. There were no other significant interactions or main effects for pre- or post-landing EMG variables.

3.3. Ankle kinematics

Table 4 displays the ankle kinematic data from the UE and EXP trials. No significant condition by group interactions were found for any of the discrete ankle kinematic variables ($p > 0.05$). Significant group main effects were observed for time to maximum inversion and maximum inversion angle, with the CAI group demonstrating significantly less time to maximum inversion ($p = 0.041$; $d = 0.53$) and a significantly greater maximum inversion angle ($p = 0.010$; $d = 0.80$). Furthermore, a significant condition main effect for inversion angle at initial contact and maximum inversion angle was found, with significant reductions in maximum

Table 1
Descriptive and Cumberland Ankle Instability Tool (CAIT) data of the participants in the chronic ankle instability (CAI) and control (CON) groups. Data is reported as mean ± SD.

Variable	CAI ($n = 15$)	CON ($n = 15$)	p Value
Age (y)	21.3 ± 1.6	21.5 ± 1.5	0.730
Height (m)	1.71 ± 0.11	1.70 ± 0.11	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 No. of Ankle Sprains*	6.0 ± 3.2	0.0 ± 0.0	< 0.001

* Indicates subjectively reported variable.

Table 2
Latency of the peroneus longus (PL) and peroneus brevis (PB) during unexpected and expected trials (mean ± SD).

	Condition		*p* Value		
Variable	Unexpected	Expected	Condition × Group	Condition	Group
*Peroneus Longus Latency (ms)**					
CAI	70.08 ± 20.25	50.05 ± 16.08	0.208	0.004	< 0.001
Control	46.36 ± 12.89	37.87 ± 14.22			
*Peroneus Brevis Latency (ms)**					
CAI	53.56 ± 13.77	48.67 ± 16.71	0.173	0.011	0.208
Control	53.23 ± 16.00	38.07 ± 14.83			

* Criteria for latency, measured in milliseconds (ms), was determined as the point at which the post-landing muscle activity went 5 standard deviations above average pre-landing muscle activity.

Table 3
Normalized muscle activity and co-contraction index (CCI) data pre- and post-initial contact during unexpected and expected trials (mean ± SD).

	Condition		*p* Value		
Variable	Unexpected	Expected	Condition × Group	Condition	Group
Pre-Initial Contact Muscle Activity (%MVIC)					
Tibialis Anterior					
CAI	3.74 ± 2.67	5.25 ± 5.16	0.523	0.244	0.758
Control	3.86 ± 3.05	4.31 ± 5.45			
Medial Gastrocnemius					
CAI	3.06 ± 2.67	2.67 ± 2.12	0.251	0.801	0.942
Control	2.65 ± 2.81	3.25 ± 4.96			
Peroneus Longus					
CAI	4.43 ± 3.09	3.54 ± 2.51	0.692	0.054	0.714
Control	5.01 ± 3.92	3.68 ± 2.48			
Peroneus Brevis					
CAI	3.80 ± 2.18	3.62 ± 1.91	0.558	0.328	0.908
Control	4.18 ± 3.16	3.45 ± 3.82			
Sagittal Plane CCI					
CAI	0.53 ± 0.25	0.54 ± 0.23	0.192	0.960	0.379
Control	0.48 ± 0.23	0.47 ± 0.22			
Frontal Plane CCI					
CAI	0.66 ± 0.22	0.60 ± 0.16	0.451	0.919	0.423
Control	0.66 ± 0.23	0.70 ± 0.21			
Post-Initial Contact Muscle Activity (%MVIC)					
Tibialis Anterior					
CAI	2.96 ± 1.88	3.90 ± 2.62	0.383	0.009	0.483
Control	2.72 ± 1.09	3.21 ± 1.74			
Medial Gastrocnemius					
CAI	8.02 ± 5.50	8.17 ± 6.02	0.572	0.455	0.215
Control	5.00 ± 4.82	6.12 ± 7.16			
Peroneus Longus					
CAI	5.42 ± 3.17	4.16 ± 2.91	0.543	0.108	0.831
Control	5.32 ± 3.75	4.74 ± 3.75			
Peroneus Brevis					
CAI	7.01 ± 2.63	6.50 ± 3.34	0.150	0.137	0.519
Control	6.81 ± 5.44	5.20 ± 2.85			
Sagittal Plane CCI					
CAI	0.57 ± 0.25	0.62 ± 0.25	0.466	0.825	0.565
Control	0.58 ± 0.23	0.51 ± 0.24			
Frontal Plane CCI					
CAI	0.58 ± 0.21	0.75 ± 0.21	0.556	0.001	0.983
Control	0.60 ± 0.23	0.86 ± 0.23			

inversion angle ($p < 0.001$; $d = 0.95$) and significantly greater inversion angle at initial contact ($p = 0.003$; $d = 0.73$) during the EXP trial compared to the UE trial. No other significant interactions or main effects were noted.

4. Discussion

The primary objective of this investigation was to assess neuromuscular control and ankle kinematics in individuals with and without CAI during unexpected and expected ankle inversion perturbations after a single leg drop-landing. The main findings in the

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Table 4
Ankle kinematic data during unexpected and expected trials (mean ± SD).

	Condition		*p* Value		
Variable	Unexpected	Expected	Condition × Group	Condition	Group
Time to Maximum Inversion (ms)					
CAI	61.33 ± 19.91	56.36 ± 23.11	0.591	0.705	0.041
Control	68.87 ± 17.50	69.73 ± 18.77			
Inversion Angle at Initial Contact (°)					
CAI	11.35 ± 4.25	15.19 ± 5.17	0.957	0.003	0.334
Control	9.95 ± 5.44	13.66 ± 5.77			
Maximum Inversion Angle (°)					
CAI	21.39 ± 2.94	18.48 ± 3.86	0.363	< 0.001	0.010
Control	18.98 ± 2.90	15.93 ± 2.89			
Maximum Inversion Velocity (°/s)					
CAI	183.95 ± 70.67	186.86 ± 63.42	0.847	0.955	0.328
Control	167.25 ± 35.70	165.65 ± 67.99			

current investigation were that individuals with CAI demonstrated reduced time to maximum inversion, greater maximum inversion angles and prolonged latency of the PL in comparison to the control group. With respect to landing condition, greater maximum inversion angle, less inversion angle at initial contact, less TA muscle activity and frontal plane CCI 200 ms post-landing, and prolonged latency of the PB was observed during the UE trial. To the knowledge of the authors, this was the first study that examined neuromuscular control and ankle kinematics during unexpected and expected ankle inversion perturbations after a single leg drop-landing in participants with and without CAI.

4.1. Influence of chronic ankle instability

On average, significant reductions in time to maximum inversion and significantly greater maximum inversion angles were found in the CAI group in comparison to controls with medium to large effect sizes (Table 4; $d = 0.53–0.80$). Spatial and temporal ankle kinematic parameters provide a means of assessing the ability of the primary ankle evertors, particularly the PL and PB, to provide dynamic frontal plane stabilization through eccentric muscle actions and to assist with controlling ankle inversion moments during sudden and unexpected subtalar inversion (Knight & Weimar, 2012a). Previous studies have not reported any differences in time to maximum inversion between individuals with and without CAI to sudden inversion (Eechaute, Vaes, Duquet, & Van Gheluwe, 2009; Vaes, Duquet, & Van Gheluwe, 2002). However, differences in methodological approaches implemented across these studies are a likely explanation for the conflicting results. These studies utilized a trapdoor device, which produces sudden inversion of the subtalar joint by the platform unexpectedly falling away from beneath the participant while standing in a bilateral static position. The scope of this methodological approach is limited given that lateral ankle sprains typically do not occur when the floor falls away in a closed kinetic chain (Hopkins et al., 2007; Knight & Weimar, 2012a), and may not provide a reliable and valid assessment of the ability of the peroneal musculature to control frontal plane movement of the subtalar joint during a dynamic ankle inversion perturbation. Given that a single leg drop-landings onto a tilted surface was utilized in the current study to closely replicate the mechanism of a lateral ankle sprain, increased maximum inversion angles and faster time to maximum inversion in the CAI group suggests a reduced ability to prevent excessive frontal plane movement during an ankle inversion perturbation when landing on one foot.

Individuals with CAI also demonstrated significantly longer latency of the PL with a large effect size (Table 2; $d = 1.20$). Damage to the sensory receptors located within the lateral ankle ligaments has been suggested to result in an inability of the gamma motoneuron system to adjust the sensitivity of the muscle spindles, making them less sensitive to any unexpected and/or rapid lengthening of the peroneal musculature (Hertel, 2008). Consequently, disruptions in the gamma motoneuron loop would lead to reductions alpha motor unit activation and a prolonged reaction time to aberrant ankle positioning (Hertel, 2002; Hiller et al., 2011). Although reports of no differences in latency of the peroneal musculature between CAI and controls exist (Eechaute et al., 2009; Munn et al., 2010; Vaes et al., 2002), longer latency of the peroneal musculature has been reported in individuals with CAI during sudden inversion (Donahue, Docherty, & Riley, 2014; Hopkins et al., 2009; Sierra-Guzmán et al., 2018; Vaes, Van Gheluwe, & Duquet, 2001). It should be considered that the EMG processing techniques used in the published scientific literature to determine the latency of the peroneal musculature during inversion perturbations varies widely and is a plausible explanation for the lack of consistent findings in CAI cohorts. In the present study, we used a threshold of 5 SD above the average 200 ms muscle activity prior to ground contact to be consistent with previous studies examining latency of the PL and PB during a single leg drop-landing (Knight & Weimar, 2011a, 2011b). Thus, our findings would suggest damaged mechanoreceptors within the lateral ankle ligaments can alter spinal level motor control in individuals with CAI that negatively influence feedback neuromuscular control of the lateral ankle musculature. Consequently, this causes a delay in the reaction time of the lateral ankle musculature to potentially injurious ankle inversion perturbations and may cause the ankle to give way into excessive inversion and result in a recurrent lateral ankle sprain.

4.2. Influence of landing condition

An additional objective of this study was to examine anticipatory motor control strategies to ankle inversion perturbations during a single leg drop-landing onto a tilted surface. When participants anticipated the inversion perturbation, significantly greater ankle inversion angle at initial contact and significant reductions in maximum ankle inversion angle were observed with medium to large effect sizes (Table 4; d = 0.73–0.95). That is, participants in both the CAI and control groups displayed similar discrete ankle kinematic parameters during the EXP landing condition. These findings are consistent with previous literature that has reported that knowledge of an inversion perturbation can alter post-landing discrete ankle kinematic parameters (Dicus & Seegmiller, 2012; Gehring et al., 2014; Simpson et al., 2018b). Dicus and Seegmiller (2012) were the first to examine ankle kinematics to unexpected and expected single leg landings onto a tilted surface in a group of healthy subjects and reported significant reductions in maximum ankle inversion angles when the inversion perturbation was expected. Similarly, Gehring et al. (2014) used a trapdoor in a walkway to also examine the influence of anticipation to inversion perturbations during walking gait and found reductions in maximum ankle inversion angle with expectation to the ankle inversion perturbation (Gehring et al., 2014). Although these studies did not include an ankle sprain coper or CAI group comparison, the main effects for landing condition observed in the current study suggests similar anticipatory motor control strategies may be utilized between CAI and control groups to increase frontal plane stabilization in attempt to reduce the magnitude of frontal plane ankle displacement when there is knowledge of a destabilizing perturbation.

Additionally, we also observed significant increases in TA muscle activity and frontal plane CCI with moderate to large effects (Table 3; d = 0.40–0.97) across both groups for the post-landing period during the EXP landing condition. Although some studies have reported reductions in preparatory and reactive muscle activity on the affected ankle in individuals with CAI during jump-landings (Caulfield et al., 2004; Delahunt et al., 2006; Kunugi et al., 2017), other studies have found no differences (Brown, Ross, Mynark, & Guskiewicz, 2004; Levin et al., 2015), or increased muscle activity on the affected ankle (Gutierrez et al., 2012). It has been suggested that CAI may not influence reflexive activation of the ankle musculature, but rather, alter spinal or supraspinal level feedforward motor control strategies (Hertel, 2008; Simpson et al., 2018a). While there is some evidence that supports this notion, only a few studies have investigated the potential anticipatory motor control strategies to inversion perturbations during landing in individuals with CAI (Gutierrez et al., 2012; Levin et al., 2015). The increased post-landing TA muscle activity we observed during the EXP landing condition across both groups is likely a protective motor control strategy that arises subsequent to initial foot contact during an inversion perturbation to place the talocrural joint in a more tightly packed position to protect the lateral ankle ligaments from excessive frontal plane displacement. Likewise, the increase in TA muscle activity also resulted in increased post-landing frontal plane CCI during the EXP trial, which also coincided with reductions in maximum ankle inversion angle. Therefore, these findings are evidence that similar motor control strategies may be utilized in individuals with and without CAI when there is knowledge of a potentially injurious perturbation during landing.

4.3. Study limitations

There were some limitations to the present study that should be discussed. Primarily, our sample size could have been too small resulting in a lack of power to adequately detect any interaction (i.e. condition × group) effects. Therefore, our results should be considered with a mild degree of caution in regards to the sample size. Secondly, to ensure participant safety, especially for those with CAI, only an inversion perturbation of 20° was used to simulate the mechanism of a lateral ankle sprain. This resulted in inversion angles and velocities that were below the discrete kinematic parameters that have been observed during real-time injury scenarios. Additionally, participants were made aware in the informed consent and familiarization trial that they would be landing on an inversion platform during the experimental trial. Although each participant was blinded to the platform and the trial that the platform was used, there is still a possibility of some anticipatory responses during the unexpected trial. Finally, only participants with and without CAI were included in the current study. Given that many individuals that sustain an acute lateral ankle sprain return to high-level activity without any residual impairments, investigating a group of ankle sprain copers in future research would further substantiate the clinical implications of our findings.

5. Conclusion

The findings from the study indicate alterations to feedback neuromuscular control and ankle kinematics in individuals with CAI during a single leg drop-landing onto an inversion platform. However, similar feedforward motor control strategies were utilized in both groups during both landing conditions. Additional research is warranted to further examine the potential anticipatory and reactive motor control strategies in individuals with CAI to destabilizing perturbations. Identifying these deficits would further highlight the clinical applications of our findings. As a result, this data would assist clinicians and researchers in developing effective perturbation training programs intended to improve the sensorimotor function following a lateral ankle sprain, mitigate the risk of recurrent injury and the potential to develop CAI.

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