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Directional deficits in reactive postural control during perturbations among groups of chronic ankle instability, ankle sprain coper, and healthy control

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Unanticipated postural control measures may better identify mechanisms of ankle sprains in real-life situations. The purpose of this study was to identify directional deficits in reactive postural control during unanticipated horizontal perturbations among groups of chronic ankle instability (CAI), ankle sprain coper, and healthy control. Sixty-eight volunteers (24 CAI patients, 23 ankle sprain copers, and 21 healthy controls) participated in this study. The participants performed a single-leg stance with unanticipated horizontal perturbations in four random directions of anterior, posterior, medial, and lateral. Anterior-posterior time to stabilization (APTTS) and medial-lateral time to stabilization (MLTTS) were calculated as an indicator of reactive postural control during horizontal perturbations. A significant interaction effect of the group x perturbation directions (3 × 4) was found. Both CAI and ankle sprain coper groups showed longer APTTS and MLTTS during medial and lateral horizontal perturbations compared to the healthy control group. However, no difference was found in APTTS and MLTTS during anterior and posterior horizontal perturbations between three groups. Directional deficits in reactive postural control during medial and lateral perturbations could result from sensorimotor dysfunction as consequences of lateral ankle sprains in the CAI and ankle sprain groups.

Keywords Lateral ankle sprain, Time to stabilization, Sensorimotor control, Balance, Postural stability

Chronic ankle instability (CAI) is a condition of chronic residual symptoms resulting from the interaction of pathomechanical, sensory-perceptual, and motor-behavioral impairments following a lateral ankle sprain (LAS)[1]. However, some individuals with a history of LAS injury show no chronic residual symptoms, self-reported dysfunction, and/or giving way episodes following their initial LAS; these individuals are referred to as 'ankle sprain copers'[2]. The importance of considering ankle sprain copers in CAI research could help understand the mechanisms of CAI development and LAS injury[2]. Investigating sensorimotor adaptations in ankle sprain copers may provide an insight on how to reduce a risk of CAI development[2]. Up to 70% of individuals with LAS develop into CAI[3], and up to 78% of CAI patients would have ankle articular cartilage degradation like posttraumatic ankle osteoarthritis after 10 years post LAS[4].

The initial ankle ligamentous injury causes articular deafferentation, leading to immediate deficits in sensorimotor control[5]. Sensorimotor control involves the sensory, motor, and central integration and processing components responsible for maintaining joint homeostasis during functional movements, playing a crucial role in the regulation of postural equilibrium[6]. Previous studies have demonstrated that CAI is associated with sensorimotor dysfunction following LAS injury and contributes to postural control deficits in CAI patients[7,8]. Time to stabilization (TTS) has been the most reliable measure to identify postural control deficits in patients with and without CAI[7]. The TTS refers to the ability to maintain the equilibrium condition as quickly as possible

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following anticipated postural sway during jump landing and/or drop landing[9]. A longer TTS during landing could be a result of sensorimotor dysfunction[9].

CAI patients showed longer TTS during single-leg jump landing compared to ankle sprain copers and/or healthy controls, whereas no postural control deficits in TTS were observed during single-leg drop landing in ankle sprain copers[7,10,11]. However, postural control measurements of TTS in previous studies were conducted under controlled, anticipated, and predictable conditions, where participants could anticipate and prepare for their jump landing and/or drop landing tasks[7,10,11]. In addition, the single-leg stance (SLS) test has been widely used to assess postural control capacity in CAI and ankle sprain coper studies[12–14]. The ankle sprain copers show no postural control deficits during the SLS test[12–14].

There are several limitations in the current literature. Both static (SLS) and dynamic (jump landing) postural control tasks may not replicate the actual mechanisms of LAS injury. The task demand of the static SLS task may be too low to identify postural control deficits in ankle sprain copers. Additionally, the dynamic jump landing task for TTS has been conducted under anticipated conditions. These two measures may not replicate actual LAS mechanisms as ankle sprains typically occur in sudden, uncontrolled, and unanticipated situations. Since LAS injuries often involve a combination of foot adduction, inversion, and/or internal rotation[15], it could be reasonable that CAI patients would have directional deficits in postural control.

To fill the current research gaps, postural control measures should be more challenging and unanticipated by giving sudden horizontal perturbations in several directions. Identifying directional postural control deficits during perturbations could help develop injury prevention and/or rehabilitation strategies for LAS. Therefore, the purpose of this study was to identify directional deficits in reactive postural control during horizontal perturbations in SLS among groups of CAI, ankle sprain coper, and healthy control. Based on the previous study[7], we hypothesized that CAI patients would show directional deficits in reactive postural control (longer TTS) in four perturbation directions compared to ankle sprain copers and healthy controls. In addition, we hypothesized that ankle sprain copers would show reactive postural control similar to healthy controls.

Methods

Research design

The research design was a case-control laboratory trial. Participants completed a single data collection session in a biomechanics laboratory. The independent variables were group (CAI, ankle sprain coper, and healthy control) and perturbation directions (anterior, posterior, medial, and lateral). The dependent variables were anterior-posterior time to stabilization (APTTS) and medial-lateral time to stabilization (MLTTS) from x- and y-axis of ground reaction force (GRF).

Participants

A total of 68 physically active individuals: 24 CAI patients, 23 ankle sprain copers, 21 healthy controls were recruited with an age of 18 to 45 years (Table 1). Of the CAI patients, 9 (38%) had a history of unilateral ankle sprains, and 15 (63%) had a history of bilateral ankle sprains. Patients with bilateral CAI selected the limb they perceived as having greater instability as their SLS testing limb based on the previous study[16]. Among the ankle sprain copers, 9 (39%) had a history of a single ankle sprain, while 4 (17%) and 10 (43%) had a history of unilateral and bilateral ankle sprains, respectively. A priori sample size was calculated using G*Power ver. 3.1.9.4 (Franz Faul, Universität Kiel, Germany; Test family = F tests; Statistical test = ANOVA: repeated measures, between factors; Type of power analysis = α priori). Based on a previous study investigating the contribution of lower extremity kinematics during an assessment of dynamic postural control in patients with CAI[17], a feasible sample size of 68 participants was selected based on effect size f = 0.30, α error probability = 0.05, and power (1-β error probability) = 0.80. Inclusion and exclusion criteria for the CAI and ankle sprain coper groups were based on the suggested criteria from the International Ankle Consortium[18]. Participants were identified using the Foot and Ankle Ability Measure (FAAM)[19] and the Modified Ankle Instability Instrument (MAII)[20] questionnaires.

	Group, Mean (SD)				
Characteristic	**Chronic Ankle Instability**	**Ankle Sprain Coper**	**Healthy Control**	$F_{2,65}$	*P*
Sex (male/female)	12/12	12/11	10/11		
Age (years)	30.08 (4.21)	29.30 (4.11)	31.05 (4.30)	0.95	0.39
Height (cm)	172.67 (8.50)	169.83 (7.87)	170.86 (8.50)	0.71	0.50
Mass (kg)	69.33 (13.83)	68.00 (15.36)	65.81 (12.58)	0.36	0.70
FAAM ADL (%)	80.33 (9.31)	98.30 (2.20)	100	85.17	< 0.01[a, b]
FAAM Sport (%)	60.42 (13.91)	94.43 (5.15)	100	137.00	< 0.01[a, b]
MAII (No. yes)	3.50 (1.06)	0	0	237.79	< 0.01[a, b]
Ankle sprains (No.)	5.63 (3.92)	1.17 (0.94)	0	35.31	< 0.01[a, b]
Failed trials (No.)	4.29 (1.55)	3.91 (1.38)	1.24 (0.94)	34.34	< 0.01[a, c]

Table 1. Participant demographics. *ADL* activities of daily living, *FAAM* foot and ankle ability measure, *MAII* modified ankle instability instrument, *No.* number, *SD* standard deviation. [a] Indicates a significant difference between the chronic ankle instability and healthy control group. [b] Indicates a significant difference between the chronic ankle instability and ankle sprain coper group. [c] Indicates a significant difference between the ankle sprain coper and healthy control group.

Specific inclusion and exclusion criteria for each group are presented in Table 2. This study was approved by the Institutional Review Board of CHA University (IRB No. 1044308-202104-HR-017-02) and was implemented in accordance with the Declaration of Helsinki. All participants provided written informed consent prior to their participation. All experimental procedures were performed in accordance with relevant guidelines and regulations.

Experimental procedures

Anthropometric data including age, height, and mass were recorded for each participant (Table 1). We examined reactive postural control during the SLS by giving sudden and unanticipated horizontal perturbations in four random directions (anterior, posterior, medial, and lateral) using a robotic-based force plate platform (XY stage). The XY stage was customized and developed to allow the platform to perform linear translation into 8 directions (the same directions of the star excursion balance test [SEBT]) by the Department of Robotics and Mechatronics Engineering at XXX[21]. The magnitude of the robotic-based perturbation device was controlled by time (0.1–2.0 s), frequency (0.5–5.0 Hz), and a maximal distance of 90 mm. Testing protocols were selected based on pilot data collection with a time of 0.4 s, 2.5 Hz, and distance of 30 mm. Prior to actual data collection, participants performed at least 3 practice trials in each of four perturbation directions to reduce learning effects in postural control measures. Participants performed 20 s trials of SLS with barefoot on a force plate platform with eyes open. Participants maintained their hands on their iliac crest, their non-weight-bearing leg of 30 deg of hip flexion, and 90 deg of knee flexion[22]. The weight-bearing leg was fully extended at the knee, and the foot was in a neutral position with the second toe and the center of the heel aligned vertically. They were instructed to remain as motionless as possible while focusing on a visual target placed 5 m in front of them (Fig. 1). We examined a total of 15 trials, including 12 successful trials (three trials per four perturbation directions) and 3 dummy trials, to minimize the learning effect and anticipation of the perturbation directions. Additionally, the onset of the initial perturbation was provided differently for each participant within 5–10 s after they assumed the SLS position. The perturbation directions were randomized for each participant using a random function in Excel. The participants held their SLS position for 10–15 s after the end of the perturbation. There was a 60 s rest period between each trial to minimize fatigue effects. The current testing protocol took us around and/or over 1-hour per participant including the practice (12 trials) and testing (15 trials) sessions with a 60-sec resting period and failed trials (1–7 trials per participant). We followed failed trials based on the balance error scoring system including (i) moving the hands off of the iliac crest, (ii) a step, stumble, or fall, (iii) abduction or flexion of their hip or trunk more than 30°, (iv) lifting the forefoot or heel off from the force plate, and (v) being unable to remain a SLS position less than 20 s[22]. If failed trials occurred, the testing trial was repeated until 3 successful testing trials were obtained in all four directions. An average of failed trials in each group is presented in Table 1.

Chronic Ankle Instability	Ankle Sprain Coper	Healthy Control
Inclusion Criteria		
1. A history of at least ≥ 1 severe LAS, which was associated with inflammatory symptoms like pain, swelling, loss of function, etc.	1. A history of at least ≥ 1 severe LAS, which was associated with inflammatory symptoms like pain, swelling, loss of function, etc.	1. No history of LAS.
2. The initial LAS must have occurred at least 12 months prior to the study.	2. The initial LAS must have occurred at least 12 months prior to the study.	2. MAII: No 'yes' answers on questions 4 to 8.
3. The initial LAS was required immobilization and/or non-weight bearing for ≥ 3 days or external supports for ≥ 7 days or both.	3. The initial LAS was required immobilization and/or non-weight bearing for ≥ 3 days or external supports for ≥ 7 days or both.	3. FAAM ADL: 100%
4. The most recent LAS must have occurred more than 3 months prior to the study.	4. A return to moderate levels of weight-bearing physical activity without chronic residual symptoms within 12 months.	4. FAAM Sport: 100%
5. Participants should report at least 2 'giving way' episodes in the 6 months prior to the study.	5. MAII: No 'yes' answers on questions 4 to 8. (self-reported ankle instability)	
6. MAII: ≥2 'yes' answers on questions 4 to 8. (self-reported ankle instability)	6. FAAM ADL: ≥90% (self-reported ankle function)	
7. FAAM ADL: <90% (self-reported ankle function)	7. FAAM Sport: ≥80% (self-reported ankle function)	
8. FAAM Sport: <80% (self-reported ankle function)		
Exclusion Criteria		
1. A history of previous surgeries (e.g., bones, joint structures, and/or nerves).		
2. A history of fractures in the lower extremity.		
3. A history of neurological disorders.		
4. Acute injury to musculoskeletal structures in the lower extremity in the past 3 months.		

Table 2. Inclusion and exclusion criteria for patients with chronic ankle instability and/or ankle sprain coper. *ADL* activities of daily living, *FAAM* foot and ankle ability measure, *LAS* lateral ankle sprain, *MAII* modified ankle instability instrument.

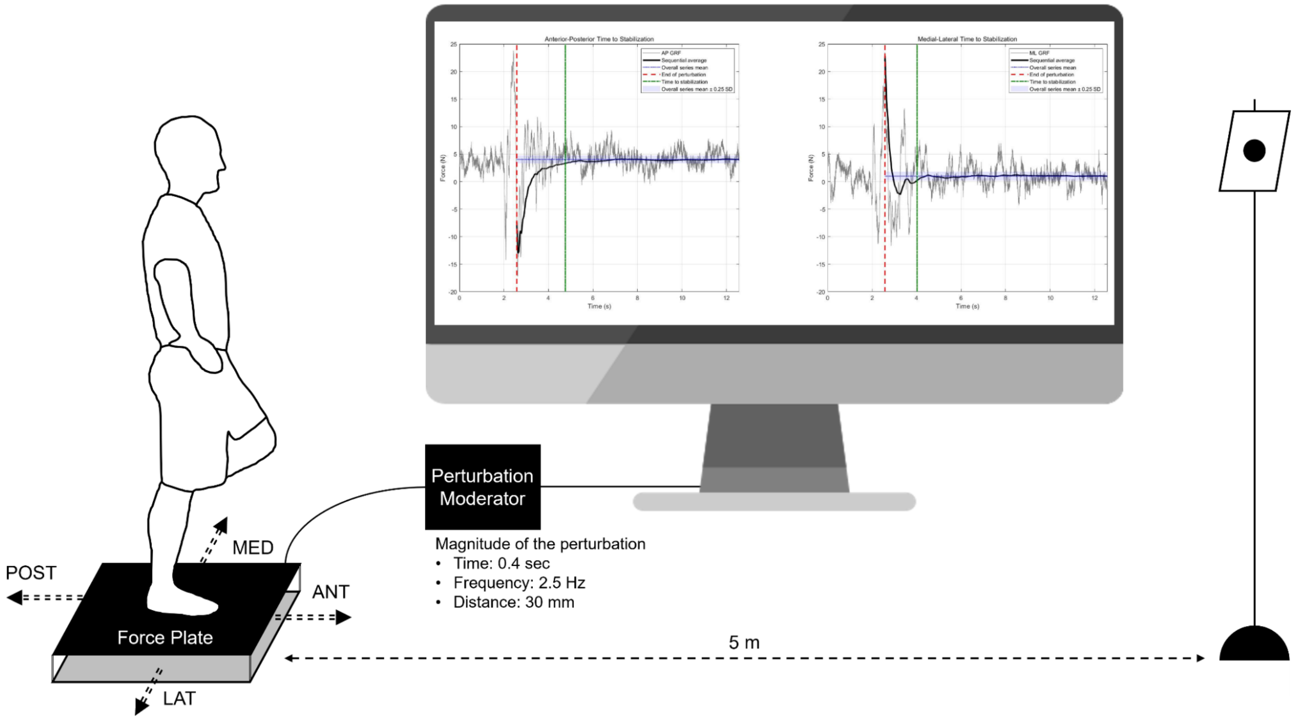

Fig. 1. Testing procedure for sudden and unanticipated perturbations in the anterior, posterior, medial, and lateral directions during single-leg stance task using a robotic-based force plate platform. *ANT* anterior, *LAT* lateral, *MED* medial, *POST* posterior.

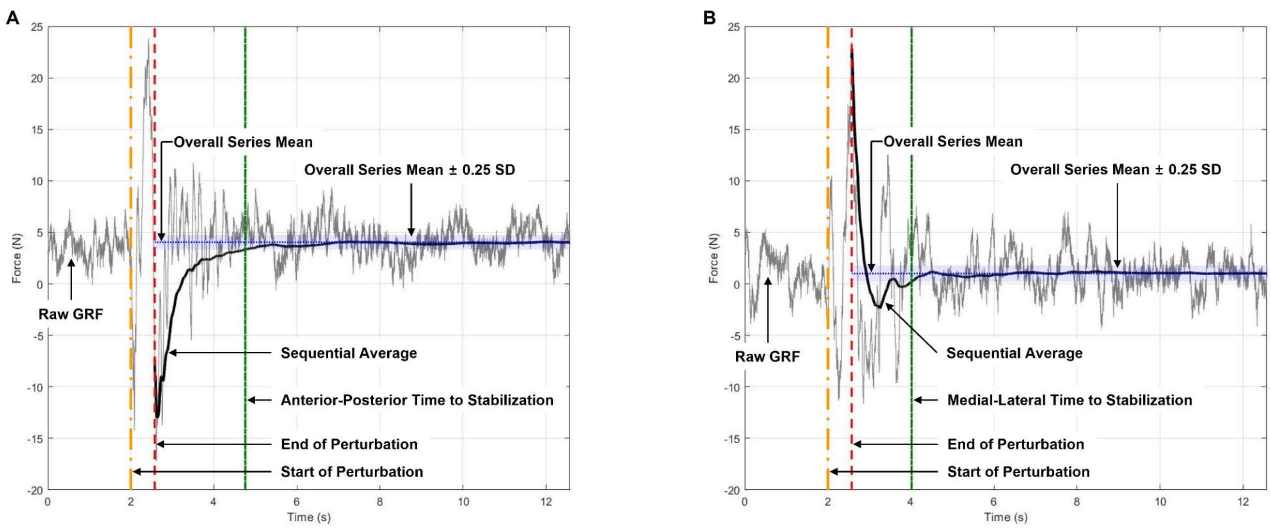

Fig. 2. A graphical representation of the calculation of time to stabilization using the sequential estimation: (**A**) anterior-posterior time to stabilization, (**B**) medial-lateral time to stabilization. *GRF*, ground reaction force, *SD*, standard deviation.

Data analysis

Raw GRF data of x- and y-axis were analyzed using a custom-written MATLAB code (MathWorks Inc., Natick, MA, US). Sampling rate for GRF data was set at 1000 Hz. APTTS and MLTTS were calculated through the technique of sequential estimation (Fig. 2), using an algorithm to calculate a cumulative average of the data points from the SLS trials in series by successively adding in one point at a time[23]. This cumulative average was then compared against the overall series mean of the GRF[23]. The series consists of all data points collected during the 10-second period after the end of perturbation[23]. The participant was considered to stable position when the sequential average remained within 0.25 standard deviations of the overall series mean[23]. An average of three successful trials in each of four perturbation directions were used for statistical analyses.

Statistical analysis

All data analyses were performed using JMP Pro 17 software (SAS Institute Inc., Cray, NC, US). A 3 × 4 two-way repeated measures analysis of variances were used to examine an interaction of the group (CAI, ankle sprain coper, and healthy control) by perturbation direction (anterior, posterior, medial, and lateral). Tukey honest significant difference post-hoc tests were used for pairwise comparisons. The effect sizes of repeated measures analysis of variances were calculated as partial eta squared. Effect sizes were interpreted as ≥ 0.01 was small, ≥ 0.06 was medium, and ≥ 0.14 was large[24]. A significant level was set at < 0.05.

Results

Interaction effect (group X perturbation direction) and main effect

The results of an interaction effect and a main effect are shown in Table 3. We found a significant interaction between the group and the perturbation direction. Specifically, there was a significant interaction for medial and lateral horizontal perturbations, but not for anterior and posterior horizontal perturbations. The results of post-hoc pairwise comparisons are shown in Fig. 3; Table 3.

CAI group vs. healthy control group

Compared to the healthy control group, the CAI group showed longer APTTS and MLTTS during medial horizontal perturbation. Compared to the healthy control group, the CAI group showed longer APTTS and MLTTS during lateral horizontal perturbation. However, no significant interaction effect was found in the APTTS and MLTTS during anterior and posterior horizontal perturbations, respectively.

Ankle sprain coper group vs. healthy control group

Compared to the healthy control group, the ankle sprain coper group showed longer APTTS and MLTTS during medial horizontal perturbation. Compared to the healthy control group, the ankle sprain coper group showed longer APTTS and MLTTS during lateral horizontal perturbation. However, no significant interaction effect was found in the APTTS and MLTTS during anterior and posterior horizontal perturbations, respectively.

CAI group vs. ankle sprain coper group

No significant interaction effect was found in the APTTS and MLTTS during anterior, posterior, medial, and lateral horizontal perturbations, respectively.

Discussion

This study was designed to examine directional deficits in reactive postural control among groups of CAI, ankle sprain coper, and healthy control. We hypothesized that CAI patients would exhibit directional deficits in reactive postural control for both APTTS and MLTTS during horizontal perturbations compared to ankle sprain copers and healthy controls, while ankle sprain copers would demonstrate reactive postural control ability similar to healthy controls. Overall, the current results partially support our hypotheses. First, CAI patients demonstrated longer APTTS and MLTTS during medial and lateral horizontal perturbations (Fig. 1). Second, contrary to our

	Group, Mean (SD)			Difference (95% CI)		Difference (95% CI)		Difference (95% CI)		Group effect		Direction effect		Interaction	
	CAI	Coper	Control	CAI-Control	P	Coper-Control	P	CAI-Coper	P	$F_{2,260}$	$P\ (\eta^2_p)$	$F_{3,260}$	$P\ (\eta^2_p)$	$F_{6,260}$	$P\ (\eta^2_p)$
APTTS (sec)															
Anterior	1.54 (0.36)	1.31 (0.41)	1.43 (0.36)	0.11 (-0.29 to 0.52)	1.00	-0.12 (-0.29 to 0.53)	1.00	0.23 (-0.16 to 0.63)	0.74	51.06	< 0.01 (0.28)	107.15	< 0.01 (0.55)	11.32	< 0.01 (0.21)
Posterior	1.51 (0.41)	1.58 (0.40)	1.31 (0.39)	0.20 (-0.20 to 0.61)	0.89	0.27 (-0.14 to 0.68)	0.57	-0.07 (-0.33 to 0.46)	1.00						
Medial	2.72 (0.43)	2.59 (0.33)	1.74 (0.44)	0.97 (0.57 to 1.38)	< 0.01	0.84 (0.43 to 1.25)	< 0.01	0.13 (-0.27 to 0.53)	1.00						
Lateral	2.71 (0.37)	2.66 (0.51)	1.66 (0.51)	1.05 (0.64 to 1.45)	< 0.01	1.00 (0.59 to 1.41)	< 0.01	0.05 (-0.35 to 0.45)	1.00						
MLTTS (sec)															
Anterior	1.60 (0.41)	1.41 (0.39)	1.29 (0.35)	0.32 (-0.08 to 0.71)	0.25	0.12 (-0.28 to 0.52)	1.00	0.20 (-0.19 to 0.58)	0.87	57.30	< 0.01 (0.31)	142.01	< 0.01 (0.62)	10.20	< 0.01 (0.19)
Posterior	1.41 (0.34)	1.46 (0.33)	1.35 (0.37)	0.06 (-0.33 to 0.45)	1.00	0.11 (-0.28 to 0.51)	1.00	-0.05 (-0.33 to 0.43)	1.00						
Medial	2.85 (0.39)	2.70 (0.42)	1.81 (0.46)	1.04 (0.65 to 1.43)	< 0.01	0.89 (0.49 to 1.28)	< 0.01	0.15 (-0.23 to 0.54)	0.98						
Lateral	2.77 (0.42)	2.61 (0.46)	1.77 (0.43)	1.01 (0.62 to 1.40)	< 0.01	0.85 (0.45 to 1.24)	< 0.01	0.16 (-0.22 to 0.55)	0.96						

Table 3. Results for time to stabilization by group and direction. *APTTS* anterior-posterior time to stabilization, *CAI* chronic ankle instability, *CI* confidence interval, *MLTTS* medial-lateral time to stabilization, *sec* second, *SD* standard deviation, η^2_p partial eta squared.

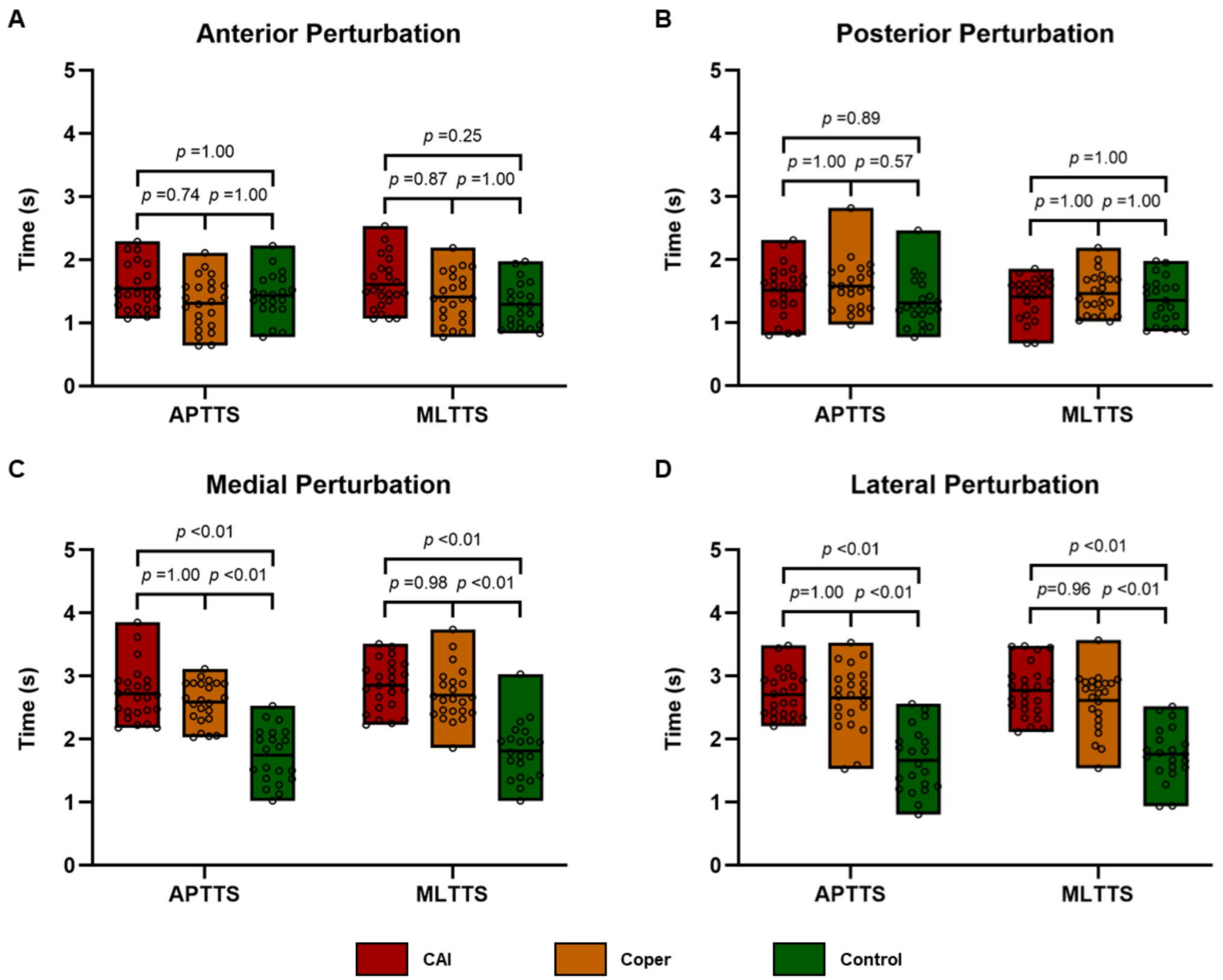

Fig. 3. Results of time to stabilization for (**A**) anterior, (**B**) posterior, (**C**) medial, and (**D**) lateral perturbations among groups of CAI, coper, and control. *APTTS* anterior-posterior time to stabilization, *CAI* chronic ankle instability, *MLTTS* medial-lateral time to stabilization.

hypothesis, ankle sprain copers with a history of ankle sprains also demonstrated the same directional deficits in reactive postural control (Fig. 1). Third, both CAI and ankle sprain coper groups exhibited no reactive postural control deficits in APTTS and MLTTS during anterior and posterior horizontal perturbations (Fig. 1). These findings suggest that individuals with a history of ankle sprains (CAI patients and ankle sprain copers) appear to have directional balance deficits during horizontal perturbations in the frontal plane, but not in the sagittal plane.

Our finding is consistent with previous literatures that CAI patients demonstrated longer TTS compared to healthy controls[7,10,11]. However, conflicting results also exist regarding directional deficits in postural control among individuals with and without CAI[25–30]. For example, three studies[25–27] reported longer TTS in both the anterior-posterior and medial-lateral directions in CAI patients, while two studies reported longer TTS in the anterior-posterior[17,28] and medial-lateral directions[29,30], respectively. In contrast to previous findings[25–30], we found reactive postural control deficits in the frontal plane only during sudden and unanticipated horizontal perturbations in CAI patients. The discrepancies between our findings and previous findings may be the result of differences in testing methodologies[25–30]. For example, most previous studies[25–30] investigated postural control deficits in CAI patients using single-leg jump landing or drop landing tasks. These studies did not account for directional postural control deficits and examined postural control deficits in four directions solely through movements restricted to a single direction. In contrast, we evaluated postural control deficits by applying unanticipated horizontal perturbations in random directions during a quiet SLS task to account for the directional aspect of postural control. Therefore, our findings, which identified reactive postural control deficits in the frontal plane for CAI patients, may provide meaningful insights for the successful prevention and/or rehabilitation of CAI development.

In this study, ankle sprain copers demonstrated reactive postural control deficits during medial and lateral horizontal perturbations (Table 3). Previous studies on postural control in ankle sprain copers have shown conflicting results[30–33]. A recent systematic review reports that ankle sprain copers show a postural control abilities similar to healthy individuals during static SLS, dynamic SEBT, and gait termination tasks[31]. On the other hand, several studies have reported postural control deficits in ankle sprain copers during dynamic single-leg jump landing or drop landing tasks[30,32,33]. For example, Wikstrom et al.[32]. reported that coper group show greater anterior-posterior stability index and dynamic postural stability index during forward single-leg jump landing compared to the control group. Particularly, the coper group show the greatest scores (impaired postural control) for all dynamic postural stability variables among groups of CAI, coper, and control[32]. In addition, Wright et al.[30] reported ankle sprain copers show postural control deficits in the sagittal plane during forward single-leg drop landing, but not in the frontal plane. Similarly, Watabe et al.[33] reported that coper group found longer APTTS and anterior-posterior maximal COP excursion during forward, lateral, and diagonal single-leg drop landing compared to the control group. These findings suggest that ankle sprain copers may potentially have postural control deficits in the sagittal plane rather than the frontal plane. However, postural control deficits in the sagittal plane may result from the jump-landing direction in which the task is performed. For example, Wikstrom et al.[34]. found that lateral and diagonal jump-landings produced increased medial-lateral stability index scores and forward jump-landing produced increased vertical stability index scores in healthy individuals. Liu and Heise[35] also found that medial and lateral jump-landing directions demonstrated longer MLTTS, whereas forward and backward jump-landing directions demonstrated longer APTTS in healthy individuals. The researchers suggest that the effects of jump-landing directions on postural control be exacerbated in individuals with lower extremity impairments[34]. Although a recent study reported that jump-landing directions affect postural stability in patients with anterior cruciate ligament reconstruction[36], there is little empirical evidence to support the notion that it also affects individuals with a history of LAS injury. Therefore, our findings, which excluded this influence, are derived from a novel testing protocol, and more importantly, unanticipated perturbations could be the key to distinguishing whether ankle sprain copers have potential postural control deficits or not.

Contrary to our hypothesis, ankle sprain copers demonstrated reactive postural control deficits similar to CAI patients (Table 3). This finding has important research and clinical implications. Most previous studies have included ankle sprain copers based on the minimum recommended criteria in CAI research[2]. For example, ankle sprain copers are typically identified by patient-reported outcome measures (PROMs), which include subjective assessment tools such as self-reported ankle instability (e.g., AII, Cumberland Ankle Instability Tool, and Identification of Functional Ankle Instability) and self-reported ankle function (e.g., FAAM and Foot and Ankle Outcome Score) questionnaires[2]. They are considered to be in a successfully recovered condition as shown in the PROMs in which they have no chronic residual symptoms and/or recurrent injuries in the past one year following their initial LAS injury[1,2]. Interestingly, our findings indicate that ankle sprain copers seem to have recovered from their LAS injury, as no significant differences were observed compared to healthy controls in the MAII, FAAM-ADL, and FAAM-Sport scores (Table 1). However, these individuals still exhibited reactive postural control deficits. In other words, our findings suggest that although ankle sprain copers may perceive themselves as fully recovered from their LAS injury, underlying sensorimotor dysfunction may still persist. Therefore, it should be considered that the selection criteria for ankle sprain copers should include not only PROMs but also functional performance tests.

Observed directional deficits in reactive postural control in both CAI and ankle sprain coper groups could be associated with a common continuum of disability following LAS injury[37]. Cascading events following LAS injury include ligament damage (anterior talofibular ligament [ATFL] and calcaneofibular ligament [CFL]), impaired sensory pathways to the brain, surrounding ankle structural changes, inhibition of spinal reflexes, and/or impaired sensorimotor control[37]. Importantly, impaired reactive postural control during frontal plane perturbations could result from the consequences of structural ligament damage in the frontal plane for individuals with a history of LAS injury. LAS injury results in damage to static stabilizers of the ankle, such as ATFL and CFL, which provide static stability to the ankle in the frontal plane[15,38]. Unfortunately, this could result in increased pathologic talocrural joint and ligament laxity (ATFL and CFL) in both the anterior-posterior direction and medial-lateral directions[39–41]. This mechanical ankle instability could, in turn, lead to postural control deficiencies[1,15,37]. For example, postural control deficits reported in CAI patients with mechanical ankle instability during SLS (increased center of pressure [COP] excursion and area)[42,43] and single-leg jump landing (greater dynamic postural stability index scores)[44]. Moreover, increased anterior and posterior joint laxity of the ankle was correlated with increased COP area during SLS and a shorter posterolateral reach distance during the SEBT[45]. Based on previous studies[42–45], the impaired postural control observed during medial and lateral horizontal perturbations in this study supported the cascade of events associated with structural damage related to LAS injury[1,15,37].

While speculative, it could be inferred that the directional deficits in reactive postural control observed during medial and lateral perturbations in both the CAI and ankle sprain coper groups may result from sensorimotor dysfunction in the dynamic stabilizers of the musculature responsible for the frontal plane[1], in addition to mechanical structural alterations of the ankle in the frontal plane. Given that muscle activation following unanticipated perturbations occurs with latencies between 70 and 180 ms post-perturbation[46], the peroneal muscles play a crucial role in maintaining postural equilibrium in the frontal plane[8]. However, delayed peroneal reaction time in individuals with a history of LAS injury is considered both a contributing factor[7] and a primary characteristic[8] associated with the development of CAI. Furthermore, arthrogenic muscle inhibition in the peroneal muscles of the injured limb was observed in patients with CAI[47]. Importantly, this sensorimotor dysfunction is not limited to the distal musculature (peroneal muscles) but has also been observed in the proximal musculature (gluteal muscles). For example, CAI patients demonstrated reduced motor activation of the frontal-plane musculature during walking[16] and jump landing/cutting tasks[48], with the activation of the peroneus longus and gluteus medius negatively affected in the frontal plane. This interpretation can be supported by a systematic review and meta-analysis that reported tri-planar hip strength (hip external rotator, abductor, and extensor) deficits in CAI patients[49,50]. Although this study collected only GRF data to investigate directional deficits in reactive postural control, future research should investigate sensorimotor dysfunction in individuals with a history of LAS injury based on our findings, through kinematic and electromyographic analyses.

There are several limitations in this study. First, we did not collect neuromechanical data related to variables for identifying pathomechanical laxity and/or sensorimotor dysfunction, which limits our ability to determine whether the directional deficits are caused by mechanical instability and/or functional instability. Therefore, future research is needed to identify the impact of pathomechanical laxity and/or somatosensory impairments on reactive postural control deficits in the frontal plane for individuals with a history of LAS injury. Second, as the current research was conducted in a university setting with collegiate students, current findings shouldn't be inferred to other adolescent and/or older age populations. Third, the postural control task used in this study was static SLS, and the results would be different if a dynamic balance task is conducted. Lastly, the sample sizes were not numerically matched across the CAI, ankle sprain coper, and healthy control groups. Therefore, potential differences due to unequal sample sizes between groups may have influenced the results.

In conclusion, this study is novel as we used the robotic-based perturbation force plate platform, which enables the creation of sudden and unanticipated horizontal perturbations in four directions. As such, this study examined directional deficits in reactive postural control among groups of CAI, ankle sprain coper, and healthy control. Our results show that CAI and ankle sprain coper groups had longer APTTS and MLTTS only during medial and lateral horizontal perturbations, but not anterior and posterior horizontal perturbations. These findings indicate directional deficits in reactive postural control among individuals with a history of LAS injury (CAI patients and ankle sprain copers). For clinicians, individuals with a history of LAS injury may have potential sensorimotor dysfunction in reactive postural control, especially in the frontal plane. Therefore, clinicians should provide perturbation balance training to improve sensorimotor control in the frontal plane.

Data availability

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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Author contributions
M.K. wrote the manuscript, S.K. collected the data, J.K., W.C., and S.O. analyzed and interpreted the data, J.T.H. reviewed and edited the manuscript, S.J.S. designed the study. All authors critically revised and approved the final manuscript.

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Declarations

Competing interests
The authors declare no competing interests.

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