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Sensory Reweighting System Differences on Vestibular Feedback With Increased Task Constraints in Individuals With and Without Chronic Ankle Instability

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Context: Chronic ankle instability (CAI) is associated with a less flexible and adaptable sensorimotor system. Thus, individuals with CAI may present an inadequate sensory reweighting system, inhibiting their ability to place more emphasis (upweight) on reliable sensory feedback to control posture. However, how individuals with CAI reweight sensory feedback to maintain postural control in bilateral and unilateral stances has not been established.

Objectives: To examine (1) group differences in how the sensory reweighting system changes to control posture in a simple double-limb stance and a more complex single-limb stance (uninjured limb and injured limb) under increased environmental constraints manipulating somatosensory and visual information for individuals with and without CAI and (2) the effect of environmental and task constraints on postural control.

Design: Case-control study.

Setting: Laboratory.

Patients or Other Participants: A total of 21 individuals with CAI (age = 26.4 ± 5.7 years, height = 171.2 ± 9.8 cm, mass = 76.6 ± 15.17 kg) and 21 individuals without CAI (control group; age = 25.8 ± 5.7 years, height = 169.5 ± 9.5 cm, mass = 72.4 ± 15.0 kg) participated.

Main Outcome Measure(s): We examined the equilibrium scores based on the first 10 seconds of trials in which participants completed 6 environmental conditions of the Sensory Organization Test during 3 tasks (double-limb and single-limb [uninjured and injured] stances). Sensory reweighting ratios for sensory systems (somatosensory, vision, and vestibular) were computed from paired equilibrium scores based on the first 10 seconds of the trials.

Results: We observed 3-factor interactions between groups, sensory systems, and tasks ($F_{4,160} = 3.754$, $P = .006$) and for group, task, and environment ($F_{10,400} = 2.455$, $P = .007$). The CAI group did not downweight vestibular feedback compared with the control group while maintaining posture on the injured limb ($P = .03$). The CAI group demonstrated better postural stability than the control group while standing with absent vision (ie, eyes closed), fixed surroundings, and a moving platform on the injured limb ($P = .03$).

Conclusions: The CAI group relied on vestibular feedback while maintaining better postural stability than the control group in injured-limb stance. Group differences in postural control depended on both environmental (absent vision and moving platform) and task (injured limb) constraints.

Key Words: multiple ankle sprains, modified sensory reliance, dynamic systems theory, multisensory integration, postural control

Key Points

- The chronic ankle instability group did not downweight vestibular feedback and yet had better postural control performance than the control group while maintaining posture on their injured limbs.
- The group differences in postural control depended on both environmental (vision or absent vision and surroundings or platform movement or lack thereof) and task (double-, uninjured-, or injured-limb stance) constraints.
- Taking a multisensory feedback approach by challenging vestibular feedback with and without vision may optimize rehabilitation interventions for individuals with chronic ankle instability.

An initial ankle sprain results in mechanical and perceived impairments at the ankle, contributing to the development of chronic ankle instability (CAI).[1,2] Individuals with CAI experience subsequent ankle sprains and develop lifetime functional disabilities during daily living. The cause of subsequent ankle sprains in individuals with CAI has been attributed to articular deafferentation, which is hypothesized to result from damaged mechanoreceptors in the ankle-joint capsule and ligaments from an initial ankle sprain disrupting somatosensory feedback to the central nervous system.[3] This disruption may diminish individuals' ability to obtain relevant somatosensory feedback. The inability to obtain relevant somatosensory feedback may contribute to alteration in overall haptic perception and postural instability, resulting in less flexible and adaptable sensorimotor systems in individuals with CAI. In contrast, individuals without CAI present flexible and adaptable sensorimotor systems and can freely integrate redundant sensory feedback from 3 primary sensory systems (somatosensory, vestibular, and vision) to coordinate desired motor behaviors, known as *multisensory integration*, driven by the sensory reweighting system.[4]

Postural stability provides the basis for optimal motor behaviors in daily activity and sports performance, especially in ever-changing environments and when tasks become more complex. According to the dynamic systems theory, an inherent dependent relationship exists between organismic (health) status, environment, and task, and individuals self-organize emerging constraints from these elements to achieve desired task constraints, such as maintaining postural control in bilateral and unilateral stances.[5] The sensory reweighting system places emphasis (ie, upweight) on the most relevant sensory feedback relative to changes in the environment and integrates multisensory feedback applicable to accomplishing different task goals. For instance, individuals without CAI generally upweight 70% on somatosensory, 20% on vestibular, and 10% on visual feedback to maintain postural control in bilateral stance under a stable environment without constraints; however, when somatosensory feedback becomes disrupted by a sudden change in environmental constraints from a stable surface to an unstable surface, individuals without CAI freely reweight emphasis on visual and vestibular feedback to maintain postural stability.[4] Thus, the ability to reweight emphasis on relevant sensory feedback relative to changes in environmental constraints is critical to maintaining postural stability as task constraints increase.[4,6] For instance, individuals with CAI who present with less flexible and adaptable sensorimotor systems may present sensory reweighting deficits resulting in postural instability. However, the current CAI literature lacks an understanding of how increased environmental constraints affect the sensory reweighting system to control posture with task constraints, such as maintaining posture in a simple bilateral stance and in a more complex unilateral (uninjured- or injured-limb) stance.

Individuals with CAI upweight visual feedback to compensate for somatosensory deficits while controlling posture in a single-limb stance compared with healthy controls (ie, individuals without CAI).[7] Eye closure (ie, absent vision) leads to an increase in functional connectivity between the thalamus and somatosensory cortex in the brain, leading to a nonvisually dominated processing mode.[8,9] Therefore, somatosensory feedback contributions to postural control in individuals with CAI cannot be ruled out solely based on balance scores in single-limb stance with and without eyes closed. Accordingly, the sensory reweighting system in individuals with CAI and whether they upweight visual feedback to maintain posture in bilateral and unilateral stances compared with individuals without CAI is still unknown.

Understanding the sensory reweighting system of individuals with CAI is an essential initial step in developing an intervention program that strengthens congruency in multisensory integration to enhance haptic perceptual and behavioral performance. Therefore, the primary purpose of our study was to examine the sensory reweighting system changes to control posture in a simple double-limb stance and a more complex uninjured- or injured-limb stance under increased environmental constraints, manipulating somatosensory and visual information, for individuals with and without CAI. The secondary purpose was to determine the effect of environmental and task constraints on postural stability. We hypothesized that the CAI group would increase reliance on visual feedback to control posture during injured-limb stance compared with uninjured- and double-limb stances and compared with the matched stance limbs of a control group without CAI. We also expected the CAI group to present greater postural instability in injured-limb stance, particularly when environmental constraints become more complex.

Table 1. Participant Demographics, Patient-Reported Outcome Measure Scores, and Preference Ratios

Variable	Chronic Ankle Instability Group (n = 21)	Control Group (n = 21)	*P* Value
	No.		
Sex, females/males	13/8	13/8	
	Mean ± SD		
Age, y	26.38 ± 5.73	25.76 ± 5.71	.73
Height, cm	171.81 ± 9.78	169.45 ± 9.47	.43
Mass, kg	76.57 ± 15.17	72.38 ± 15.06	.37
NASA-PASS score	6.24 ± 0.83	6.24 ± 1.04	>.99
IdFAI score	18.71 ± 5.22	1.43 ± 1.83	<.001
No. of ankle sprains	6.79 ± 7.74	0.00 ± 0.00	<.001
No. of episodes of ankle "giving way"	12.29 ± 6.64	0.00 ± 0.00	<.001
Preference ratio			
Double-limb stance	1.02 ± 0.04	1.03 ± 0.07	.70
Uninjured-limb stance	1.14 ± 0.10	1.15 ± 0.10	.91
Injured-limb stance	1.10 ± 0.10	1.19 ± 0.12	.01[a]
C3-$V_dS_mP_f$/C2-$V_aS_fP_f$	1.11 ± 0.09	1.15 ± 0.13	.27
C6-$V_dS_mP_m$/C5-$V_aS_fP_m$	1.09 ± 0.15	1.24 ± 0.20	.006[a]

Abbreviations: C2-$V_aS_fP_f$, condition 2: absent vision, fixed surroundings, fixed platform; C3-$V_dS_mP_f$, condition 3: distorted vision, moving surroundings, fixed platform; C5-$V_aS_fP_m$, condition 5: absent vision, fixed surroundings, moving platform; C6-$V_dS_mP_m$, condition 6: distorted vision, moving surroundings, moving platform; IdFAI, Identification of Functional Ankle Instability; NASA-PASS, National Aeronautics and Space Administration Physical Activity Status Scale.
[a] Indicates difference.

METHODS

Study Design

We implemented a laboratory case-control and mixed-model design to examine postural control and the sensory reweighting system in individuals with and without CAI.

Participants

A total of 42 physically active individuals with and without unilateral CAI participated in this study (Table 1). Individuals with and without CAI were defined based on the International Ankle Consortium position statement.[10,11] No participant had symptoms of inflammation, surgeries of the brain or the lower extremity, concussion within the 6 months before study enrollment, chronic musculoskeletal conditions, connective tissue disease and disorders, or vestibular or visual disorders and peripheral neuropathies that may influence postural control. Individuals in the control group were matched to individuals in the CAI group for sex, age (± 2 years), height (cm, ±5%),

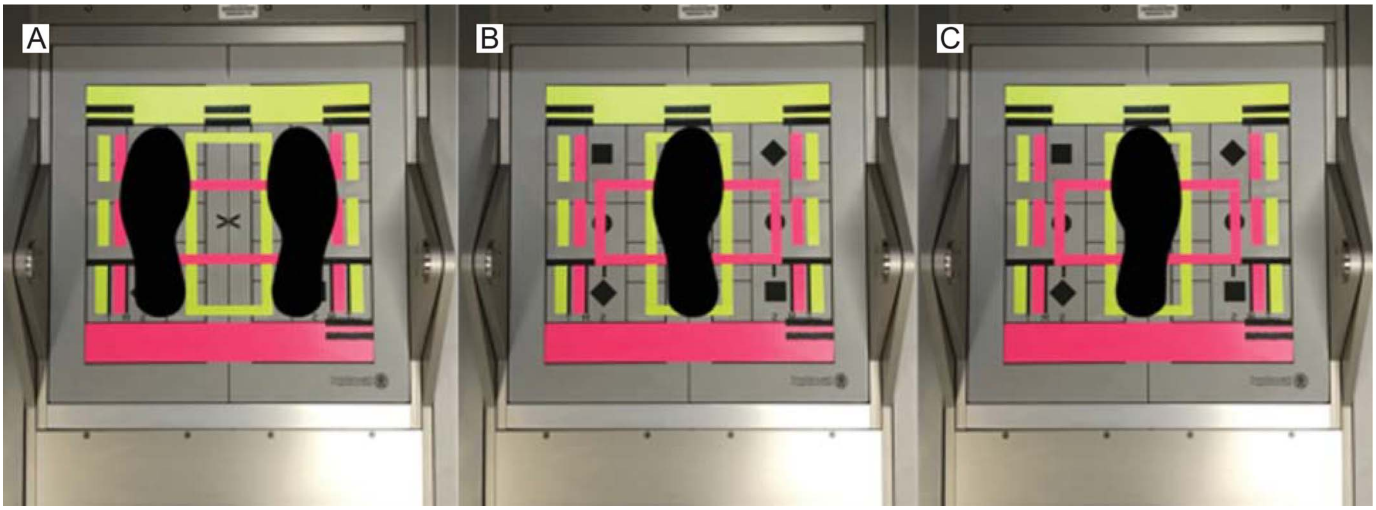

Figure. Foot position for the Sensory Organization Test in A, double-limb stance and B and C, single-limb stance (injured and uninjured limb).

mass (kg, ±3%), *limb dominance* (defined as the limb used to kick a ball), and the National Aeronautics and Space Administration Physical Activity Status Scale (scale, ±1). Individuals in the control group were assigned an injured limb based on the matched limb dominance of participants in the CAI group. Participants provided written informed consent, and the study was approved by the Institutional Review Board of the University of North Carolina at Greensboro.

Procedures

Participants attended 1 laboratory session and completed a standardized medical history questionnaire including questions about their lower extremity medical history and completion of rehabilitation after ankle sprains, self-reported ankle instability and function via the Identification of Functional Ankle Instability score, and physical activity status on arrival. Participants then performed a 5-minute warm-up on a bicycle at a self-selected intensity and completed demographic measures, joint hypermobility tests, lower extremity anatomic alignment measures, and postural tests. Hypermobility and anatomic tests were part of a separate research study and were not reported in the results of this study. Participants were outfitted with a vest with a safety harness before standing barefoot on a computerized NeuroCom (SMART EquiTest; NeuroCom International Inc) dynamic posturography platform in double-, uninjured-, or injured-limb stance (Figure).

Sensory Organization Test. The Sensory Organization Test (SOT) is a criterion-standard test designed to identify individuals' ability to integrate somatosensory, visual, and vestibular feedback to maintain posture. The SOT comprises 6 conditions (Table 2) designed to manipulate somatosensory and visual feedback in a combination of the sway-referenced support surface (platform) and visual surroundings with and without vision. Briefly, conditions transition from simple to more complex environmental constraints to isolate different sensory systems in the following manner: condition 1: normal vision, fixed surroundings, fixed platform (C1-$V_nS_fP_f$); condition 2: absent vision, fixed surroundings, fixed platform (C2-$V_aS_fP_f$); condition 3: distorted vision, moving surroundings, fixed platform (C3-$V_dS_mP_f$); condition 4: distorted vision, fixed surroundings, moving platform (C4-$V_dS_fP_m$); condition 5: absent vision, fixed surroundings, moving platform (C5-$V_aS_fP_m$); and condition 6: distorted vision, moving surroundings, moving platform (C6-$V_dS_mP_m$). Participants' bilateral medial malleoli were aligned perpendicular to the transverse axis of platform rotation. They kept their feet a standardized distance apart based on their height for bilateral stance and positioned the foot in the center of the platform for unilateral stance (Figure). We instructed participants to maintain their faces forward, keep their upper extremities relaxed by their sides, and stand as motionless as possible while completing the SOT. Each condition consisted of three 20-second trials, and a total of 18 trials

Table 2. Descriptions of 6 Sensory Organization Test Conditions

Sensory Organization Test Condition	Sensory Feedback					
	Manipulation Modalities					
	Support Surface	Eyes	Visual Surroundings	Manipulated	Absent	Tested
C1-$V_nS_fP_f$	Fixed	Open	Fixed	None		None
C2-$V_aS_fP_f$	Fixed	Closed	Fixed	None	Vision	Somatosensory
C3-$V_dS_mP_f$	Fixed	Open	Sway referenced	Vision		Somatosensory
C4-$V_dS_fP_m$	Sway referenced	Open	Fixed	Somatosensory		Vision
C5-$V_aS_fP_m$	Sway referenced	Closed	Fixed	Somatosensory	Vision	Vestibular
C6-$V_dS_mP_m$	Sway referenced	Open	Sway referenced	Somatosensory, vision		Vestibular

Abbreviations: C1-$V_nS_fP_f$, condition 1: normal vision, fixed surroundings, fixed platform; C2-$V_aS_fP_f$, condition 2: absent vision, fixed surroundings, fixed platform; C3-$V_dS_mP_f$, condition 3: distorted vision, moving surroundings, fixed platform; C4-$V_dS_fP_m$, condition 4: distorted vision, fixed surroundings, moving platform; C5-$V_aS_fP_m$, condition 5: absent vision, fixed surroundings, moving platform; C6-$V_dS_mP_m$, condition 6: distorted vision, moving surroundings, moving platform.

per stance were completed. Individual tasks (stance limbs) were assessed in counterbalanced order within each group to evenly distribute any potential learning effect. Participants were given a 30-second rest between trials and a 1-minute rest between conditions. They were allowed to tap down on the platform with nonstance toes multiple times after 10 seconds to continue with full 20-second trials in uninjured- and injured-limb stances; however, they were directed to do their best to maintain single-limb postural stability to complete each 20-second trial. The trials were stopped, eliminated, and repeated if participants tapped down on nonstance toes before 10 seconds or completely stood on a nonstance limb after 10 seconds.

Balance Measure. The SOT of NeuroCom computes equilibrium scores, measuring the center of gravity at 100 Hz. Equilibrium scores quantify how well the center-of-gravity sway ($\theta_{max} - \theta_{min}$) remains within the expected angular limits of stability (12.5°), normalizing it by 100. An equilibrium score of 100 represents *perfect postural stability*, whereas an equilibrium score of 0 represents *postural instability* in individuals with and without CAI. The raw data from NeuroCom were exported to spreadsheets (Excel version 360; Microsoft Corp) and imported into a custom R program in RStudio (version 4.0.0; RStudio, Inc) to compute the equilibrium scores based on the first 10 seconds of the trials (Equilibrium$_{10}$).

Sensory Reweighting Measure. The SOT assessment calculates sensory reweighting ratios among 3 primary sensory systems (somatosensory, vision, and vestibular) by using the averaged equilibrium scores from specific pairs of SOT conditions according to Equations 1, 2, and 3.[12] The ratios identify participants' ability to emphasize weight on sensory feedback to maintain postural stability while performing the SOT in double-, uninjured-, and injured-limb stances. The sensory reweighting ratios of 100 represent *more emphasis* (ie, upweight) on the sensory feedback, while the sensory reweighting ratios of 0 represent *no emphasis* (ie, downweight) on the sensory feedback. We computed sensory reweighting ratios based on Equilibrium$_{10}$ scores using a custom R program in RStudio:

$$\text{Somatosensory: } \frac{\text{Condition 2}}{\text{Condition 1}} \times 100, \tag{1}$$

$$\text{Vision: } \frac{\text{Condition 4}}{\text{Condition 1}} \times 100, \tag{2}$$

$$\text{Vestibular: } \frac{\text{Condition 5}}{\text{Condition 1}} \times 100. \tag{3}$$

Preference Ratio. The SOT assessment also calculates the preference ratio by using the averaged Equilibrium$_{10}$ from specific pairs of SOT conditions according to Equation 4.[12] The ratio identifies the degree to which individuals rely on distorted visual feedback over absent vision. A high preference ratio implies individuals benefit more from distorted vision than absent vision and vice versa for a low preference ratio:

$$\text{Preference: } \frac{\text{Condition 3} + \text{Condition 6}}{\text{Condition 2} + \text{Condition 5}}. \tag{4}$$

Statistical Analysis

A 1-way analysis of variance was conducted to compare group differences in demographic variables (age, height, mass, and physical activity scale) and the preference ratio in double-, uninjured-, and injured-limb stances. A 2 (group) × 3 (sensory systems) × 3 (task: stance limbs) repeated-measures analysis of variance was conducted to examine the sensory reweighting system while maintaining postural stability during the SOT in double- and single-limb stances on the uninjured and injured limbs. To examine the effect of environmental and task constraints on postural control differences while manipulating environmental and task constraints during the SOT assessment, we performed a 2 (group) × 3 (task) × 6 (environment: SOT conditions) analysis of variance. Tukey post hoc analyses were performed when we observed interactions. When post hoc pairwise comparisons were different, Cohen *d* effect size (ES) values were calculated with corresponding 95% CIs between the group means to determine the magnitude of difference in Equilibrium$_{10}$ and sensory reweighting ratios.[13] Effect sizes were interpreted as *weak* ($d \leq 0.40$), *moderate* ($d = 0.40$–0.80), or *strong* ($d \geq 0.80$). All statistical analyses were performed using SPSS software (version 27; IBM Corp) with an a priori α level of .05. Data normality was tested using the Kolmogorov-Smirnov test, confirming a normal distribution for all variables ($P > .05$).

RESULTS

No group differences were found related to age, height, mass, or physical activity level ($P > .05$; Table 1). The CAI group had a larger number of ankle sprains and higher Identification of Functional Ankle Instability scores than the control group ($P < .001$; Table 1). The preference ratio in injured-limb stance was lower in the CAI than in the control group ($P = .01$; Table 1).

Sensory Reweighting System

A 3-factor interaction ($F_{4,160} = 3.754$; $P = .006$) for group, sensory systems, and task constraints was found for the sensory reweighting system analysis. The CAI group had a moderate inability to downweight vestibular feedback compared with the control group while controlling posture in injured-limb stance ($P = .03$; Table 3). In addition, the control group strongly downweighted vestibular feedback in uninjured-limb ($P < .001$) and injured-limb ($P < .001$) stances compared with double-limb stance (Table 4). No differences in vestibular reliance (ie, downweighting) between individual tasks were noted for the CAI group ($P > .05$; Table 5). Both groups strongly upweighted somatosensory feedback in double-limb stance compared with uninjured-limb ($P < .001$) and injured-limb ($P < .001$; Tables 4 and 5) stances. No differences existed in visual reliance between individual tasks for the control and CAI groups ($P > .05$; Tables 4 and 5). Strong differences were found in sensory reweighting between somatosensory, visual, and vestibular in double-limb ($P < .001$; somatosensory > vision and vestibular; vision > vestibular), uninjured-limb ($P < .001$; vision > somatosensory and vestibular; somatosensory > vestibular), and injured-limb ($P < .001$; vision > somatosensory and vestibular; somatosensory > vestibular) stances for both CAI and control groups (Tables 4 and 5).

Postural Control in Increased Environmental (SOT Conditions) and Task (Stance Limbs) Constraints

A 3-factor interaction ($F_{10,400} = 2.455$, $P = .007$) for the group, environmental, and task constraints was found. The CAI group had moderately greater Equilibrium$_{10}$ while maintaining posture during C5-$V_aS_fP_m$ in injured-limb stance than

Table 3. Sensory Reweighting Ratios for Sensory Systems and Task Constraints in the Chronic Ankle Instability and Control Groups

Sensory System	Task	Group: Chronic Ankle Instability	Group: Control	*P* Value	Effect Size (95% CI)
Somatosensory	Double-limb stance	97.35 ± 2.15	97.28 ± 2.87	.93	0.03 (–0.56, 0.62)
	Uninjured-limb stance	81.74 ± 6.93	80.70 ± 6.01	.61	0.16 (–0.43, 0.75)
	Injured-limb stance	81.36 ± 4.54	78.59 ± 7.89	.17	0.43 (–0.17, 1.03)
Vision	Double-limb stance	93.09 ± 5.31	92.77 ± 3.65	.82	0.07 (–0.52, 0.66)
	Uninjured-limb stance	94.39 ± 3.58	93.93 ± 5.09	.74	0.10 (–0.49, 0.70)
	Injured-limb stance	94.48 ± 3.94	94.80 ± 4.62	.81	0.07 (–0.52, 0.67)
Vestibular	Double-limb stance	71.11 ± 10.01	73.18 ± 8.82	.48	0.22 (–0.37, 0.81)
	Uninjured-limb stance	70.61 ± 9.52	65.07 ± 8.43	.05	0.62 (0.01, 1.22)
	Injured-limb stance	70.13 ± 7.69	63.19 ± 11.85	.03[a]	0.69 (0.09, 1.30)

[a] Indicates difference.

the control group ($P = .03$; Table 6). Moderate to strong differences existed across all combinations of individual environments for double-limb (P range, $<.001$–.048), uninjured-limb (P range, $<.001$–.03), and injured-limb (P range, $<.001$–.01) stances in both groups except for comparisons between (1) C2-$V_aS_fP_f$ and C3-$V_dS_mP_f$ in double-limb stance for both groups ($P > .05$); (2) C2-$V_aS_fP_f$ and C6-$V_dS_mP_m$ in uninjured-limb stance for both groups ($P > .05$); and (3) C2-$V_aS_fP_f$ and C6-$V_dS_mP_m$ in injured-limb stance for the control group ($P > .05$; Tables 7 and 8). Both groups exhibited the highest $Equilibrium_{10}$ scores in C1-$V_nS_fP_f$ and the lowest scores in C5-$V_aS_fP_m$ while maintaining posture in double-, uninjured-, and injured-limb stances (Tables 9 and 10). Moderate to strong differences existed in postural stability between stances, with better postural stability in double-limb stance than uninjured-limb (P range, $<.001$–.03) and injured-limb (P range, $<.001$–.04) stances in individual environments, respectively, for both groups, except in C6-$V_dS_mP_m$ for the CAI group, in which no difference existed in $Equilibrium_{10}$ between double-, uninjured-, and injured-limb stances ($P > .05$; Table 9 and 10). Both groups similarly maintained posture during individual conditions in uninjured- and injured-limb stances ($P > .05$; Tables 9 and 10).

DISCUSSION

We are the first to examine how the sensory reweighting system changes to control posture with increased task constraints and how postural control is affected by environmental and task constraints in individuals with and without CAI. The unique findings were that the CAI group did not downweight vestibular feedback while controlling posture standing on the injured limb. Both CAI and control groups distributed weight differently on each sensory feedback while performing individual tasks. Somatosensory feedback was upweighted the most in maintaining posture in double-limb stance, whereas visual feedback was upweighted the most while maintaining posture in uninjured- and injured-limb stances. Furthermore, the group differences in postural control depended on environmental and task constraints. Overall, individuals with CAI maintained a posture very similar to that of healthy controls.

Table 4. Pairwise Comparisons of Sensory Reweighting Ratios for Sensory Systems and Task Constraints in the Control Group

Sensory System	Task, Mean ± SD: Double-Limb Stance	Uninjured-Limb Stance	Injured-Limb Stance	*P* Value	Effect Size (95% CI)
Somatosensory	97.28 ± 2.87	80.70 ± 6.01		<.001[a]	3.52 (2.58, 4.46)
	97.28 ± 2.87		78.59 ± 7.89	<.001[a]	3.15 (2.26, 4.03)
		80.70 ± 6.01	78.59 ± 7.89	.20	0.30 (–0.29, 0.90)
Vision	92.77 ± 3.65	93.93 ± 5.09		.32	0.26 (–0.33, 0.86)
	92.77 ± 3.65		94.80 ± 4.62	.07	0.49 (–0.11, 1.09)
		93.93 ± 5.09	94.80 ± 4.62	.46	0.18 (–0.41, 0.77)
Vestibular	73.18 ± 8.82	65.07 ± 8.43		<.001[a]	0.94 (0.32, 1.56)
	73.18 ± 8.82		63.19 ± 11.85	<.001[a]	0.96 (0.33, 1.58)
		65.07 ± 8.43	63.19 ± 11.85	.24	0.18 (–0.41, 0.78)
Task	**Sensory System, Mean ± SD: Somatosensory**	**Vision**	**Vestibular**		
Double-limb stance	97.28 ± 2.78		73.18 ± 8.82	<.001[a]	3.69 (2.71, 4.66)
	97.28 ± 2.78	92.77 ± 3.65		<.001[a]	1.39 (0.73, 2.05)
		92.77 ± 3.65	73.18 ± 8.82	<.001[a]	2.90 (2.06, 3.75)
Uninjured-limb stance	80.70 ± 6.01		65.07 ± 8.43	<.001[a]	2.05 (1.32, 2.78)
	80.70 ± 6.01	93.93 ± 5.09		<.001[a]	2.38 (1.60, 3.15)
		93.93 ± 5.09	65.07 ± 8.43	<.001[a]	4.14 (3.10, 5.19)
Injured-limb stance	78.59 ± 7.89		63.19 ± 11.85	<.001[a]	1.53 (0.86, 2.20)
	78.59 ± 7.89	94.80 ± 4.62		<.001[a]	2.51 (1.72, 3.30)
		94.80 ± 4.62	63.19 ± 11.85	<.001[a]	3.51 (2.57, 4.46)

[a] Indicates difference.

Table 5. **Pairwise Comparisons of Sensory Reweighting Ratios for Sensory Systems and Task Constraints in the Chronic Ankle Instability Group**

Sensory System	Task, Mean ± SD			P Value	Effect Size (95% CI)
	Double-Limb Stance	Uninjured-Limb Stance	Injured-Limb Stance		
Somatosensory	97.35 ± 2.15	81.74 ± 6.93		<.001[a]	3.04 (2.17, 3.91)
	97.35 ± 2.15		81.36 ± 4.54	<.001[a]	4.50 (3.39, 5.61)
		81.74 ± 6.93	81.36 ± 4.54	.83	0.06 (–0.53, 0.66)
Vision	93.09 ± 5.31	94.39 ± 3.58		.26	0.29 (–0.31, 0.88)
	93.09 ± 5.31		94.48 ± 3.94	.22	0.30 (–0.30, 0.89)
		94.39 ± 3.58	94.48 ± 3.94	.94	0.02 (–0.57, 0.61)
Vestibular	71.11 ± 10.01	70.61 ± 9.52		.82	0.05 (–0.54, 0.64)
	71.11 ± 10.01		70.13 ± 7.69	.67	0.11 (–0.48, 0.70)
		70.61 ± 9.52	70.13 ± 7.69	.76	0.06 (–0.54, 0.65)
	Sensory System, Mean ± SD				
Task	Somatosensory	Vision	Vestibular		
Double-limb stance	97.35 ± 2.15		71.11 ± 10.01	<.001[a]	3.62 (2.66, 4.59)
	97.35 ± 2.15	93.09 ± 5.31		<.001[a]	1.05 (0.42, 1.68)
		93.09 ± 5.31	71.11 ± 10.01	<.001[a]	2.74 (1.92, 3.57)
Uninjured-limb stance	81.74 ± 6.93		70.61 ± 9.52	<.001[a]	1.34 (0.68, 1.99)
	81.74 ± 6.93	94.39 ± 3.58		<.001[a]	2.29 (1.53, 3.05)
		94.39 ± 3.58	70.61 ± 9.52	<.001[a]	3.31 (2.40, 4.22)
Injured-limb stance	81.36 ± 4.54		70.13 ± 7.69	<.001[a]	1.78 (1.08, 2.48)
	81.36 ± 4.54	94.48 ± 3.94		<.001[a]	3.09 (2.21, 3.96)
		94.48 ± 3.94	70.13 ± 7.69	<.001[a]	3.28 (2.37, 4.18)

[a] Indicates difference.

Individuals with CAI exhibit somatosensory deficits after an initial ankle sprain, resulting in postural instability.[3,14] Likewise, an inability to use somatosensory feedback has been reported in individuals with CAI while performing the SOT.[15] Conversely, our CAI group did not have postural instabilities or an inability to use somatosensory feedback. In double-limb stance, individuals with CAI upweighted somatosensory feedback more than vestibular and visual feedback. The lack of group differences in sensory reweighting on somatosensory feedback in the injured limb may simply be a result of the CAI group self-reporting having undergone rehabilitation after their initial ankle injury. The evidence in the literature supports our contention and demonstrates that individuals with unilateral CAI who underwent rehabilitation targeting somatosensation improved postural control in both limbs, indicating possible reweighting on somatosensory feedback.[16]

Table 6. **Pairwise Comparisons of Equilibirum$_{10}$ Scores for Environmental and Task Constraints in the Chronic Ankle Instability and Control Groups**

Environment: Sensory Organization Test Condition	Task	Group, Mean ± SD		P Value	Effect Size (95% CI)
		Chronic Ankle Instability	Control		
C1-$V_nS_fP_f$	Double-limb stance	94.62 ± 1.55	94.75 ± 1.30	.77	0.09 (–0.50, 0.68)
	Uninjured-limb stance	88.83 ± 3.27	89.19 ± 2.43	.69	0.12 (–0.47, 0.72)
	Injured-limb stance	89.49 ± 2.36	89.16 ± 2.44	.66	0.14 (–0.45, 0.73)
C2-$V_aS_fP_f$	Double-limb stance	92.11 ± 2.45	92.17 ± 2.97	.94	0.02 (–0.57, 0.61)
	Uninjured-limb stance	72.56 ± 6.09	71.99 ± 5.89	.76	0.10 (–0.50, 0.69)
	Injured-limb stance	72.82 ± 4.34	70.11 ± 7.67	.17	0.43 (–0.16, 1.03)
C3-$V_dS_mP_f$	Double-limb stance	91.64 ± 3.50	92.51 ± 2.55	.36	0.28 (–0.31, 0.88)
	Uninjured-limb stance	81.99 ± 4.20	80.33 ± 5.60	.28	0.34 (–0.26, 0.93)
	Injured-limb stance	80.65 ± 4.17	80.17 ± 6.77	.78	0.09 (–0.51, 0.68)
C4-$V_dS_fP_m$	Double-limb stance	88.08 ± 5.32	87.90 ± 3.70	.90	0.04 (–0.55, 0.63)
	Uninjured-limb stance	83.85 ± 4.51	83.77 ± 4.86	.96	0.02 (–0.57, 0.61)
	Injured-limb stance	84.55 ± 4.24	84.54 ± 4.68	.99	0.00 (–0.59, 0.59)
C5-$V_aS_fP_m$	Double-limb stance	67.32 ± 9.76	69.34 ± 8.44	.48	0.22 (–0.37, 0.81)
	Uninjured-limb stance	62.82 ± 9.47	58.06 ± 7.86	.08	0.55 (–0.05, 1.15)
	Injured-limb stance	62.80 ± 7.37	56.38 ± 10.95	.03[a]	0.69 (0.08, 1.30)
C6-$V_dS_mP_m$	Double-limb stance	71.12 ± 8.39	73.44 ± 10.59	.44	0.24 (–0.35, 0.84)
	Uninjured-limb stance	71.73 ± 8.77	67.95 ± 8.10	.15	0.45 (–0.15, 1.05)
	Injured-limb stance	67.84 ± 9.07	68.57 ± 7.85	.78	0.09 (–0.51, 0.68)

Abbreviations: Equilibrium$_{10}$, equilibrium based on the first 10-s trials; C1-$V_nS_fP_f$, condition 1: normal vision, fixed surroundings, fixed platform; C2-$V_aS_fP_f$, condition 2: absent vision, fixed surroundings, fixed platform; C3-$V_dS_mP_f$, condition 3: distorted vision, moving surroundings, fixed platform; C4-$V_dS_fP_m$, condition 4: distorted vision, fixed surroundings, moving platform; C5-$V_aS_fP_m$, condition 5: absent vision, fixed surroundings, moving platform; C6-$V_dS_mP_m$, condition 6: distorted vision, moving surroundings, moving platform.
[a] Indicates difference.

Table 7. Pairwise Comparisons of Equilibirum$_{10}$ Scores for Environmental and Task Constraints in the Chronic Ankle Instability Group

	Environment: Sensory Organization Test Condition							
Task	C1-$V_nS_fP_f$	C2-$V_aS_fP_f$	C3-$V_dS_mP_f$	C4-$V_dS_fP_m$	C5-$V_aS_fP_m$	C6-$V_dS_mP_m$	*P* Value	Effect Size (95% CI)
Double-limb stance	94.75 ± 1.30	92.17 ± 2.97					<.001[a]	1.13 (0.49, 1.76)
	94.75 ± 1.30		92.51 ± 2.55				.001[a]	1.11 (0.47, 1.74)
	94.75 ± 1.30			87.90 ± 3.70			<.001[a]	2.47 (1.69, 3.25)
	94.75 ± 1.30				69.34 ± 8.44		<.001[a]	4.21 (3.15, 5.27)
	94.75 ± 1.30					73.44 ± 10.59	<.001[a]	2.82 (1.99, 3.66)
		92.17 ± 2.97	92.51 ± 2.55				.59	0.12 (–0.47, 0.71)
		92.17 ± 2.97		87.90 ± 3.70			<.001[a]	1.27 (0.62, 1.92)
		92.17 ± 2.97			69.34 ± 8.44		<.001[a]	3.61 (2.65, 4.57)
		92.17 ± 2.97				73.44 ± 10.59	<.001[a]	2.41 (1.63, 3.18)
			92.51 ± 2.55	87.90 ± 3.70			<.001[a]	1.45 (0.79, 2.12)
			92.51 ± 2.55		69.34 ± 8.44		<.001[a]	3.72 (2.74, 4.69)
			92.51 ± 2.55			73.44 ± 10.59	<.001[a]	2.48 (1.69, 3.26)
				87.90 ± 3.70	69.34 ± 8.44		<.001[a]	2.85 (2.01, 3.69)
				87.90 ± 3.70		73.44 ± 10.59	<.001[a]	1.82 (1.12, 2.53)
					69.34 ± 8.44	73.44 ± 10.59	.03[a]	0.43 (–0.17, 1.03)
Uninjured-limb stance	89.19 ± 2.43	71.99 ± 5.89					.001[a]	3.82 (2.82, 4.81)
	89.19 ± 2.43		80.33 ± 5.60				<.001[a]	2.05 (1.32, 2.78)
	89.19 ± 2.43			83.79 ± 4.86			<.001[a]	1.41 (0.75, 2.07)
	89.19 ± 2.43				58.06 ± 7.86		<.001[a]	5.35 (4.09, 6.62)
	89.19 ± 2.43					67.95 ± 8.10	<.001[a]	3.55 (2.60, 4.50)
		71.99 ± 5.89	80.33 ± 5.60				<.001[a]	1.46 (0.80, 2.13)
		71.99 ± 5.89		83.79 ± 4.86			<.001[a]	1.31 (0.66, 1.96)
		71.99 ± 5.89			58.06 ± 7.86		<.001[a]	1.24 (0.60, 1.89)
		71.99 ± 5.89				67.95 ± 8.10	.053	0.57 (–0.03, 1.17)
			80.33 ± 5.60	83.79 ± 4.86			<.001[a]	0.66 (0.05, 1.27)
			80.33 ± 5.60		58.06 ± 7.86		<.001[a]	3.26 (2.36, 4.17)
			80.33 ± 5.60			67.95 ± 8.10	<.001[a]	1.78 (1.08, 2.48)
				83.79 ± 4.86	58.06 ± 7.86		<.001[a]	3.94 (2.92, 4.95)
				83.79 ± 4.86		67.95 ± 8.10	<.001[a]	2.37 (1.60, 3.14)
					58.06 ± 7.86	67.95 ± 8.10	<.001[a]	1.24 (0.59, 1.88)
Injured-limb stance	89.16 ± 2.44	70.11 ± 7.67					<.001[a]	3.35 (2.43, 4.26)
	89.16 ± 2.44		80.17 ± 6.77				<.001[a]	1.77 (1.07, 2.46)
	89.16 ± 2.44			84.54 ± 4.68			<.001[a]	1.24 (0.59, 1.88)
	89.16 ± 2.44				56.38 ± 10.95		<.001[a]	4.13 (3.09, 5.18)
	89.16 ± 2.44					68.57 ± 7.85	<.001[a]	3.54 (2.60, 4.49)
		70.11 ± 7.67	80.17 ± 6.77				<.001[a]	1.39 (0.73, 2.05)
		70.11 ± 7.67		84.54 ± 4.68			<.001[a]	2.27 (1.51, 3.03)
		70.11 ± 7.67			56.38 ± 10.95		<.001[a]	1.45 (0.79, 2.12)
		70.11 ± 7.67				68.57 ± 7.85	.41	0.20 (–0.39, 0.79)
			80.17 ± 6.77	84.54 ± 4.68			<.001[a]	0.75 (0.14, 1.36)
			80.17 ± 6.77		56.38 ± 10.95		<.001[a]	2.61 (1.81, 3.42)
			80.17 ± 6.77			68.57 ± 7.85	<.001[a]	1.56 (0.88, 2.23)
				84.54 ± 4.68	56.38 ± 10.95		<.001[a]	3.34 (2.43, 4.26)
				84.54 ± 4.68		68.57 ± 7.85	<.001[a]	2.47 (1.69, 3.26)
					56.38 ± 10.95	68.57 ± 7.85	<.001[a]	1.28 (0.63, 1.93)

Abbreviations: Equilibrium$_{10}$, equilibrium based on the first 10-s trials; C1-$V_nS_fP_f$, condition 1: normal vision, fixed surroundings, fixed platform; C2-$V_aS_fP_f$, condition 2: absent vision, fixed surroundings, fixed platform; C3-$V_dS_mP_f$, condition 3: distorted vision, moving surroundings, fixed platform; C4-$V_dS_fP_m$, condition 4: distorted vision, fixed surroundings, moving platform; C5-$V_aS_fP_m$, condition 5: absent vision, fixed surroundings, moving platform; C6-$V_dS_mP_m$, condition 6: distorted vision, moving surroundings, moving platform.
[a] Indicates difference.

Other potential explanations for the lack of group differences in sensory reweighting on somatosensory feedback in the injured limb could be attributable to (1) sensory feedback available from proximal joints (knee and hip) and musculotendinous receptors at the ankle or (2) altered central organization to heighten feedforward command to modulate the sensitivity of the gamma-spindle system. These mechanisms could mask potential somatosensory deficits at the ankle and allow individuals with CAI to maintain posture like that of individuals without CAI. For instance, a few research groups used anesthesia or nerve blocks at the ankle to deprive somatosensory feedback to individuals without CAI and found no alteration in postural control or other somatosensory assessments.[17–20] Future research can be done to explore how to isolate somatosensory feedback at the ankle during SOT assessments to determine its contributions to postural control.

Accomplishing a given task such as maintaining postural stability requires the ability to flexibly adapt to reweight on relevant sensory feedback according to changes in environmental constraints. The general consensus is that the central nervous system puts more emphasis on the most reliable sensory feedback and puts less emphasis on the least reliable sensory feedback to accomplish a task goal in an ever-changing environment.[4] Emphasis on specific sensory feedback depends on amplitudes of sensory stimuli motion (eg, moving trajectories), described as *intramodality* and *intermodality dependencies*.[21,22] Current evidence indicates visual feedback is upweighted when the amplitude of visual or somatosensory stimuli, or both, increases, meaning both

Table 8. **Pairwise Comparisons of Equilibirum$_{10}$ Scores for Environmental and Task Constraints in the Control Group**

Task	Environment: Sensory Organization Test Condition						*P* Value	Effect Size (95% CI)
	C1-$V_nS_fP_f$	C2-$V_aS_fP_f$	C3-$V_dS_mP_f$	C4-$V_dS_fP_m$	C5-$V_aS_fP_m$	C6-$V_dS_mP_m$		
Double-limb stance	94.62 ± 1.55	92.11 ± 2.45					<.001[a]	1.22 (0.58, 1.87)
	94.62 ± 1.55		91.64 ± 3.50				<.001[a]	1.10 (0.47, 1.74)
	94.62 ± 1.55			88.08 ± 5.32			<.001[a]	1.67 (0.98, 2.36)
	94.62 ± 1.55				67.32 ± 9.76		<.001[a]	3.91 (2.90, 4.91)
	94.62 ± 1.55					71.12 ± 8.39	<.001[a]	3.90 (2.89, 4.90)
		92.11 ± 2.45	91.64 ± 3.50				.45	0.16 (–0.44, 0.75)
		92.11 ± 2.45		88.08 ± 5.32			<.001[a]	0.97 (0.35, 1.60)
		92.11 ± 2.45			67.32 ± 9.76		<.001[a]	3.48 (2.55, 4.42)
		92.11 ± 2.45				71.12 ± 8.39	<.001[a]	3.40 (2.47, 4.32)
			91.64 ± 3.50	88.08 ± 5.32			<.001[a]	0.79 (0.18, 1.40)
			91.64 ± 3.50		67.32 ± 9.76		<.001[a]	3.32 (2.41, 4.23)
			91.64 ± 3.50			71.12 ± 8.39	<.001[a]	3.19 (2.30, 4.08)
				88.08 ± 5.32	67.32 ± 9.76		<.001[a]	2.64 (1.83, 3.45)
				88.08 ± 5.32		71.12 ± 8.39	<.001[a]	2.41 (1.64, 3.19)
					67.32 ± 9.76	71.12 ± 8.39	.048[a]	0.42 (–0.18, 1.01)
Uninjured-limb stance	88.83 ± 3.27	72.56 ± 6.09					<.001[a]	3.33 (2.42, 4.24)
	88.83 ± 3.27		81.99 ± 4.20				<.001[a]	1.82 (1.11, 2.52)
	88.83 ± 3.27			83.85 ± 4.51			<.001[a]	1.26 (0.62, 1.91)
	88.83 ± 3.27				62.82 ± 9.47		<.001[a]	3.67 (2.70, 4.64)
	88.83 ± 3.27					71.73 ± 8.77	<.001[a]	2.58 (1.78, 3.38)
		72.56 ± 6.09	81.99 ± 4.20				<.001[a]	1.80 (1.10, 2.50)
		72.56 ± 6.09		83.85 ± 4.51			<.001[a]	2.11 (1.37, 2.84)
		72.56 ± 6.09			62.82 ± 9.47		<.001[a]	1.22 (0.58, 1.87)
		72.56 ± 6.09				71.73 ± 8.77	.69	0.11 (–0.48, 0.70)
			81.99 ± 4.20	83.85 ± 4.51			.03[a]	0.43 (–0.17, 1.02)
			81.99 ± 4.20		62.82 ± 9.47		<.001[a]	2.62 (1.81, 3.42)
			81.99 ± 4.20			71.73 ± 8.77	<.001[a]	1.49 (0.82, 2.16)
				83.85 ± 4.51	62.82 ± 9.47		<.001[a]	2.84 (2.00, 3.67)
				83.85 ± 4.51		71.73 ± 8.77	<.001[a]	1.74 (1.04, 2.43)
					62.82 ± 9.47	71.73 ± 8.77	<.001[a]	0.98 (0.35, 1.60)
Injured-limb stance	89.49 ± 2.36	72.82 ± 4.34					<.001[a]	4.77 (3.61, 5.93)
	89.49 ± 2.36		80.65 ± 4.17				<.001[a]	2.61 (1.81, 3.41)
	89.49 ± 2.36			84.55 ± 4.24			<.001[a]	1.44 (0.78, 2.10)
	89.49 ± 2.36				62.80 ± 7.37		<.001[a]	4.88 (3.70, 6.06)
	89.49 ± 2.36					67.84 ± 9.07	<.001[a]	3.27 (2.36, 4.17)
		72.82 ± 4.34	80.65 ± 4.17				<.001[a]	1.84 (1.13, 2.54)
		72.82 ± 4.34		84.55 ± 4.24			<.001[a]	2.73 (1.91, 3.56)
		72.82 ± 4.34			62.80 ± 7.37		<.001[a]	1.66 (0.97, 2.34)
		72.82 ± 4.34				67.84 ± 9.07	.01[a]	0.70 (0.09, 1.31)
			80.65 ± 4.17	84.55 ± 4.24			<.001[a]	0.93 (0.31, 1.55)
			80.65 ± 4.17		62.80 ± 7.37		<.001[a]	2.98 (2.12, 3.84)
			80.65 ± 4.17			67.84 ± 9.07	<.001[a]	1.81 (1.11, 2.52)
				84.55 ± 4.24	62.80 ± 7.37		<.001[a]	3.62 (2.66, 4.58)
				84.55 ± 4.24		67.84 ± 9.07	<.001[a]	2.36 (1.59, 3.13)
					62.80 ± 7.37	67.84 ± 9.07	.01[a]	0.61 (0.01, 1.21)

Abbreviations: Equilibrium$_{10}$, equilibrium based on the first 10-s trials; C1-$V_nS_fP_f$, condition 1: normal vision, fixed surroundings, fixed platform; C2-$V_aS_fP_f$, condition 2: absent vision, fixed surroundings, fixed platform; C3-$V_dS_mP_f$, condition 3: distorted vision, moving surroundings, fixed platform; C4-$V_dS_fP_m$, condition 4: distorted vision, fixed surroundings, moving platform; C5-$V_aS_fP_m$, condition 5: absent vision, fixed surroundings, moving platform; C6-$V_dS_mP_m$, condition 6: distorted vision, moving surroundings, moving platform.

[a] Indicates difference.

intramodality and intermodality dependencies for visual feedback are present.[21,22] Conversely, no intermodality dependencies for somatosensory feedback are present when the amplitude of visual stimuli increases.[21] Based on these results, the presence of intermodality dependency may explain the mechanisms of why both groups in our study upweighted visual feedback while performing the SOT in all stances.

Increased emphasis on visual feedback has been reported in individuals with somatosensory and vestibular deficits compared with healthy controls.[23,24] In contrast, we found no group differences in visual reliance, yet the greater emphasis on visual feedback continued across all task constraints and became dominant when somatosensory feedback decreased in uninjured- and injured-limb stances. In addition, the preference ratio revealed both groups benefited from distorted visual feedback to maintain postural control, except in the injured limb for the CAI group. The SOT combines 2 conditions where the platform is fixed and moving in computing the preference ratio.[12] Somatosensory feedback becomes dominant for postural control when the platform is fixed, specifically with absent vision, and vestibular feedback becomes dominant when the platform moves.[25] Thus, we computed a subset of the preference ratio by separating those 2 conditions and discovered the CAI group did not rely on distorted vision to control posture in injured-limb stance when vestibular feedback was dominant.

The vestibular system is a gravitational receptor; provides feedback on the head, trunk, and eye positions in space; and plays a veridical role in inferring self-motion.[25,26] Thus, the vestibular system always works in conjunction with either

Table 9. Pairwise Comparisons of Equilibirum$_{10}$ Scores for Environmental and Task Constraints in the Chronic Ankle Instability Group

Environment: Sensory Organization Test Condition	Task, Mean ± SD			P Value	Effect Size (95% CI)
	Double-Limb Stance	Uninjured-Limb Stance	Injured-Limb Stance		
C1-$V_nS_fP_f$	94.62 ± 1.55	88.83 ± 3.27		<.001[a]	2.26 (1.15, 3.02)
	94.62 ± 1.55		89.49 ± 2.36	<.001[a]	2.57 (1.77, 3.37)
		88.83 ± 3.27	89.49 ± 2.36	.26	0.23 (–0.36, 0.82)
C2-$V_aS_fP_f$	92.11 ± 2.45	72.56 ± 6.09		<.001[a]	4.23 (3.15, 5.27)
	92.11 ± 2.45		72.82 ± 4.34	<.001[a]	5.47 (4.19, 6.76)
		72.56 ± 6.09	72.82 ± 4.34	.86	0.05 (–0.54, 0.64)
C3-$V_dS_mP_f$	91.64 ± 3.50	81.99 ± 4.20		<.001[a]	2.49 (1.71, 3.28)
	91.64 ± 3.50		80.65 ± 4.17	<.001[a]	2.85 (2.01, 3.69)
		81.99 ± 4.20	80.65 ± 4.17	.23	0.32 (–0.27, 0.91)
C4-$V_dS_fP_m$	88.08 ± 5.32	83.85 ± 4.51		<.001[a]	0.86 (0.24, 1.48)
	88.08 ± 5.32		84.55 ± 4.24	<.001[a]	0.73 (0.12, 1.35)
		83.85 ± 4.51	84.55 ± 4.24	.50	0.16 (–0.43, 0.75)
C5-$V_aS_fP_m$	67.32 ± 9.76	62.82 ± 9.47		.03[a]	0.47 (–0.13, 1.07)
	67.32 ± 9.76		62.80 ± 7.37	.04[a]	0.52 (–0.08, 1.12)
		62.82 ± 9.47	62.80 ± 7.37	.99	0.00 (–0.59, 0.59)
C6-$V_dS_mP_m$	71.12 ± 8.39	71.73 ± 8.77		.77	0.07 (–0.52, 0.66)
	71.12 ± 8.39		67.84 ± 9.07	.12	0.38 (–0.22, 0.97)
		71.73 ± 8.77	67.84 ± 9.07	.057	0.44 (–0.16, 1.03)

Abbreviations: Equilibrium$_{10}$, equilibrium based on the first 10-s trials; C1-$V_nS_fP_f$, condition 1: normal vision, fixed surroundings, fixed platform; C2-$V_aS_fP_f$, condition 2: absent vision, fixed surroundings, fixed platform; C3-$V_dS_mP_f$, condition 3: distorted vision, moving surroundings, fixed platform; C4-$V_dS_fP_m$, condition 4: distorted vision, fixed surroundings, moving platform; C5-$V_aS_fP_m$, condition 5: absent vision, fixed surroundings, moving platform; C6-$V_dS_mP_m$, condition 6: distorted vision, moving surroundings, moving platform.

[a] Indicates difference.

somatosensory or visual systems and serves as a reference of self-motion, especially when a conflict exists between sensory feedback, other somatosensory and visual feedback becomes less reliable, or both.[27–30] In contrast, the visual system recognizes objects and provides feedback on moving objects and scenes in the environment.[30–32] When an object is moving along with self-motion, visual feedback separates object motion from self-motion by referencing nonvisual feedback such as somatosensory and vestibular feedback.[32] Congruency of visual feedback and referencing nonvisual feedback are given with a fixed platform and fixed surroundings (C1-$V_nS_fP_f$, C2-$V_aS_fP_f$). However, when both visual feedback and referencing somatosensory feedback are distorted with a moving platform and surroundings (C6-$V_dS_mP_m$), especially increased task constraints standing in a unilateral stance, variability increases with visual-vestibular congruency in self-motion feedback. When visual-vestibular conflicts are induced, vestibular feedback

Table 10. Pairwise Comparisons of Equilibirum$_{10}$ Scores for Environmental and Task Constraints in the Control Group

Environment: Sensory Organization Test Condition	Task, Mean ± SD			P Value	Effect Size (95% CI)
	Double-Limb Stance	Uninjured-Limb Stance	Injured-Limb Stance		
C1-$V_nS_fP_f$	94.75 ± 1.30	89.19 ± 2.43		<.001[a]	2.85 (2.01, 3.69)
	94.75 ± 1.30		89.16 ± 2.44	<.001[a]	2.86 (2.02, 3.70)
		89.19 ± 2.43	89.16 ± 2.44	.96	0.01 (–0.58, 0.60)
C2-$V_aS_fP_f$	92.17 ± 2.97	71.99 ± 5.89		<.001[a]	4.33 (3.25, 5.41)
	92.17 ± 2.97		70.11 ± 7.67	<.001[a]	3.79 (2.80, 4.78)
		71.99 ± 5.89	70.11 ± 7.67	.22	0.27 (–0.32, 0.87)
C3-$V_dS_mP_f$	92.51 ± 2.55	80.33 ± 5.60		<.001[a]	2.80 (1.97, 3.63)
	92.51 ± 2.55		80.17 ± 6.77	<.001[a]	2.41 (1.64, 3.19)
		80.33 ± 5.60	80.17 ± 6.77	.89	0.03 (–0.57, 0.62)
C4-$V_dS_fP_m$	87.90 ± 3.70	83.85 ± 4.86		<.001[a]	0.96 (0.33, 1.58)
	87.90 ± 3.70		84.54 ± 4.68	.002[a]	0.80 (0.18, 1.41)
		83.77 ± 4.86	84.54 ± 4.68	.46	0.16 (–0.43, 0.75)
C5-$V_aS_fP_m$	69.34 ± 8.44	58.06 ± 7.86		<.001[a]	1.38 (0.73, 2.04)
	69.34 ± 8.44		56.38 ± 10.95	<.001.[a]	1.33 (0.67, 1.98)
		58.06 ± 7.86	56.38 ± 10.95	.26	0.18 (–0.42, 0.77)
C6-$V_dS_mP_m$	73.44 ± 10.59	67.95 ± 8.10		.01[a]	0.58 (–0.02, 1.19)
	73.44 ± 10.59		68.57 ± 7.85	.02[a]	0.52 (–0.08, 1.12)
		67.95 ± 8.10	68.57 ± 7.85	.76	0.08 (–0.51, 0.67)

Abbreviations: Equilibrium$_{10}$, equilibrium based on the first 10-s trials; C1-$V_nS_fP_f$, condition 1: normal vision, fixed surroundings, fixed platform; C2-$V_aS_fP_f$, condition 2: absent vision, fixed surroundings, fixed platform; C3-$V_dS_mP_f$, condition 3: distorted vision, moving surroundings, fixed platform; C4-$V_dS_fP_m$, condition 4: distorted vision, fixed surroundings, moving platform; C5-$V_aS_fP_m$, condition 5: absent vision, fixed surroundings, moving platform; C6-$V_dS_mP_m$, condition 6: distorted vision, moving surroundings, moving platform.

[a] Indicates difference.

as a gravitational receptor has a fundamental role in the perception of verticality to maintain postural stability.[26] Collectively, we contend that visual-vestibular conflicts were present for the CAI group to maintain posture in injured-limb stance, and vestibular feedback helped to transform visual feedback from the visual-scene reference frame into the gravity-centered reference frame to achieve postural stability. Moreover, the CAI group did not downweight on vestibular feedback and did not benefit from distorted vision compared with the control group.

The CAI group displayed a moderate trend (ES = 0.62 with a 95% CI that did not cross zero) of not downweighting vestibular feedback in the uninjured limb compared with the control group. The SOT systematically manipulated somatosensory and visual systems in a combination of the sway-referenced support surface and visual surroundings with and without vision and created somatosensory and visual feedback conflicts. Moreover, the vestibular ratio was computed by comparing C5-$V_aS_fP_m$, where the vestibular feedback became the dominant input, somatosensory feedback was distorted with a moving platform, and vision was absent, and C1-$V_nS_fP_f$, where all sensory systems were intact. Therefore, we hypothesize that the CAI group could not downweight on vestibular feedback, which serves as a dominant input for maintaining postural stability like that of the control group during uninjured-limb stance. However, the control group continued to benefit from distorted somatosensory feedback to maintain postural control and downweighted on vestibular feedback as a dominant input to substitute relevant sensory information to maintain posture in injured- and uninjured-limb stances.

Postural control in the CAI and control groups depended on both environmental and task constraints, meaning postural stability depended on a combination of the type of sensory systems manipulated and task difficulties. The CAI group displayed better postural stability in injured-limb stance during C5-$V_aS_fP_m$ compared with the control group, and a similar trend (ES = 0.55) was exhibited in uninjured-limb stance. Based on our earlier discussions, reliance on vestibular feedback in uninjured- and injured-limb stances resulted in better postural stability in the CAI group. Both groups maintained better postural stability in double-limb stance than uninjured- and injured-limb stances, respectively, except in C6-$V_dS_mP_m$ for the CAI group, which maintained very similar posture in all stances. Superior postural stability in double-limb stance compared with unilateral stance was expected in both groups because it is easier to maintain the center of mass within a wider base of support than a narrow base of support. However, finding similar postural control in uninjured- and injured-limb stances for the CAI group did not support our hypothesis. This result may be simply due to not detecting somatosensory deficits in the CAI group, the use of redundant sensory feedback from the proximal joints we have discussed, or both. Changes in postural control were observed in almost all combinations of environmental constraints within individual stances for each group. The similar postural control differences between individual conditions in double-limb stance were consistent with those of healthy men reported in the literature.[33] The best postural stability in the SOT was observed where the task was simplest and all sensory systems were intact (ie, C1-$V_nS_fP_f$). In contrast, the worst postural instability was observed when the task became most difficult and only vestibular feedback was available as a reliable source (ie, C5-$V_aS_fP_m$). Thus, multisensory integration results in better postural control than unisensory integration. Indeed, unisensory integration may be problematic because it is linked to postural instabilities associated with injuries, such as falls in older adults.[34] Furthermore, postural instability exhibited by both groups during conditions where vision was absent may suggest an essential role of visual feedback to differentiate self-motion from external motion, specifically when self-motion becomes greater with a unilateral stance and a moving platform.

Our results highlight the need to consider vestibular-system upweighting during postural control assessment and training in individuals with CAI. Evaluating single-limb postural control and confounding vestibular information may produce larger postural control deficits in this population. In clinical practice, for example, the horizontal head impulse test is widely used to assess the horizontal vestibular-ocular reflex, indicating a person's inability to maintain eye stability during head movements due to vestibular dysfunction.[35,36] Perhaps combining this test with a single-limb postural control assessment may elucidate sensory reweighting dysfunction. In addition, head movement while maintaining posture in double- and single-limb stances also can be used in conjunction with stable and unstable surfaces with and without visual feedback. Given that sensory reweighting depends on contextual constraints (ie, environment and task), clinicians can consider the rehabilitation progress of individuals when incorporating a multisensory feedback approach into a rehabilitation intervention that challenges vestibular feedback in individuals with CAI. Based on our findings, sensory reweighting and the integration of a multisensory feedback approach for those individuals with CAI need to be further explored.

A limitation of our study was not accounting for chronicity after the initial ankle sprain. The duration of exposure to CAI may affect the sensory reweighting system and postural control with the increased complexity of the environmental and task constraints. Future research could be done to examine the association between chronicity and the sensory reweighting system.

CONCLUSIONS

The CAI group did not downweight vestibular feedback while maintaining posture in injured-limb stance compared with the control group. However, not downweighting vestibular feedback could be a compensatory reliance for individuals with CAI, as they maintained postural stability better than individuals without CAI. Furthermore, postural control in both groups was dependent on the type of sensory systems manipulated (ie, environment) and task constraints (ie, stance limbs). Clinicians may take a multisensory-feedback approach with interventions by challenging vestibular feedback, with and without vision, during increased task constraints, which may optimize postural control in individuals with CAI.

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