Balance Training Improves Function and Postural Control in Those with Chronic Ankle Instability

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ABSTRACT

MCKEON, P. O., C. D. INGERSOLL, D. C. KERRIGAN, E. SALIBA, B. C. BENNETT, and J. HERTEL. Balance Training Improves Function and Postural Control in Those with Chronic Ankle Instability. *Med. Sci. Sports Exerc.*, Vol. 40, No. 10, pp. 1810–1819, 2008. **Purpose:** The purpose of this randomized controlled trial was to determine the effect of a 4-wk balance training program on static and dynamic postural control and self-reported functional outcomes in those with chronic ankle instability (CAI). **Methods:** Thirty-one young adults with self-reported CAI were randomly assigned to an intervention group (six males and 10 females) or a control group (six males and nine females). The intervention consisted of a 4-wk supervised balance training program that emphasized dynamic stabilization in single-limb stance. Main outcome measures included the following: self-reported disability on the Foot and Ankle Disability Index (FADI) and the FADI Sport scales; summary center of pressure (COP) excursion measures including area of a 95% confidence ellipse, velocity, range, and SD; time-to-boundary (TTB) measures of postural control in single-limb stance including the absolute minimum TTB, mean of TTB minima, and SD of TTB minima in the anteroposterior and mediolateral directions with eyes open and closed; and reach distance in the anterior, posteromedial, and posterolateral directions of the Star Excursion Balance Test (SEBT). **Results:** The balance training group had significant improvements in the FADI and the FADI Sport scores, in the magnitude and the variability of TTB measures with eyes closed, and in reach distances with the posteromedial and the posterolateral directions of the SEBT. Only one of the summary COP-based measures significantly changed after balance training. **Conclusions:** Four weeks of balance training significantly improved self-reported function, static postural control as detected by TTB measures, and dynamic postural control as assessed with the SEBT. TTB measures were more sensitive at detecting improvements in static postural control compared with summary COP-based measures.

Key Words: ANKLE SPRAIN, DYNAMIC BALANCE, FUNCTIONAL OUTCOMES, REHABILITATION, TIME-TO-BOUNDARY

Ankle sprains are among the most common injuries in the physically active population (4). The most common predisposing factor to experiencing an ankle sprain is a previous history of ankle sprain (1). The subjective feeling of the ankle "giving way" after an initial ankle sprain and repetitive bouts of instability resulting in numerous ankle sprains has been termed chronic ankle instability (CAI) (16). CAI has been linked to many different contributing factors, including deficits in postural control (2,12,17,21,26,27).

Balance training has been purported to be an effective modality in the rehabilitation and prevention of recurrent sprains in those with CAI; however, there is limited evidence of its effectiveness (3,9,26,28). For example, Eils and Rosenbaum (9) reported a 60% decrease in self-reported episodes of the ankle "giving way" into inversion in individuals with CAI 1 yr after undergoing 6 wk of balance and coordination training, but they did not report values for a control group for comparison. Traditionally, balance training has involved single-limb stance activities on stable and unstable surfaces (9,28). Although self-reported improvements in functional status have been demonstrated in response to balance training (9,26), there is conflicting evidence that postural control improvements occur as a result of balance training in individuals with CAI (3,9,26). The traditional measures used to assess the improvements in postural control may have lacked the sensitivity to detect improvements (21). Moreover, these balance training programs may have not appropriately challenged the sensorimotor system to elicit a detectable change in postural control. A balance training program that emphasizes the dynamic stabilization after perturbations such as predictable and unpredictable changes in direction, landing

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from a hop, and dynamic reaching tasks may prove more beneficial than the traditional balance training programs.

Several investigators (2,26,27) have demonstrated that individuals experiencing CAI have a decreased ability to effectively maintain single-limb stance. This has traditionally been assessed using a variation of the Romberg test on a force plate. Traditional force plate measures of postural control such as average center of pressure (COP) excursion velocity and COP excursion area have not consistently detected postural control deficits associated with CAI (22) and have not detected significant improvements associated with rehabilitation in this population (23). A novel approach to assessing postural control differences in single-limb stance related to CAI is time-to-boundary (TTB) analysis (20,21). TTB is a spatiotemporal analysis of COP data points. It quantifies the theoretical amount of time an individual has to make a postural correction to maintain postural stability. In a comparison of females with CAI and healthy female controls, Hertel and Olmsted-Kramer (21) demonstrated that the magnitude and the variability of TTB measures in single-limb stance were lower in the CAI group. The CAI group had significantly less time to make postural corrections and did so in a less variable manner than healthy controls. It was hypothesized that this reduction in magnitude of TTB measures was related to a diminished ability to respond effectively to changes in postural control demands (21). In those with CAI, the reduction in the variability of the TTB measures may be indicative of a more constrained sensorimotor system (13,29). Traditional COP-based measures of COP excursion velocity, range, and SD failed to detect these postural control alterations (21). Currently, there is no evidence to suggest that these TTB deficits can be improved through rehabilitation. Perhaps TTB measures may provide greater insight into postural control alterations associated with balance training in those with CAI where traditional COP-based measures have not.

The effects of CAI on dynamic postural control have also been examined. The Star Excursion Balance Test (SEBT) is an assessment of dynamic postural control consisting of a series of lower-extremity reaching tasks in different directions (17). Significant deficits in dynamic postural control in individuals with CAI have been detected with the use of the SEBT (11). Individuals with CAI demonstrated a significantly decreased ability to reach while standing on the injured limb compared with their uninjured limbs and matched controls (24). The anterior (A), the posteromedial (PM), and the posterolateral (PL) directions have been shown to be the most effective in assessing dynamic balance in those with CAI (17). Currently, there is limited evidence to suggest that deficits in SEBT reach distance associated with CAI can be corrected through rehabilitation (15).

To date, there have been no randomized controlled trials that have examined the effects of supervised dynamic balance training on static and dynamic postural control as well as self-reported functional outcomes in those with CAI. Therefore, the purpose of this study was to determine the effect of a 4-wk supervised balance training program on static and dynamic postural control and self-reported functional outcomes in those with CAI. We hypothesized that individuals with CAI who underwent dynamic balance training would have significant improvements in self-reported functional status, static postural control as assessed by TTB measures and traditional COP-based measures, and dynamic postural control as assessed with the SEBT.

METHODS

Study design. This study was a randomized controlled trial in which individuals with self-reported CAI were randomly assigned to one of two groups: a balance training group or a control group. The balance training group underwent 12 supervised balance training sessions during a 4-wk period. The control group maintained the same level of activity before study enrollment for the duration of 4 wk. Measures of self-reported function and static and dynamic postural control were taken before and after the 4-wk intervention in both the balance training and the control groups.

Subjects. Thirty-one physically active individuals with a self-reported history of CAI were recruited to participate in the study. Inclusion criteria were a history of more than one ankle sprain and residual symptoms, including subsequent episodes of the ankle giving way as quantified by four or more "yes" responses on the Ankle Instability Instrument (8). Also included were self-reported symptoms of disability due to ankle sprains qualified by a score of 90% or less on the Foot and Ankle Disability Index (FADI) and the FADI Sport surveys. These instruments have demonstrated high intersession reliability and have been shown to be valid in detecting differences related to CAI and improvements after rehabilitation in those with CAI (14). The FADI contains 26 items related to activities of daily living, and the FADI Sport contains eight items that evaluate perceived disability due to foot or ankle injury in activities associated with physical activity and sport participation (14). All subjects had no history of lower-extremity injury, including ankle sprain, within the past 6 wk, no history of lower-extremity surgery, and no balance disorders, neuropathies, diabetes, or other conditions known to affect balance. If a subject reported bilateral ankle instability, the self-reported worse limb was used for analysis and training. Before testing, all subjects signed an informed consent form approved by the university institutional review board.

Once informed consent was obtained, subjects were randomly assigned to either a balance training group or a control group. The randomization was concealed and prepared by an independent investigator. The balance training group consisted of six males and 10 females ((mean ±SD) age = 22.2 ± 4.5 yr; height = 168.9 ± 7.7 cm; mass = 63.0 ± 8.8 kg) and reported 6.3 ± 7.1

previous sprains with 10.7 ± 7.0 months since the last significant sprain. They reported a mean ± SD score of 85.5 ± 8.4% on the FADI and 69.9+12% on the FADI Sport. The control group consisted of six males and nine females (mean ± SD age = 19.5 ± 1.2 yr; height = 173.1 cm; mass = 67.3 kg) and reported 4.6 ± 2.5 previous significant ankle sprains with 5.5 ± 3.9 months since the last significant sprain. The mean ± SD FADI and the FADI Sport scores were 82.9 ± 7.4% and 66.4 ± 9.8%, respectively.

INSTRUMENTATION

Static postural control was assessed with the Accusway Plus force plate (AMTI; Watertown, MA). Force and moment signals were filtered with a fourth-order, zero lag, low-pass filter with a cutoff frequency of 5 Hz. COP data were calculated from the three-dimensional force and moment signals and sampled at a rate of 50 Hz (20).

PROCEDURES

Static postural control. Subjects performed three trials of single-limb stance on each leg with eyes open and closed on a force plate (Accusway Plus; AMTI) for 10 s (20,21). Subjects were instructed to stand as still as possible during testing with arms folded across their chests, holding the opposite limb at approximately 45° of knee flexion and 30° of hip flexion in accordance with a previously established protocol (18,20,21). If a subject touched down with the opposite limb, made contact with the stance limb, or was unable to maintain standing posture during the 10-s trial, the trial was terminated and repeated.

Dynamic postural control. The SEBT has demonstrated high intersession reliability and has been shown to be valid in detecting deficits associated with CAI (12,17,19). Subjects were positioned and aligned with a tape measure secured to the floor in accordance with Hertel et al. (17). Subjects maintained a single-limb stance while reaching as far as possible along a cloth tape measure secured to the floor in the relevant line of direction with their opposite limb, made a light touch on the line, and returned to the starting position (12). The reach distances of three trials of the A, the PM, and the PL directions were recorded for each limb (17). These directions have been shown to assess unique aspects of dynamic postural control. A trial was discarded and repeated if a subject placed excessive weight on the reaching limb, removed the stance foot from the starting position, or lost balance (10). Reach distance was normalized to the subject's leg length in accordance with previously established methods (10). The mean of three trials for each direction was used for analysis.

Data reduction. TTB measures were computed using previously described methods (20). The mean of three trials for each measure was used for analysis. To calculate TTB, we modeled each subject's foot as a rectangle, based on length and width measurements, to separate the anteroposterior (AP) and mediolateral (ML) components of COP (20). TTB measures estimated the time it would take the COP to reach the boundary of the base of support if the COP were to continue on its trajectory without a change in velocity (20). TTB was processed with the use of a custom software program in MatLab (MathWorks, Inc, Natick, MA). For each COP data point in the ML direction (COPML), the instantaneous position and velocity were used to calculate TTB. The distance between COPML_i and the previous COPML data point was calculated and divided by the sampling rate (0.02 s) to determine the velocity of COPML_i. If COPML_i was moving medially, the distance from the COPML_i instantaneous position to the respective (medial) boundary of the foot was determined. By dividing the COPML_i distance to the boundary by its velocity, the theoretical time it would take COPML_i to reach the medial border of the foot if it continued on the same trajectory without a change in velocity or direction was calculated (20). If the COP data point was moving laterally, the distance of the COP data point to the lateral border of the foot was determined. TTB in the AP direction (TTBAP) was calculated similarly to TTB in the ML direction (TTBML) using the AP borders of the foot. Each TTB series in the ML and AP directions produced a data sequence of peaks and valleys. The valleys represented the TTB minima, the lowest values in the TTB series. These data points represent the critical times where the sensorimotor system had the least time to make a postural correction to maintain single-limb stance over the base of support (20). From the identification of TTB minima, the absolute minimum TTB (the lowest minimum value), the mean of the TTB minima (measurement of TTB magnitude), and the SD of TTB minima (measurement of TTB variability) were computed separately for the ML and the AP directions. The mean of each measure for the three eyes-open and eyes-closed trials was used for statistical analysis.

Traditional COP-based measures of the SD of COP excursions, range of COP excursions (distance between the maximum and the minimum COP positions), and mean velocity of COP excursions (total COP excursion length in centimeters divided by the 10-s trial time) in the ML and the AP directions were calculated. The area of the 95% confidence ellipse of COP excursions was also calculated. The mean of each measure for the three eyes-open and eyes-closed trials was used for statistical analysis.

BALANCE TRAINING PROGRAM

Subjects randomly assigned to the 4-wk progressive balance-training program participated in 12 supervised training sessions, three sessions per week (25,26). Each session lasted approximately 20 min. The progressive balance training program (see Appendix) was designed to challenge a subject's ability to maintain a single-limb stance

TABLE 1. Pretest and posttest scores on the FADI and the FADI Sport for the balance training and control groups.

	Balance Training Group		Control Group			
	Pretest	Posttest	Pretest	Posttest	Group Effect	Time Effect
FADI, %	85.5 ± 8.4	93.7 ± 7.4*,†	82.9 ± 7.4	81.40 ± 18.1	0.68	0.98
FADI Sport, %	69.9 ± 12.1	85.0 ± 14.4*,†	66.5 ± 9.8	66.3 ± 11.8	1.63	1.25

There was a significant group × time interaction for both instruments. There was no difference between groups at pretest, but there was a significant difference between posttest measures between groups and a significant difference in self-reported function at posttest for the balance training group, $P < 0.05$. Group effect sizes were calculated from posttest scores. Time effect sizes were calculated from the pretest and posttest measures of the balance training group.

* $P < 0.05$ for pretest to posttest comparisons within the balance training group.

† $P < 0.05$ for between-groups comparisons at posttest.

while performing various balance activities (3,7). During each session, subjects performed dynamic balance activities designed to challenge recovery of single-limb balance efficiently after a perturbation and to effectively develop spontaneous strategies to execute movement goals. As a subject developed proficiency within the program, the task and environmental constraints placed on the sensorimotor system were progressively increased. Each activity contained seven levels of difficulty through which subjects advanced. These novel activities were intended to promote the restoration of functional variability within the sensorimotor system. Activities included 1) hop to stabilization, 2) hop to stabilization and reach, 3) hop to stabilization box drill, 4) progressive single-limb stance balance activities with eyes open, and 5) progressive single-limb stance activities with eyes closed.

Statistical analysis. The independent variables were group (balance training and control) and time (pretest and posttest). Separate 2 × 2 repeated-measures ANOVA were used to assess changes in the dependent measures due to balance training. FADI and FADI Sport measures were compared both between and within groups. Postural control measures were separated into TTB measures and traditional COP-based measures and were analyzed independently. Eyes-open trials during static postural control were analyzed separately from eyes closed. For SEBT measures, the three reach distances were analyzed separately. Tukey's HSD was used for *post hoc* pairwise comparisons to explain any significant interactions. Alpha level was set *a priori* at $P < 0.05$. Cohen's D measures of effect size (5) were determined by calculating the mean difference between groups (balance training and control) or tests (pretest and posttest) and dividing it by the reference SD (pretest or control). The strength of effect sizes was determined as small (≤0.4), moderate (0.41–0.7), and large effects (≥0.71) (5).

RESULTS

Self-Reported Function

Means (±SD) and effect sizes for FADI and FADI Sport measures are listed in Table 1. There was a significant group × time interaction for the FADI ($P = 0.03$) and the FADI Sport ($P = 0.009$) scores. *Post hoc* comparisons revealed that that there were no significant differences between the pretest measures for the FADI and the FADI Sport between groups. The balance training group FADI and FADI Sport measures were significantly greater after balance training compared with their pretest measures and were also significantly greater than the control group posttest measures.

Static Postural Control

TTB measures. For the eyes-open trials, there were no significant interactions or main effects for any of the TTB measures (Table 2).

For the eyes-closed TTB measures, there were significant group × time interactions for the absolute minimum TTBML, the mean of TTBML minima, the mean of TTBAP minima, and the SD of TTBAP minima. *Post hoc* comparisons revealed that there was a significant increase in these measures for the balance training group from pretest to posttest. The balance training group also had significantly higher TTB measures compared with the control group at posttest on the absolute minimum TTBML, the mean of TTBAP minima, and the SD of TTBAP minima.

TABLE 2. Pretest and posttest TTB in the ML and AP directions with eyes open.

	Balance Training Group		Control Group			
	Pretest	Posttest	Pretest	Posttest	Group Effect	Time Effect
Abs. Min. TTBML	1.22 ± 0.37	1.36 ± 0.53	1.12 ± 0.18	1.23 ± 0.26	0.50	0.38
Abs. Min. TTBAP	4.14 ± 1.47	4.13 ± 0.95	3.48 ± 0.87	4.22 ± 0.79	−0.11	−0.006
Mean Min. TTBML	4.56 ± 1.59	5.09 ± 2.38	4.29 ± 1.15	4.53 ± 1.13	0.50	0.33
Mean Min. TTBAP	13.88 ± 4.44	13.90 ± 4.01	11.90 ± 3.1	13.20 ± 1.9	0.37	0.004
SD Min. TTBML	3.35 ± 1.42	4.48 ± 2.98	3.25 ± 1.22	3.62 ± 1.27	0.68	0.80
SD Min. TTBAP	9.07 ± 3.16	8.43 ± 3.26	8.01 ± 2.45	7.93 ± 1.67	0.30	−0.20

There were no significant changes in pretest to posttest for either group. Group effect sizes were calculated from posttest scores. Time effect sizes were calculated from the pretest and posttest measures of the balance training group.

Abs., absolute; Min., minimum.

TABLE 3. Pretest and posttest measures of TTB in the ML and AP directions with eyes closed.

	Balance Training Group		Control Group			
	Pretest	Posttest	Pretest	Posttest	Group Effect	Time Effect
Abs. Min. TTBML	0.48 ± 0.10	0.56 ± 0.11*,†	0.52 ± 0.13	0.50 ± 0.10	0.60	0.80
Abs. Min. TTBAP	1.63 ± 0.63	1.74 ± 0.61	1.51 ± 0.51	1.50 ± 0.47	0.51	0.17
Mean Min. TTBML	1.84 ± 0.53	2.15 ± 0.61*,†	1.99 ± 0.50	1.89 ± 0.48	0.54	0.60
Mean Min. TTBAP	5.32 ± 1.77	6.04 ± 1.88*,†	5.05 ± 1.46	4.81 ± 1.23	0.32	0.41
SD Min. TTBML	1.61 ± 0.66	2.05 ± 0.99	1.66 ± 0.51	1.69 ± 0.70	0.51	0.67
SD Min. TTBAP	3.11 ± 1.06	3.91 ± 1.20*,†	3.27 ± 0.97	2.97 ± 0.79	1.18	0.75

There were significant group × time interactions for four of six measures. In all interactions, there was a significant increase in TTB measures at posttest for the balance training group compared with their respective pretest measures and the posttest measures of the control group, $P < 0.05$. Group effect sizes were calculated from posttest scores. Time effect sizes were calculated from the pretest and posttest measures of the balance training group.

Abs., absolute; Min., minimum.

* $P < 0.05$ for pretest to posttest comparisons within the balance training group.

† $P < 0.05$ for between-groups comparisons at posttest.

Means and SD for all TTB measures in eyes-closed testing are listed in Table 3.

Traditional COP-based measures. There were no significant group × time interactions for any of the traditional COP-based measures with eyes open; however, there was a significant time main effect for COP velocity in the AP direction ($P = 0.04$). *Post hoc* comparisons revealed that both groups had significant decreases in AP velocity in the posttest compared with the pretest. There were no other significant interactions or main effects identified for the eyes-open tests (Table 4).

For the eyes-closed trials, there was a significant group × time interaction for the COP velocity in the ML direction ($P = 0.03$). *Post hoc* comparisons revealed that the COP velocity in the ML direction significantly decreased in the balance training group from pretest to posttest. There were no significant changes within the control group or between-group comparisons pre- and posttest. There were no other significant interactions or main effects identified for the eyes-closed tests (Table 5).

Dynamic Balance

There were significant group × time interactions found for the PM ($P = 0.01$) and the PL reach ($P = 0.03$) components of the SEBT. In both directions, the balance training group had greater reach distances in the posttest measures compared with the pretest measures. Moreover, the balance training group reached farther than the control group on posttest measures but not on pretest measures. There were no significant changes in the anterior reach direction between pretest and posttest measures for either group (Table 6).

DISCUSSION

We found that 4 wk of balance training significantly improved self-reported function, static postural control as detected by TTB measures, and dynamic postural control as assessed with the SEBT. These measures were specifically chosen to provide patient-oriented laboratory and clinical evidence, respectively, of the effectiveness of balance training in this population with CAI.

After undergoing 4 wk of balance training, individuals with CAI reported a significant improvement in self-reported function. The effect sizes for the pretest to posttest change for the balance training group on the FADI and the FADI Sport were 0.97 and 1.23, respectively. The effect sizes for the improvements in the FADI and the FADI Sport compared with the control group at posttest were 0.68 and 1.58, respectively. The present study was a randomized controlled trial in which one group was randomly chosen to participate in balance training and one was not. The control group did not have a significant change in functional status after 4 wk, which indicates that the balance training was effective in restoring self-reported function. Rozzi et al. (26) reported similar improvements on the Ankle Joint Functional Assessment Tool when comparing a group with CAI to a group of healthy controls who underwent balance training. They found that individuals who underwent 4 wk of training on the Biodex Stability System had improvements in self-reported function, regardless of group membership.

TABLE 4. Pretest and posttest COP measures with eyes open.

	Balance Training Group		Control Group			
	Pretest	Posttest	Pretest	Posttest	Group Effect	Time Effect
COPML SD	0.19 ± 0.04	0.18 ± 0.05	0.19 ± 0.03	0.18 ± 0.03	0	−0.20
COPAP SD	0.24 ± 0.06	0.26 ± 0.06	0.27 ± 0.07	0.26 ± 0.05	0	0.33
Range of COPML	0.87 ± 0.18	0.85 ± 0.23	0.91 ± 0.12	0.87 ± 0.12	−0.16	−0.11
Range of COPAP	1.14 ± 0.25	1.22 ± 0.27	1.28 ± 0.38	1.15 ± 0.14	0.50	0.32
Velocity of COPML	0.92 ± 0.27	0.89 ± 0.34	0.93 ± 0.14	0.86 ± 0.15	0.20	−0.11
Velocity of COPAP	0.76 ± 0.27	0.74 ± 0.26*	0.90 ± 0.34	0.71 ± 0.08*	0.38	−0.07
COP area	5.19 ± 2.33	5.34 ± 2.54	6.10 ± 2.08	5.52 ± 1.20	−0.15	0.06

There were no significant differences found for either group between pretest and posttest. Group effect sizes were calculated from posttest scores. Time effect sizes were calculated from the pretest and posttest measures of the balance training group.

An effect size of zero was calculated when the comparison means were equal.

* Significantly decreased compared with pretest values, time main effect ($P = 0.04$).

TABLE 5. Pretest and posttest COP measures with eyes closed.

	Balance Training Group		Control Group			
	Pretest	Posttest	Pretest	Posttest	Group Effect	Time Effect
COPML SD	0.44 ± 0.10	0.40 ± 0.07	0.43 ± 0.08	0.42 ± 0.06	0.33	0.57
COPAP SD	0.48 ± 0.14	0.50 ± 0.15	0.42 ± 0.06	0.51 ± 0.13	0.07	0.14
Range of COPML	1.71 ± 0.29	2.38 ± 0.75	2.59 ± 0.75	2.63 ± 0.71	−0.39	−0.52
Range of COPAP	2.15 ± 0.51	1.95 ± 0.53	2.03 ± 0.40	2.09 ± 0.54	−0.38	0
Velocity of COPML	2.18 ± 0.48	1.93 ± 0.55*,†	2.02 ± 0.40	2.11 ± 0.43	−0.42	−0.52
Velocity of COPAP	1.95 ± 0.81	1.82 ± 0.76	2.01 ± 0.61	2.04 ± 0.54	−0.41	−0.16
COP area	24.1 ± 12.4	23.8 ± 12.3	26.4 ± 10.4	27.1 ± 9.0	−0.37	0.02

There was a significant group × time interaction found for the COPML velocity. The balance training group had significantly lower COPML velocity at posttest compared with their pretest velocity and the posttest velocity of the control group, $P < 0.05$. Group effect sizes were calculated from posttest scores. Time effect sizes were calculated from the pretest and posttest measures of the balance training group.

* $P < 0.05$ for pretest to posttest comparisons within the balance training group.

† $P < 0.05$ for between-groups comparisons at posttest.

Measures of static postural control also significantly improved in the balance training group compared with the control group. We hypothesized that TTB measures would improve but COP-based measures would not. We did not observe significant changes in TTB measures or COP-based measures in the balance training group with eyes open. This may indicate that visual information provides an adequate amount of feedback to compensate for any postural control impairments due to CAI that may be present in this population. However, when vision was removed, significant improvements in postural control were detected in four of six TTB measures and only one of the seven COP-based measures. As previously reported, TTB measures seemed to detect different aspects of postural control than the COP-based measures (20,21).

TTB measures provide an estimate of the coordination of the sensorimotor system as it attempts to maintain postural control over a fixed base of support (20,29,30). These measures examine the spatiotemporal relationship between the COP and the boundaries of the base of support. The mean of the TTB minima estimates the average amount of time the sensorimotor system had to make a postural correction before reaching the boundaries of the base of support to maintain an upright stance. Individuals with CAI have been shown to have significant deficits in the mean of TTB minima compared with healthy controls (21). To our knowledge, this is the first study to show that deficits in TTB magnitude can be changed through rehabilitation. The balance training group and the control group did not differ at baseline for any of the TTB measures. After balance training, the mean of TTB minima in the ML and the AP direction significantly increased in the balance training group compared with their pretest measures and the posttest measures of the control group. The effect sizes for these changes were 0.6 and 0.41 for the ML and the AP directions, respectively. This indicated that overall, the balance training group had a significantly greater amount of time to make a postural correction after undergoing balance training.

Variability of postural control, represented by the SD of TTB minima, has been proposed to provide insight into constraints acting on the sensorimotor system (21). A lower SD indicates a more constrained sensorimotor system as it attempts to maintain postural control. Individuals with CAI have been shown to have significant deficits in the SD of TTB minima (21), which suggests that CAI places greater constraints on the sensorimotor system of these individuals. To our knowledge, this is the first study to show that deficits in TTB variability can be changed through rehabilitation. The balance training group had a significant increase in the SD of TTBAP minima compared with their pretest measures and the posttest measures of the control group. The effect size for the pretest to posttest change for the balance training group was 0.76. There was not a significant interaction detected for the SD of TTBML minima; however, the effect size of the baseline to posttest comparison of the balance training group was 0.67. This moderate effect indicated that the balance training group, after undergoing balance training, had a less constrained sensorimotor system compared with pretest measures.

From the dynamical systems perspective, the sensorimotor system has multiple degrees of freedom that afford a variety of strategies to be generated to maintain postural control (29). The constraints that act to limit these degrees

TABLE 6. Pretest and posttest normalized reach distances on the SEBT.

	Balance Training Group		Control Group			
	Pretest	Posttest	Pretest	Posttest	Group Effect	Time Effect
Anterior reach	0.70 ± 0.10	0.67 ± 0.08	0.68 ± 0.06	0.67 ± 0.05	0	−0.38
PM reach	0.82 ± 0.14	0.91 ± 0.13*,†	0.81 ± 0.08	0.80 ± 0.06	1.83	0.64
PL reach	0.77 ± 0.15	0.87 ± 0.13*,†	0.76 ± 0.08	0.78 ± 0.09	1.0	0.67

There were significant group × time interactions for the PM and PL reaches. The balance training group reached significantly farther than their pretest measures and the posttest measures of the control group, $P < 0.05$. Group effect sizes were calculated from posttest scores. Time effect sizes were calculated from the pretest and posttest measures of the balance training group.

An effect size of zero was calculated when the comparison means were equal.

* $P < 0.05$ for pretest to posttest comparisons within the balance training group.

† $P < 0.05$ for between-groups comparisons at posttest.

of freedom include the complexity of the task, the changes in the environment, and the health of the individuals (6). These constraints interact to shape these postural control strategies to maintain an upright stance. However, CAI may place greater constraints on the sensorimotor system and may reduce the amount of degrees of freedom and, consequently, the amount of strategies available to maintain postural control. This has been manifested as a reduction in variability in the SD of TTB (21) or the variability of the amount of time these individuals have to make a postural correction. By purposefully and progressively manipulating the task and the environmental constraints on individuals with CAI, we believe that the balance training program aided the sensorimotor system in freeing up degrees of freedom that were not available to these individuals previously due to the constraints of CAI. After balance training, these individuals experienced a significant improvement in the SD of TTB measures, indicating that the sensorimotor system was no longer constrained to the same magnitude.

Several investigators (9,26,28) have attempted to quantify the improvements in postural control as a result of balance training in those with CAI using traditional COP-based measures. Significant improvements have not consistently been detected with the use of these measures. Similarly, in this study, only one of the seven COP-based measures was significantly different after balance training compared with the pretest measures and the control group. We posit that these measures most likely lack the sensitivity to detect improvements in postural control related to rehabilitation in those with CAI.

There were also significant improvements in the PM and the PL reach distances of the SEBT in the balance training group compared with their pretest measures as well as the control posttest measures. Improvements in these directions have been reported as a result of rehabilitation in those with CAI (15). These changes reflect a significant improvement in dynamic postural control. These improvements may be related to the decrease in constraints placed on the sensorimotor system as a result of balance training. We did not find a change in the anterior reach direction. This may be due to local joint changes associated with CAI. The anterior direction may provide different constraints to the sensorimotor system than the other two reaching directions. This direction may be more sensitive to arthrokinematic impairments, such as reduced posterior talar glide or decreased dorsiflexion range of motion (31).

Balance training, which emphasized postural control stabilization in single-limb stance dynamically, was effective in significantly improving self-reported function, static postural control as measured by TTB, and SEBT reach distance in the PM and the PL directions. Further investigation examining the effects of this type of training in combination with interventions that address local deficits associated with CAI is warranted. Addressing both global sensorimotor function and local arthrokinematic impairments may elicit a greater response in these measures. It is also important to note that although changes in these measures seem to follow improvements in self-reported function, it has yet to be determined whether these sensorimotor changes reduce the risk of reinjury in this population. The effect of balance training as a preventive treatment to reduce the recurrence of ankle sprains needs to be systematically investigated in this population.

An additional consideration for future research is the comparison of this type of balance training intervention against more traditional forms of rehabilitation for those with CAI. In this study, the control group maintained the same level of function for 4 wk without incorporating any other interventions. We recommend that future clinical studies examine the effects of dynamic balance training against more traditional forms of rehabilitation. It will be very beneficial to determine which components of rehabilitation are most advantageous to the patient in improving postural control and self-reported function as well as decreasing recurrent ankle sprains.

CONCLUSION

The 4-wk progressive balance training program that emphasized dynamic stabilization after landing from a hop in a variety of directions and conditions significantly improved self-reported functional status, static postural control as assessed with measures of TTB magnitude and variability, and dynamic postural control as assessed with SEBT reach distance. By purposefully manipulating task and environmental constraints in those with CAI, we believe that progressive balance training significantly enhanced the ability of the sensorimotor system to overcome the sensorimotor constraints related to CAI.

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Appendix: Balance Training Protocol

Single-Limb Hops to Stabilization (10 Repetitions per Direction)

Subject performed 10 hops in each direction. Each repetition consisted of a hop from the starting position to the target position (18, 27, or 36 inches). After stabilizing balance in a single-limb stance, participants hopped in the exact opposite direction back to the starting position and stabilized in the single-limb stance.

Four directions of hops (Fig. 1): 1) anterior/posterior, 2) medial/lateral, 3) anterolateral/posteromedial, and 4) anteromedial/posterolateral. Participants were not able to move to the next level in each category until they demonstrated 10 repetitions error-free. Errors were determined on the basis of the following:

a. Touching down with opposite limb
b. Excessive trunk motion (>30° lateral flexion)
c. Removal of hands from hips during hands on hips activities
d. Bracing the nonstance limb against the stance limb
e. Missing the target

Hop to Stabilization and Reach (Five Repetitions)

Combined with the mentioned exercises, however, after stabilization in the single-limb stance, participants had to reach back to the starting position. Repetitions were counted in the same manner mentioned previously. Participants hopped, stabilized, and reached back to the starting position. Then they hopped back to the starting position and reached to the target position.

Participants were not able to advance to the next level in each direction until they demonstrated five repetitions error-free. Errors were determined on the basis of the following:

a. All errors associated with hop to stabilization
b. Using the reaching leg for a substantial amount of support during reaching component

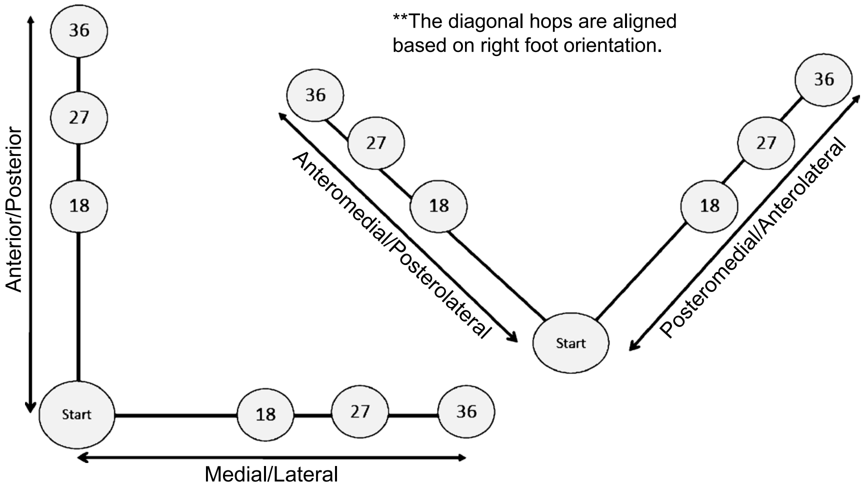

FIGURE 1—Directions and distances (in inches) for hop to stabilization activities.

All directions for Hop to Stabilization and Hop to Stabilization and Reach had seven levels of difficulty to progress:

1. 18-inch hop. Allowed to use arms to aid in stabilizing balance after landing.
2. 18-inch hop with hands on hips while stabilizing balance after landing.
3. 27-inch hop. Allowed to use arms to aid in stabilizing balance after landing.
4. 27-inch hop with hands on hips while stabilizing balance after landing.
5. 36-inch hop. Allowed to use arms to aid in stabilizing balance after landing.
6. 36-inch hop with hands on hips while stabilizing balance after landing.
7. 36-inch hop from a 6-inch platform.

Unanticipated Hop to Stabilization

Participants stood in the middle of a nine-marker grid (see Figure 2). A sequence of numbers was displayed on a computer screen in front of the participants. Each number corresponded to a target position to which they would hop. As the progression of numbers changed, participants would hop to the new target position. The hop to stabilization rules were applied for this activity; however, in this case, participants were allowed to use any combination of hops (AP, ML, AM/PL, or AL/PM) they desired to accomplish the goal of getting through the sequence error-free. As a participant developed proficiency, the amount of time per move was reduced. In each session, participants performed three sequences of numbers.

Levels of unanticipated hop to stabilization

Level 1: 5 s per move.

Level 2: 3 s per move.

Level 3: 1 s per move.

Level 4: If subject can progress to completion of all moves within 1 s without error, a foam pad will be placed on one of the numbers during the sequence. The subject will then continue the progression at the same level of intensity. If he or she cannot complete the course error-free, the time constraint will be reduced to the level below.

Level 5: If subject can progress to completion of all moves at Level 3 with the foam pad error-free, a step will be added to an additional number.

Level 6: If a subject progresses error-free, an additional foam pad will be added to one of the numbers, resulting in two foam pads and one step.

Level 7: If a subject progresses error-free, an additional step will be included, resulting in two foam pads and two steps.

Errors were determined on the basis of the following:

a. Touching down with opposite limb
b. Excessive trunk motion (>30° lateral flexion)
c. Removal of hands from hips during hands on hips activities
d. Bracing the nonstance limb against the stance limb
e. Missing the target

Each sequence of numbers was random such as 9, 7, 1, 6, 4, 5, 3, 8, 2.

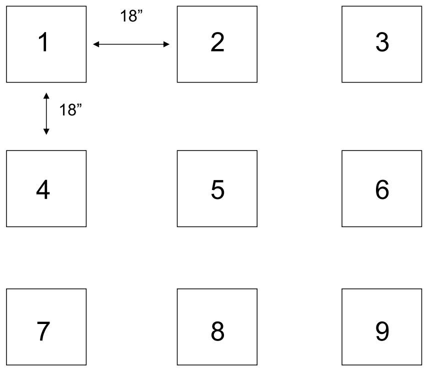

FIGURE 2—Nine marker grid for unanticipated hop to stabilization.

Single-Limb Stance Activities

Participants performed three repetitions of single-limb stance activities. Each activity (eyes open and eyes closed) had seven levels of difficulty.

Single-limb stance eyes open
1. Arms across chest on hard floor for 60 s
2. Arms across chest for 30 s on foam pad
3. Arms across chest for 60 s on foam pad
4. Arms across chest for 90 s on foam pad

Ball toss on foam
5. 30 s with arms across chest; 20 throws with a 6-lb medicine ball
6. 60 s with arms across chest; 20 throws with a 6-lb medicine ball
7. 90 s with arms across chest; 20 throws with a 6-lb medicine ball

Single-limb stance eyes closed
1. Arms out on hard floor for 30 s
2. Arms across chest on hard floor for 30 s
3. Arms across chest on hard floor for 60 s
4. Arms out on foam pad for 30 s
5. Arms across chest for 30 s on foam pad
6. Arms across chest for 60 s on foam pad
7. Arms across chest for 90 s on foam pad

Participants were not able to advance to the next level in each category until they demonstrated three repetitions error-free. Errors were determined on the basis of the following:

a. Subjects touching down with opposite limb
b. Excessive trunk motion (>30° lateral flexion)
c. Removal of arms from across chest during specified activities
d. Bracing the nonstance limb against the stance limb

Example of a Typical Session

1. Hop to stabilization
    Anterior/posterior—Level 2, 10 repetitions
    Medial/lateral—Level 1, 10 repetitions
    Anterolateral/posteromedial—Level 2, 10 repetitions
    Anteromedial/posterolateral—Level 2, 10 repetitions
2. Unanticipated hop to stabilization—Level 1, Sequence 1
3. Hop to stabilization and reach
    Anterior/posterior—Level 2, 5 repetitions
    Medial/lateral—Level 1, 5 repetitions
    Anterolateral/posteromedial—Level 2, 5 repetitions
    Anteromedial/posterolateral—Level 2, 5 repetitions
4. Unanticipated hop to stabilization—Level 1, Sequence 2
5. Single-limb stance eyes open—Level 4, 3 repetitions
6. Single-limb stance eyes closed—Level 2, 3 repetitions