# Biomechanical Response to External Biofeedback During Functional Tasks in Individuals With Chronic Ankle Instability

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**Context:** Altered biomechanics displayed by individuals with chronic ankle instability (CAI) is a possible cause of recurring injuries and posttraumatic osteoarthritis. Current interventions are unable to modify aberrant biomechanics, leading to research efforts to determine if real-time external biofeedback can result in changes.

**Objective:** To determine the real-time effects of visual and auditory biofeedback on functional-task biomechanics in individuals with CAI.

Design: Crossover study.

Setting: Laboratory.

**Patients or Other Participants:** Nineteen physically active adults with CAI (7 men, 12 women; age =  $23.95 \pm 5.52$  years, height =  $168.87 \pm 6.94$  cm, mass =  $74.74 \pm 15.41$  kg).

**Intervention(s):** Participants randomly performed singlelimb static balance, step downs, lateral hops, and forward lunges during a baseline and 2 biofeedback conditions. Visual biofeedback was given through a crossline laser secured to the dorsum of the foot. Auditory biofeedback was given through a pressure sensor placed under the lateral foot and connected to a buzzer that elicited a noise when pressure exceeded the set threshold. Cues provided during the biofeedback conditions were used to promote proper biomechanics during each task. **Main Outcome Measure(s):** We measured the location of center-of-pressure (COP) data points during balance with eyes open and eyes closed for each condition. Plantar pressure in the lateral column of the foot during functional tasks was extracted. Secondary outcomes of interest were COP area and velocity, time to boundary during static balance, and additional plantar-pressure measures.

**Results:** Both biofeedback conditions reduced COP in the anterolateral quadrant while increasing COP in the posteromedial quadrant of the foot during eyes-open balance. Visual biofeedback increased lateral heel pressure and the lateral heel and midfoot pressure-time integral during hops. The auditory condition produced similar changes during the eyes-closed trials. Auditory biofeedback increased heel pressure during step downs and decreased the lateral forefoot pressure-time integral during lunges.

**Conclusions:** Real-time improvements in balance strategies were observed during both external biofeedback conditions. Visual and auditory biofeedback appeared to effectively moderate different functional-task biomechanics.

Key Words: external focus of attention, ankle sprains, balance

#### **Key Points**

- Individuals with chronic ankle instability responded positively to visual and auditory biofeedback during static balance.
- · Each form of external biofeedback had a unique effect on each functional task.
- · Both forms of external biofeedback have potential utility during rehabilitative exercises.

L ateral ankle sprain is continually reported as the most common musculoskeletal injury, with a large portion of patients developing chronic ankle instability (CAI) over the months and years after the initial incident.<sup>1</sup> The condition is characterized by recurring sprains, episodes of the ankle "giving way," and perceptions of instability that linger more than 12 months after the initial injury.<sup>2</sup> Several long-term consequences have been associated with CAI, including reduced physical activity levels, decreased quality of life,<sup>3</sup> and increased risk of ankle posttraumatic osteoarthritis.<sup>4</sup> Individuals with CAI often display a multitude of functional and mechanical impairments, including but not limited to reduced proprioception, decreased neuromuscular control, poor postural control, decreased dorsiflexion range of motion (ROM), decreased

ankle strength, and altered biomechanics during functional activities.<sup>2</sup>

Specifically during walking, patients with CAI experience a laterally displaced center of pressure (COP) with concurrent increases in lateral plantar-pressure magnitude and altered muscle-activation patterns.<sup>5</sup> Similarly, COP during static balance is shifted laterally in individuals with CAI, whereas healthy counterparts tend to maintain a medially positioned COP.<sup>6</sup> Given the relationships among kinematics across functional tasks,<sup>7</sup> it is likely that the altered biomechanics displayed during walking are also present during other functional tasks or movements (eg, stepping, jumping, and lunging).<sup>8,9</sup> Researchers<sup>10–13</sup> have postulated that the CAI biomechanics profile contributes to repetitive sprains and the progression of ankle posttraumatic osteoarthritis. Greater lateral plantar pressure and lateral COP trajectory place the individual closer to the mechanism of ankle injury and reduce cartilage stress on the lateral talus, which increases peak stress on the medial talar cartilage.<sup>10,11</sup> This unequal distribution of contact stress<sup>11</sup> promotes degeneration of the medial talar cartilage.<sup>4,12,13</sup> Moreover, not only is the foot malpositioned during each step, but with the associated neuromuscular-control and strength deficits, individuals have a reduced ability to protect the joint from sudden perturbation, further exacerbating the risk of reinjury. Therefore, restoring proper ankle biomechanics is imperative for maintaining long-term joint health in patients with CAI.

Previous investigators<sup>14–17</sup> tested the efficacy of rehabilitation programs involving exercises that target impairments associated with ROM, strength, balance, and functional exercises (eg, stepping, jumping, cutting) in patients with CAI. Although the rehabilitation programs effectively improved dorsiflexion ROM, strength, and balance in patients with CAI, many patients continued to describe deficits in self-reported function after the intervention.<sup>18</sup> One rationale as to why these rehabilitation programs did not fully restore function is that not all impairments associated with CAI were improved. Specifically, the COP location during static balance remained laterally positioned, and ankle inversion and muscle activation during functional movements (eg, walking, jogging, and jump landing) remained unchanged.<sup>14–17</sup> We attribute the lack of change in balance strategy and biomechanics during functional movements not to the specific exercises but rather to the lack of feedback provided to patients during the exercises. Including feedback that promotes a neutrally positioned ankle during functional exercises may prompt patients to adopt a movement strategy that is not linked to recurrent ankle sprains.

Recently, 2 novel biofeedback instruments have successfully increased muscle activation, reduced lateral plantar pressure, and shifted the COP medially during a single session of treadmill walking.<sup>19,20</sup> Both devices provide external focus-of-attention biofeedback; however, 1 device targets visual centers, whereas the other targets auditory centers. The objective of external feedback is to use an external source<sup>21</sup> to direct the attention of the individual's movement to the context of the environment<sup>22</sup> that is provided by the external source. Contrastingly, internal focus can be described as attention being directed to the individual's body so that he or she is consciously aware of movement.<sup>22</sup> External feedback has been demonstrated to be the superior mode of feedback when altering movement strategies,<sup>21</sup> yet neither external-biofeedback instrument has been studied in individuals with CAI who performed a range of tasks (eg, balance, stepping, hopping). Before implementing these novel devices into rehabilitative programs for patients with CAI, we must first identify their real-time response to each type of biofeedback during various common rehabilitative exercises. Therefore, the purpose of our study was to determine the real-time effects of auditory and visual biofeedback on biomechanics during common exercises compared with the effects of a baseline condition with no feedback. We hypothesized that both external biofeedback conditions would result in improved

biomechanics compared with those of the baseline condition.

# METHODS

# **Study Design**

We performed a crossover study to compare the real-time effects of visual and auditory external biofeedback on biomechanics during functional tasks in a cohort of physically active adults with CAI. Our independent variable was condition (baseline, visual, auditory), with baseline serving as the comparison condition. Our primary dependent variables were measures of postural control (COP location) during eyes-open and eyes-closed static balance and measures of plantar pressure (peak pressure and pressure-time integral) within the lateral foot column during step downs, lateral hops, and forward lunges. To capture a complete biomechanical profile during each task, we included the secondary variables of postural control and plantar pressure. An a priori power analysis using pilot data from our laboratory was calculated to determine sample size. We determined that a sample size of 16 was needed to obtain an  $\alpha$  of .05, power of 0.95, and effect size of 1.

# Participants

A total of 19 physically active adults with CAI (7 men. 12) women; age =  $23.95 \pm 5.52$  years, height =  $168.87 \pm 6.94$ cm, mass =  $74.74 \pm 15.41$  kg) volunteered. Participants met the standards for CAI as determined by the International Ankle Consortium.<sup>23</sup> Briefly, they described having at least 1 significant ankle sprain that occurred at least 12 months before enrollment and the most recent sprain >3months before enrollment. Participants self-reported foot and ankle dysfunction by scoring  $\leq 85\%$  on the Foot and Ankle Ability Measure-Sport subscale. Furthermore, they scored >11 on the Identification Functional Ankle Instability questionnaire, indicating the presence of ankle instability. Physical activity levels were determined using the International Physical Activity Questionnaire short form; participants stated that they engaged in  $\geq$ 30 minutes of physical activity 3 times per week. Volunteers were excluded if they did not meet the aforementioned criteria or reported a previous ankle fracture or surgery, any underlying condition that would influence plantar pressure, or the inability to perform the tasks. All participants provided written informed consent, and the study was approved by our university's institutional review board.

### Instrumentation

Single-limb static balance was performed using an AccuSway Optimized force platform (Advanced Medical Technology, Inc) sampling at a rate of 50 Hz, and the data were processed using Balance Clinic (Advanced Medical Technology, Inc) software. Plantar pressure was collected via the pedar-x (Novel Electronics Inc, Saint Paul, MN) system sampling at a rate of 200 Hz. Calibration was conducted to ensure that plantar pressure was recorded only when the foot was in contact with the ground and excluded aerial phases.

Visual biofeedback was given via a class IIIA crossline laser diode (Calpac Lasers, Steamboat Springs, CO) powered by 2 AA batteries that has previously been used and described in detail.<sup>20,24</sup> Auditory biofeedback<sup>19</sup> was supplied via a thin (14-  $\times$  25.4-  $\times$  0.203-mm) FlexiForce Load Sensor (Tekscan, Inc, South Boston, MA). The pressure sensor was connected to a FlexiForce Quickstart Board (31.75  $\times$  31.75 mm) and a potentiometer (Tekscan, Inc) with an attached buzzer, powered by a 9-V battery. The setup of each biofeedback device is presented in Figure 1.

#### Procedures

Under each of the 3 conditions, participants performed 4 tasks: single-limb balance, step down, lateral hop, and forward lunge. Balance trials were always conducted first because they required participants to be barefoot; however, the remaining 3 tasks were randomized for each participant by using a Latin square. After the balance trials were completed, participants were fitted with standard, neutral athletic shoes (model M680V3; New Balance Inc, Brighton, MA) with the plantarpressure insoles placed inside. Practice trials were allowed for each task under each condition, and each task was completed under each condition before another task was started. The baseline condition for all tasks was always performed first using standard instructions. The visual and auditory biofeedback conditions were performed randomly for each task using a Latin square. All data were captured for the limb with CAI. If a participant reported a bilateral history of ankle sprains, the selfperceived worse limb was tested.

**Balance and Functional Tasks.** Static balance was performed while participants stood barefoot on a force plate with the uninvolved limb placed in 30° of hip flexion and 45° of knee flexion and their hands on their hips.<sup>25</sup> They were instructed to "stand as still as possible while maintaining the test position" and allowed 3 practice trials. During the baseline condition, no other instructions were provided. Participants performed 3 practice trials followed by 3 successful 10-second trials recorded with their eyes open and eyes closed. *Failed trials*, in which the participant moved out of the test position, were repeated. A maximum of 10 total attempts were allowed for each condition.

To perform the step-down trial, participants started from a 30-cm-tall box and were instructed to step down onto the ground with the involved limb first and continue their momentum forward for an additional few steps.<sup>7</sup> Three practice trials were allowed before 10 successful step-down trials were completed and used for analysis.

Participants performed lateral hops<sup>25</sup> over a piece of athletic tape that was placed along the floor and continued up the wall in front of them. They were instructed to hop laterally over the tape while focusing forward on the wall and to use the tape as a guide for hopping over the tape on the ground. All participants started with the tape toward the outside of their involved limb so that every beginning jump was lateral. A *successful trial* consisted of a lateral hop, balance maintained on landing, and a hop back to the starting position without removing their hands from their hips or taking extra steps. Based on our pilot testing, we were unable to find a consistent hop rate that could be performed successfully during all 3 testing conditions; therefore, we chose to standardize the hopping distance

rather than the hopping speed using a metronome. Participants completed 3 practice trials before 10 continuous successful trials were recorded for analysis.

Forward lunges were performed from a neutral stance with the hands on the hips.<sup>25</sup> Participants lunged with the involved limb forward into a 90°/90° position of the hip and knee and touched the back (uninvolved) knee to the ground before returning to the starting position. Three practice trials were allowed, and then a total of 10 forward lunges were performed and used for analysis.

**Biofeedback.** Visual biofeedback was provided by the crossline laser device that was secured to the dorsum of the foot using a strap (Figures 1A and B).<sup>20,24</sup> The laser remained fastened to the foot during every trial of every task to eliminate differences in COP or plantar-pressure data distribution during all trials but was turned off during the nonvisual-feedback conditions. During the visualbiofeedback conditions, the crossline laser was turned on and was visible to participants on a wall directly in front of them. Before each task was conducted, the laser was adjusted to a neutral stance and starting position. A piece of white athletic tape served as a reference for the starting point of each task. Specific instructions were given before each visual-biofeedback condition of each task, with the general instruction to "perform the task as naturally as possible while keeping the vertical line of the laser in line with the tape and limit the amount of rotation of the crossline." Participants performed 3 practice trials using visual biofeedback before we collected 10 trials for analysis.

Auditory external focus-of-attention biofeedback was provided by the auditory device and calibrated for each participant before each task (Figures 1B and C). During single-limb balance, the sensor was taped to the force plate under the head of the fifth metatarsal, which ensured consistent placement of the foot on the force plate. Laboratory shoes were cut to allow the sensor to be taped to the insole of the shoe under the fifth metatarsal while maintaining the integrity of the shoe.<sup>19</sup> Participants were instructed to shift all of their weight onto the sensor, leaning in an anterolateral direction. The potentiometer was then adjusted to the first point when noise was heard. During nonauditory-biofeedback conditions, the auditory instrument remained in place under the fifth metatarsal but was turned off by disconnecting the battery. Specific instructions were given before each auditory-biofeedback condition of each task with the general instruction to "perform the task as naturally as possible without making the buzzer elicit a noise." Participants performed 3 practice trials using auditory biofeedback before we collected 10 trials for analysis.

#### **Data Processing**

**Primary Outcomes.** During each static-balance trial, a time series of 500 COP data points (10 seconds  $\times$  50 Hz) was generated, and a custom MATLAB code (version R2019a; The MathWorks, Inc, Natick, MA) was used to determine the location of each data point in 4 quadrants of the foot (anteromedial, anterolateral, posteromedial, and posterolateral).<sup>17</sup> More data points equated to more loading in the quadrant.



Figure 1. A, The crossline laser (Calpac Lasers) powered by 2 AA batteries. B, Participant setup with both visual- and auditorybiofeedback devices. C, For the auditory device, a pressure sensor was placed inside laboratory shoes (model M680V3; New Balance Inc). The sensor was connected to a potentiometer (Tekscan, Inc) powered by a 9-V battery and attached to a buzzer.

Characteristic	Value <sup>a</sup>
Sex, males/females, No.	7/12
Age, y	$23.95 \pm 5.52$
Height, cm	$168.87 \pm 6.94$
Mass, kg	74.74 ± 15.41
Ankle sprains, No.	$2.57 \pm 1.07$
Time since last sprain, mo	$86.65 \pm 64.04$
Foot and Ankle Ability Measure, %	81.03 ± 13.46
Foot and Ankle Ability Measure–Sport Scale, %	$65.28 \pm 14.17$
Identification of Functional Ankle Instability score	$20.63\pm3.87$

<sup>a</sup> All values are mean ± SD unless otherwise indicated.

The peak pressure (kPa) and pressure-time integral (kPa $\cdot$ s) were calculated from the 10 steps performed during each task using Database Pro software (Novel Electronics Inc). A standard mask was applied to divide the foot into 9 regions; our primary regions of interest were the lateral heel, lateral midfoot, and lateral forefoot.

Secondary Outcomes. The COP 95% confidence eclipse area  $(cm^2)$  and mean velocity (cm/s) were calculated using Balance Clinic software with a fourth order, zero-lag, low-pass filter with a cutoff frequency of 5 Hz. Time-to-boundary variables (absolute minima and standard deviation of the minima) were calculated in the anteroposterior and mediolateral directions using a custom MATLAB code. Smaller area, velocity, and time-to-boundary values indicated worse postural control.

Additional plantar-pressure measures were extracted and consisted of contact area ( $cm^2$ ), contact time (milliseconds), maximum force (N), and force-time integral (N·s). The remaining regions created from the applied mask were the medial heel, the medial midfoot, medial forefoot, central forefoot, great toe, and lesser toes. We also included a total foot region.

#### **Statistical Analysis**

Separate within-factor repeated-measures analyses of variance were used (SPSS version 26; IBM Corp) to compare the means for each dependent variable across the 3 conditions (baseline, visual, auditory). We report only the comparisons of baseline with each biofeedback condition and do not report comparisons between the biofeedback conditions. We set the  $\alpha$  level a priori at .05. In accordance with modern statistical recommendations,<sup>26</sup> we did not control for multiple comparisons. Rather, we calculated Hedges g effect sizes (ESs) and associated 95% CIs and interpreted the results as different if  $P \leq .05$  and the ESs were moderate to large with 95% CIs that did not cross 0.

## RESULTS

All participant characteristics are provided in Table 1. Results for the primary outcomes are presented in Figure 2 and Tables 2 through 5. Results for all secondary outcomes are available in Supplementary Tables 1 through 4.

#### **Static Balance**

Results for the primary outcomes during eyes-open and eyes-closed balance are shown in Figure 2 and Tables 2 and 3. Results for the secondary outcomes appear in Supplementary Table 1.

The visual- and auditory-biofeedback conditions during eyes-open static balance reduced the number of COP data points in the anterolateral foot quadrant (P = .002; ESs = 0.80 and 0.86, respectively) while simultaneously increasing COP data points in the posteromedial quadrant compared with the baseline condition (P = .01; ESs = -0.74 and -0.89, respectively). Furthermore, the auditory-biofeedback condition reduced the number of COP data points in the posterolateral foot quadrant compared with baseline (P = .003; ES = 0.72; Figure 2 and Table 2).

During the eyes-closed trials, we observed a decrease in COP data points in the anterolateral foot quadrant (P < .001, ES = 0.95) and an increase in data points in the posteromedial foot quadrant (P = .006, ES = -0.97) during the auditory-biofeedback condition compared with baseline (Figure 2 and Table 3).

#### Step Down

Results for the primary variables during the step-down task are given in Tables 4 and 5 and for the secondary variables in Supplementary Tables 2 through 4. Compared with baseline, the auditory-biofeedback condition increased the lateral heel peak pressure (P = .03, ES = -0.68; Table 4) and pressure-time integral (P = .003, ES = -0.75; Table 5). The auditory-biofeedback condition reduced the pressure-time integral of the lateral forefoot compared with baseline (P = .001, ES = 0.70; Table 5).

#### Lateral Hop

Results for the primary variables during the lateral hop are provided in Tables 4 and 5 and for the secondary variables in Supplementary Tables 2 through 4. Visual

Table 2. Center-of-Pressure Data Points for Each Foot Quadrant During the Eyes-Open Static-Balance Trial in the Baseline and Visualand Auditory-Biofeedback Conditions

	Condition (n = 19), Mean $\pm$ SD				Effect Size (95% CI)	
Foot Quadrant	Baseline	Visual Biofeedback	Auditory Biofeedback	P Value <sup>a</sup>	Baseline and Visual Biofeedback	Baseline and Auditory Biofeedback
Anteromedial	75.1 ± 89.0	117.9 ± 144.4	143.2 ± 144.4	.03	-0.35 (-0.99, 0.29)	-0.56 (-1.20, 0.09)
Anterolateral	138.7 ± 124.2	$58.0 \pm 64.1^{b}$	$53.0\pm60.8^{\text{b}}$	.002	0.80 (0.14, 1.46) <sup>b</sup>	0.86 (0.19, 1.52) <sup>b</sup>
Posteromedial	$97.5\pm85.6$	$173.7 \pm 113.2^{b}$	$198.9 \pm 132.5^{b}$	.01	-0.74 (-1.40, -0.09) <sup>b</sup>	-0.89 (-1.56, -0.22) <sup>b</sup>
Posterolateral	$189.4 \pm 127.8$	$150.7\pm113.9$	$105.1 \pm 98.1^{b}$	.003	0.31 (-0.33, 0.95)	0.72 (0.07, 1.38) <sup>b</sup>

<sup>a</sup> Repeated-measures analysis of variance indicated a difference (P < .05).

<sup>b</sup> Different from baseline ( $P \le .05$ ), with a moderate-to-large effect size and 95% Cl that did not cross zero.



Figure 2. Percentage of pressure data points in each quadrant during the eyes-open static balance trial in the baseline and visual- and auditory-biofeedback conditions. <sup>a</sup> Indicates difference from baseline ( $P \le .05$ ). Abbreviations: AL, anterolateral; AM, anteromedial; PL, posterolateral; PM, posteromedial.

biofeedback increased the peak pressure (P = .002, ES = -0.73) and pressure-time integral (P = .001, ES = -1.01) in the lateral heel region as well as the lateral midfoot region (P = .001, ES = -0.78; Table 4). Auditory biofeedback did not change plantar pressure from baseline.

### **Forward Lunge**

Results for the primary variables during the forward lunge are supplied in Tables 4 and 5 and for the secondary variables in Supplementary Tables 2 through 4. The auditory-biofeedback condition decreased the pressure-time

Table 3. Center-of-Pressure Data Points for Each Foot Quadrant During the Eyes-Closed Static-Balance Trial in the Baseline and Visualand Auditory-Biofeedback Conditions

	Condition, Mean $\pm$ SD				Effect Size (95% CI)	
Foot Quadrant	Baseline $(n = 18)^a$	Visual Biofeedback (n = 19)	Auditory Biofeedback $(n = 18)^{a}$	<i>P</i> Value	Baseline and Visual Biofeedback	Baseline and Auditory Biofeedback
Anteromedial	125.9 ± 80.2	108.2 ± 77.6	109.3 ± 93.9	.45	0.22 (-0.44, 0.88)	0.19 (-0.47, 0.84)
Anterolateral	148.1 ± 73.4	116.5 ± 99.2	$82.9 \pm 60.9^{b}$	.003°	0.35 (-0.30, 1.01)	0.95 (0.26, 1.64) <sup>b</sup>
Posteromedial	94.4 ± 48.0	132.9 ± 91.7	$164.8 \pm 87.8^{b}$	.03°	-0.51 (-1.18, 0.15)	-0.97 (-1.66, -0.28) <sup>b</sup>
Posterolateral	$131.8 \pm 94.9$	$142.7 \pm 107.4$	$144.0\pm89.6$	.68	-0.10 (-0.76, 0.55)	-0.13 (-0.78, 0.52)

<sup>a</sup> One participant could not complete the eyes-closed trials during this condition.

<sup>b</sup> Different from baseline ( $P \le .05$ ), with a moderate-to-large effect size and a 95% CI that did not cross zero.

° Repeated-measures analysis-of-variance indicated a difference (P < .05).

Table 4. Peak Pressure in the Lateral Column of the Foot During the Baseline and Visual- and Auditory-Biofeedback Conditions for Each Functional Task

Task	Peak Pressure, kPa (Mean $\pm$ SD)				Effect Size (95% CI) <sup>a</sup>	
	Baseline	Visual Biofeedback	Auditory Biofeedback	P Value	Baseline and Visual Biofeedback	Baseline and Auditory Biofeedback
Step down						
Lateral heel Lateral midfoot Lateral forefoot	106.7 ± 34.7 135.9 ± 31.7 191.4 ± 38.1	135.3 ± 89.1 134.3 ± 34.8 185.4 ± 45.1	156.1 ± 94.1 <sup>b</sup> 125.8 ± 37.2 168.2 ± 38.2	.04° .09 <.001°	-0.41 (-1.06, 0.23) 0.05 (-0.59, 0.68) 0.14 (-0.50, 0.78)	-0.68 (-1.34, -0.03) <sup>b</sup> 0.29 (-0.35, 0.93) 0.60 (-0.05, 1.25)
Lateral hop						
Lateral heel Lateral midfoot Lateral forefoot	$\begin{array}{l} 106.2\pm41.8\\ 159.4\pm34.3\\ 214.1\pm54.8 \end{array}$	$139.7 \pm 47.5^{b}$ $165.5 \pm 28.8$ $203.6 \pm 43.4$	$\begin{array}{l} 114.8 \pm 47.2 \\ 156.5 \pm 40.3 \\ 210.7 \pm 60.3 \end{array}$	.001° .08 .27	-0.73 (-1.39, -0.08) <sup>b</sup> -0.19 (-0.82, 0.45) 0.21 (-0.43, 0.84)	-0.19 (-0.83, 0.45) 0.08 (-0.56, 0.71) 0.06 (-0.58, 0.69)
Forward lunge						
Lateral heel Lateral midfoot Lateral forefoot	193.1 ± 35.0 105.1 ± 22.2 99.1 ± 28.0	188.3 ± 42.7 103.1 ± 23.3 100.9 ± 27.8	201.4 ± 45.4 96.9 ± 18.3 85.4 ± 22.7	.03° .005° <.001°	0.12 (-0.52, 0.76) 0.09 (-0.55, 0.73) -0.07 (-0.70, 0.57)	-0.20 (-0.84, 0.44) 0.40 (-0.24, 1.04) 0.52 (-0.12, 1.17)

<sup>a</sup> A negative effect size represents an increase and a positive effect size represents a decrease in the biofeedback condition from baseline.

<sup>b</sup> Different from baseline ( $P \le .05$ ), with a moderate-to-large effect size and a 95% CI that did not cross zero.

<sup>c</sup> Repeated-measures analysis of variance indicated a difference (P < .05).

integral (P < .001, ES = 0.78) in the lateral forefoot (Table 5). Visual biofeedback did not change plantar pressure during the forward lunge.

#### DISCUSSION

The purpose of our study was to determine the real-time effects of 2 novel external focus-of-attention biofeedback devices on static balance and functional-task biomechanics in a cohort of individuals with CAI. Our results partially supported our central hypothesis that both visual and auditory biofeedback would produce changes in static balance and biomechanics during functional tasks. Both modes of external biofeedback contributed to changes in static balance but individually targeted functional activities. Our study provides initial evidence for the utility of various external-biofeedback media in targeting multiple rehabilitation exercises for maximizing motor control and learning.

During eyes-open and eyes-closed static balance, the auditory-biofeedback condition produced a beneficial shift in COP location from the anterolateral to the posteromedial foot quadrant. The visual-biofeedback condition produced similar changes in COP location in the eyes-open trials. According to previous researchers,<sup>6</sup> healthy individuals had more COP data points in the posteromedial foot quadrant, whereas individuals with CAI had more in the anterolateral foot quadrant. Despite a real-time advantageous shift in COP location, our secondary time-to-boundary outcomes (Supplementary Table 1) indicated an initial worsening of postural control during these trials. The goal of developing balance-training programs through the perspective of dynamic systems theory<sup>27</sup> is to manipulate the task in a way that allows patients to explore new avenues for handling a changing environment. We speculate that having less stability is natural, as these individuals are discovering a new COP location, and evidence<sup>28</sup> has suggested that

Table 5. Pressure-Time Integral in the Lateral Column of the Foot During the Baseline and Visual- and Auditory-Biofeedback Conditions for Each Functional Task

Task	Pressure-Time Integral, kPa $\cdot$ s (Mean $\pm$ SD)				Effect Size (95% CI) <sup>a</sup>	
	Baseline	Visual Biofeedback	Auditory Biofeedback	P Value	Baseline and Visual Biofeedback	Baseline and Auditory Biofeedback
Step down						
Lateral heel Lateral midfoot Lateral forefoot	$16.5 \pm 8.1$ $48.8 \pm 20.7$ $89.4 \pm 18.8$	$\begin{array}{c} 22.9\pm15.0\\ 52.5\pm23.6\\ 90.4\pm27.0 \end{array}$	$26.7 \pm 17.1^{b}$ $45.1 \pm 25.3$ $74.2 \pm 23.8^{b}$	.003° .02° <.001°	-0.52 (-1.16, 0.13) -0.16 (-0.80, 0.47) -0.04 (-0.68, 0.60)	-0.75 (-1.41, -0.09) <sup>t</sup> 0.16 (-0.48, 0.80) 0.70 (0.04, 1.35) <sup>b</sup>
Lateral hop						
Lateral heel Lateral midfoot Lateral forefoot	$\begin{array}{r} 31.8  \pm  18.4 \\ 60.7  \pm  27.0 \\ 83.4  \pm  28.5 \end{array}$	$\begin{array}{c} 61.4\pm36.3^{b}\\ 88.0\pm40.6^{b}\\ 102.2\pm38.8\end{array}$	$\begin{array}{l} 40.8\pm32.1\\ 70.0\pm40.5\\ 94.1\pm38.9\end{array}$	.001° .001° .01°	$-1.01 \ (-1.68, \ -0.33)^{\text{b}}$ $-0.78 \ (-1.44, \ -0.12)^{\text{b}}$ $-0.54 \ (-1.19, \ 0.11)$	-0.33 (-0.98, 0.31) -0.26 (-0.90, 0.37) -0.31 (-0.95, 0.33)
Forward lunge						
Lateral heel Lateral midfoot Lateral forefoot	$\begin{array}{l} 119.5 \pm 29.0 \\ 102.5 \pm 26.0 \\ 94.9 \pm 33.3 \end{array}$	$\begin{array}{l} 125.9 \pm 37.5 \\ 104.8 \pm 34.1 \\ 98.6 \pm 35.1 \end{array}$	125.1 ± 37.1 86.4 ± 22.5 71.3 ± 25.6 <sup>b</sup>	.55 <.001° <.001°	-0.19 (-0.82, 0.45) -0.08 (-0.71, 0.56) -0.11 (-0.74, 0.53)	-0.17 (-0.80, 0.47) 0.64 (-0.01, 1.30) 0.78 (0.12, 1.44) <sup>b</sup>

<sup>a</sup> A negative effect size represents an increase and a positive effect size represents a decrease in the biofeedback condition from baseline.

<sup>b</sup> Different from baseline ( $P \le .05$ ), with a moderate-to-large effect size and a 95% CI that did not cross zero.

° Repeated-measures analysis of variance indicated a difference (P < .05).

postural control continues to improve over time when balance training is coupled with an external focus of attention. Furthermore, individuals with CAI have a heightened reliance on visual information, and traditional balance-training programs are unable to alter that visual reliance.<sup>29</sup> In our investigation, the auditory-biofeedback condition caused parallel changes during eyes-open and eyes-closed balance, indicating the potential for improved balance without relying on visual stimulus. As patients continue to use external biofeedback to maintain a posteromedial COP, perhaps their overall stability will also improve, but researchers will need to determine the longterm effects of our external-biofeedback devices on postural control.

The efficacy of our visual- and auditory-biofeedback devices differed among our chosen functional tasks. When performing the step down and forward lunge, participants were more responsive to auditory biofeedback, whereas during the lateral hop, they were more responsive to visual biofeedback. During the step down, auditory biofeedback caused participants to adopt a more dorsiflexed, closedpacked position during initial contact and throughout the loading phase. This strategy may benefit patients with CAI, as landing in a more plantar-flexed and inverted ankle position is thought to cause episodes of giving way or recurrent ankle sprain.<sup>9,30</sup> Auditory biofeedback during the forward lunge caused participants to reduce primary and secondary plantar-pressure measures in the lateral midfoot, lateral forefoot, and lesser toes. We observed no increases in plantar pressure in the medial foot column, which indicated that they did not adopt an overly unnatural tactic when performing these tasks. Although the COP trajectory was not measured in this study, previous authors<sup>20</sup> who analyzed walking-gait retraining noted that reductions in lateral plantar pressure were accompanied by a medial shift in COP trajectory, which is a beneficial strategy for those with CAI. The visual biofeedback during the lateral hop produced a more closed-packed landing strategy by increasing plantar pressure in the heel and midfoot regions. As with the step down, this appears to be a beneficial strategy for individuals to adopt in order to reduce the inherent risk of sustaining another inversion ankle sprain.

Our results illustrated that auditory biofeedback was beneficial during tasks performed in the sagittal plane, whereas visual biofeedback was advantageous during tasks performed in the frontal plane. Evidence of motor learning supports the use of visual biofeedback during complex tasks (eg, lateral hop) compared with auditory biofeedback during less complex tasks (eg, step down and lunge).<sup>21</sup> Although our auditory device was designed to provide biofeedback only when the lateral forefoot applied excessive pressure to the sensor and no biofeedback was given during the aerial phases, our participants were able to adjust their feet on initial contact to adhere to the cues given. However, during the lateral-hop tasks, placement of the auditory sensor may have prevented them from altering their landing strategy so as to follow the cue and still perform the task correctly. In contrast, the constant visualization of the crossline laser during the lateral-hop task may have allowed participants to determine a proper biomechanical strategy for adjusting their performance to the biofeedback. Our visual-biofeedback instructions during all tasks were to keep the vertical line of the laser

parallel to a piece of tape (ie, transverse-plane motion) and reduce the amount of rotation of the crossline (ie, frontalplane motion).

Collectively, we chose our tasks to mimic common exercises that are used during ankle rehabilitation and have been the primary focus of earlier authors.14,15,25 Both devices have been shown to be beneficial in targeting aberrant walking-gait biomechanics,<sup>19,20</sup> whereas our findings did not support one medium over the other. To optimize motor learning, Guadagnoli and Lee<sup>31</sup> proposed that, when using protocols incorporating feedback, clinicians should be flexible about and cognizant of the demands of the task being performed. Although this framework was primarily built around healthy individuals learning new motor tasks, our results add to this existing framework by including an injured population relearning a skill with ideal biomechanics. More utility may be possible in using these novice external-biofeedback devices congruently with an impairment-based rehabilitation model to improve biomechanics across various tasks.

# Limitations

Our study had limitations. First, our intent was to determine a real-time, single-dose effect; therefore, we cannot draw conclusions about the long-term ability of these visual- and auditory-biofeedback devices to improve biomechanics. Second, our work lacked a neuromuscular perspective, and future researchers should characterize the full range of biomechanical changes that occur while using these novice biofeedback devices. Our results warrant more exploration involving these external-biofeedback devices in a full impairment-based rehabilitation program to determine their overall benefit to patients with CAI.

# CONCLUSIONS

The visual- and auditory-biofeedback devices improved static balance and functional-task biomechanics differently depending on the exercise. Our findings provide an initial extrapolation of the use of external focus-of-attention biofeedback during rehabilitation after an ankle sprain. Clinicians should consider using low-cost, user-friendly external focus-of-attention biofeedback devices to improve biomechanics and balance during established rehabilitation protocols.

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