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External feedback during walking improves measures of plantar pressure in individuals with chronic ankle instability

Danielle M. Torp*, Abbey C. Thomas, Luke Donovan

University of North Carolina at Charlotte, Charlotte, NC, USA

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ABSTRACT

Background: Individuals with chronic ankle instability (CAI) commonly present with an altered walking gait which favors the lateral aspect of their foot. Current rehabilitative protocols are unable to address these gait modifications which are potentially hindering improvements in patient-reported outcomes. Protocols for gait retraining are scarce, thus there is a need to develop intervention strategies and instruments to specifically target foot motion to address gait deficits in individuals with CAI.

Research Question: To determine the ability of a novel laser device providing external visual feedback (ExFB) during real-time to cause alterations in plantar pressure measures in individuals with CAI.

Methods: Twenty-six participants with CAI walked on a treadmill while real-time plantar pressure measures were being recorded during a baseline and feedback condition. Baseline trials were compared with ExFB trials within each subject.

Results: The ExFB condition was able to significantly reduce plantar pressures on the lateral midfoot and forefoot compared to baseline. A statistically significant medial shift in center of pressure trajectory was also observed in the ExFB condition compared to baseline.

Significance: Real-time external feedback provided by a novel laser device has the ability to reduce lateral column plantar pressures during walking in individuals with CAI.

1. Introduction

Lateral ankle sprains (LAS) are considered the most common injury among physically activity people. [1] It has been projected 40% of individuals who sustain a LAS will continue to experience ankle dysfunction and go on to develop chronic ankle instability (CAI). [2] Individuals with CAI commonly exhibit a variety of clinical impairments such as compromised proprioception, [3] diminished static and dynamic balance, [4] and biomechanical alterations. [5–7] Specifically, people with CAI walk with increased ankle inversion and plantarflexion and laterally shifted plantar pressures and center of pressure (COP). [5,6] These precise biomechanical alterations correspond to the mechanism of injury for sustaining a LAS, potentially placing these individuals in a position predisposing them to sustain recurrent sprains and bouts of instability that are thought to contribute to the development of CAI.

Current rehabilitative approaches include strength, [8] balance, [8,9] and neuromuscular control [8] exercises in attempts at reducing the clinical impairments of this population. While these programs have been successful at reducing the severity of those impairments and improving patient-reported outcomes, [10] the associated biomechanical gait alterations remain unchanged. [11–13] Furthermore, the participants within these rehabilitation studies, still reported large deficits in self-reported ankle function. [8] It is hypothesized that the remaining deficits associated with self-reported function are partly attributed to the gait alterations that still exist in these patients. [8,12,14] Thus, it is recommended that gait retraining should be incorporated as an intervention for treating acute LAS and CAI. [9] While there is a need to incorporate gait retraining into an impairment-based rehabilitation program, there are limited gait retraining instruments and protocols specific for patients with CAI.

Previous research on patients with CAI has introduced auditory feedback [15] and a novel gait training device to reduce plantar pressure over the lateral column of the foot and shift COP medially. [16] While both studies successfully produced beneficial gait changes, the auditory feedback technology and gait retraining device may not be readily available to clinicians; therefore, other novel gait retraining instruments should continue to be developed and assessed.

Ideally, gait retraining instruments should be effective, low-cost, accessible by clinicians in a variety of settings, and employ the best

* Corresponding author at: 9201 University City Blvd, Department of Kinesiology, Belk 230, Charlotte, NC, 28223, USA.
E-mail address: dtorp@uncc.edu (D.M. Torp).

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motor learning strategies. Two strategies that exist to alter movement patterns are internal and external feedback. Internal feedback can be defined as focusing attention to the individuals body in order to consciously become aware of one's performance. [17] Contrastingly, external feedback is defined as directing attention of the individuals' movement in context of the environment [17]. The use of external visual feedback has been an effective mechanism for improving patient function and impairments following injury in individuals with various musculoskeletal injuries. [18]

External feedback may optimize sensory-motor loops via the central nervous system and successfully reinforce favorable repetitive actions. [18,19] Concurrent external visual feedback is able to increase fast, unconscious, and reflexive processes. [20] It is established that individuals with CAI have a compromised sensorimotor system [21] and heavily rely on visual afferent information for proprioceptive processing. [22] Current evidence [23] recognizes the inability of traditional balance training interventions to alter the visual reliance in individuals with CAI. However, external visual feedback being delivered in real time allowing for simultaneous visual and kinesthetic processing results in desired movements without instigating a reliance on the feedback. [24] Therefore, implementation of an external feedback tactic during a task such as walking should elicit beneficial results for patients with CAI.

Prior to establishing retention and prolonged effects of an external visual feedback intervention targeting gait changes in individuals with CAI, we must first determine if this population can respond to real-time external visual feedback during a task such as walking. In order to assure proper gait motions are being achieved during gait retraining, visual feedback strategies must provide accurate and precise reactions to movement. Laser pointers are well-known for guiding visual attention and widely used in other professional settings because of their accuracy. A laser beams' low divergence should allow for a precise imitation of foot motion during walking and give accurate guidance to individuals attempting to respond to the visual movement of the beam. Therefore, the purpose of this investigation was to determine whether external visual feedback using a novel laser device can cause real-time alterations of plantar pressure measures during treadmill walking in individuals with CAI. We hypothesized the external feedback condition would reduce lateral plantar pressures and medially shift COP during walking.

2. Methods

2.1. Study design

A controlled laboratory study was performed to determine effects of a real-time external visual feedback on plantar pressure outcomes in individuals with CAI during treadmill walking. The independent variable was condition: treadmill walking with no feedback (baseline) and treadmill walking with external feedback via laser (ExFB). The dependent variables were plantar pressure measures (contact area, contact time, peak pressure, and pressure-time integral) [16] in nine regions of the foot (medial heel, lateral heel, medial midfoot, lateral midfoot, medial forefoot, central forefoot, lateral forefoot, lesser toes, great toe); as well as the average center of pressure line.

2.2. Participants

Twenty-six individuals were recruited from a university community to participate in this study. All participants completed the informed consent process prior to starting the study and the study was approved by the University's Institutional Review Board. Participants were included if they were between 18 and 40 years old and met previously established criteria for CAI as recommended by the International Ankle Consortium. [25] Inclusion criteria were established as having at least one ankle sprain that occurred greater than 12 months and the most recent sprain occurring greater than 6 weeks prior to volunteering for this study. Participants self-reported their functional deficits using the Foot and Ankle Ability Measure (FAAM) Activities of Daily Living (ADL) and Sport scale with cutoff scores of < 85% and < 80%, respectively. Self-reported ankle instability was reported using the Identification of Functional Ankle Instability (IdFAI) questionnaire with a cutoff score of ≥11. In the event a participant reported history of lateral ankle sprains to both limbs, the involved limb was chosen as the one they perceived as more unstable. Participants were excluded if they did not meet the aforementioned criteria, had surgery on the lower extremity, or had any fractures in the ankle or foot region.

2.3. Instrumentation

Plantar pressure measures were collected at a sampling rate of 100 Hz using the Pedar-X plantar pressure system (Novel Inc., St. Paul, MN). The Pedar-X system consists of two pressure insoles connected to a wireless transmitter that was inserted into a belt and secured around the participant's waist. Participants were fitted with a standard, neutral athletic shoe (Asics Gel-contend 4, Irvine, CA, USA) to minimize variation between footwear. The equipment was adjusted and secured in a manner that would not inhibit natural walking.

A custom-made laser pointer was generated using a class IIIA cross-line diode (Calpac Lasers, Steamboat Springs, CO, USA). The laser was fastened onto a strap (Motion Guidance, Castle Rock, CO, USA) that was secured around the foot of interest. The battery pack was secured to the lower limb so as not to impede normal ankle mechanics or range of motion.

2.4. Procedures

Participants were instructed to look forward and walk on the treadmill at a self-selected, natural walking pace. Once this was achieved, a 30 s baseline trial (baseline) was recorded using the in-shoe plantar pressure system. Following the baseline trial, the laser was loosely attached to the dorsal aspect of their involved foot in a manner that did not alter the pressure placed on the insole. (Fig. 1) Once the laser was fixed to the foot, participants stood on the treadmill with their feet shoulder width apart and in a neutral position. This position was unique to each participants, yet it allowed for an unobstructed view of the laser cross-line projected on to the wall in front of the treadmill. Next, to provide a point of reference, a piece of athletic tape was used to

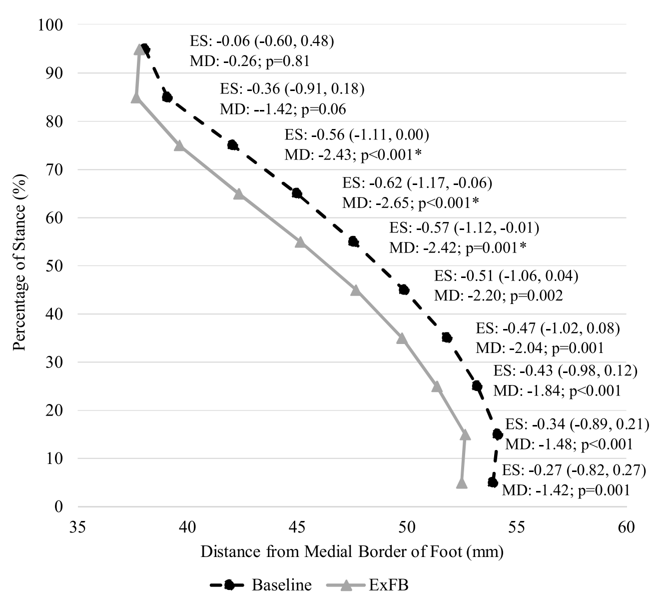

Fig. 1. Laser and battery attachment.

Fig. 2. External visual feedback condition.
A. Participant in neutral, shoulder-width stance for placement of tape for reference during external feedback condition. B. Participant in non-neutral position to show laser movement corresponding with foot motion.

mark the unique position of the vertical-line of the laser as the participants maintained the neutral, shoulder-width stance. (Fig. 2) Following the laser attachment procedures, participants were instructed to resume walking at the same speed as the baseline trial. Once walking in a normal manner, participants received the following instructions: "1) walk in a manner in which the vertical laser line aligns with the piece of tape on the wall; 2) the laser should only move up and down the piece of tape so try to walk in a manner in which the laser cross does not move left, right or rotate; 3) try to walk as normally as possible while adhering to these instructions." After the initial instructions were given, each participant was allowed time to practice the command. During this acclimation period, researchers either affirmed successful compliance to instructions or reiterated instructions verbatim. There were no time restraints set for the acclimation of instructions, however no participant exceeded 2 min. Once participants acknowledged comfort performing the task, a 30 s trial (ExFB) was recorded using the in-shoe plantar pressure system. Once the trial began, no further instruction or encouragement was provided.

2.5. Data reduction

Ten consecutive steps collected in the middle of each trial were used in analysis and processed in Novel Database Pro (Novel Inc., St Paul, MN, USA). Only measures from the involved limb (Right = 10; Left = 16) were included in the final analysis.

2.6. Plantar pressure measures

Contact area (cm^2) represents the area in each region which was in contact with the ground during stance phase. Contact time is described as the amount of time (ms) spent in each region during the stance phase. Peak pressure is described as the maximum pressure produced in a region of the foot during the stance phase and measured in kilopascals (kPa). Pressure time integral was calculated as the total pressure (kPa) in a region multiplied by the amount of time (s) spent in stance.

2.7. Center of pressure trajectory

Data points for center of pressure (COP) gait line were calculated as previously reported by studies utilizing the same system. [7,16] Center of pressure location was measured by the medial to lateral distance (mm) from the most medial and posterior portion of the involved limb. Each participant's gait line was condensed into 10% increments such as the data points from 1 to 10% of stance were averaged to represent COP at 5% of stance. Likewise, data points from 11 to 20% of stance were averaged to represent COP at 15%, etc. The final product was 10 distinct data points representing 100% of the stance phase for each trial.

2.8. Statistical analysis

Paired t-tests were conducted between baseline and ExFB condition for each dependent variable. Significance was set a-priori at $P \leq 0.05$ and analyzed using Microsoft Excel 2016 (Microsoft Corporation, Redmond, WA). Cohen's *d* effect sizes (ES) and associated 95% confidence intervals (CIs) were also calculated using Microsoft Excel 2016. Effect sizes were considered large if $d \geq 0.80$, moderate if d = 0.50-0.79, small if d = 0.20-0.49 and trivial if $d \leq 0.19$. We chose to follow recommendations of Hopkins et al. [26] and not correct for multiple comparisons, but rather interpret results as significant if $P \leq 0.05$ and effect sizes were moderate to large with associated 95% CIs that do not cross 0. [26]

3. Results

Demographics and self-reported ankle health questionnaire results can be found in Table 1.

3.1. Contact area

The contact area at the medial midfoot ($P \leq 0.001$) and great toe ($P = 0.033$; Table 2) significantly increased during the ExFB condition compared to baseline; however, both regions of the foot were associated with trivial to small effect sizes with 95% CIs that crossed 0.

3.2. Contact time

There were no significant contact time changes between baseline and ExFB condition for any of the 9 regions. (Table 2)

3.3. Peak pressure

The ExFB condition significantly decreased peak plantar pressure at the lateral midfoot ($P = 0.004$), central forefoot ($P = 0.001$), and lateral forefoot ($P = 0.002$). There was also a significant increase in peak pressure at the great toe during the ExFB condition ($P = 0.001$; Table 3). The lateral midfoot, lateral forefoot, and great toe regions were also associated with moderate to large effect sizes with corresponding 95% CIs that did not cross 0.

3.4. Pressure-time integral

The pressure-time integral significantly decreased during the ExFB

Table 1
Participant Demographics (n = 26).

	Mean ± SD
Sex	Male: 11 ; Female: 15
Age (years)	20.9 ± 2.4
Height (cm)	170.2 ± 10.2
Mass (kg)	78.4 ± 22.1
Foot and ankle ability measure ADL (%)	81.6 ± 8.6
Foot and ankle ability measure Sport (%)	67.6 ± 10.9
Identification of functional ankle instability scale	21.2 ± 3.7
Ankle sprains of involved limb	4.9 ± 4
Time since last sprain (years)	2.16 ± 2.05
Time since first sprain (years)	7.5 ± 3.8

Abbreviations: cm = centimeter; kg = kilograms; SD = standard deviation.

Table 2
Contact area measured in centimeters squared (cm^2), contact time measured in milliseconds (ms), and the nine regions of the foot during treadmill walking during baseline and external visual feedback conditions.

Region of the foot	Contact Area Mean ± SD		Contact Area Paired T-Test	Contact Area Effect Size (LL, UL)	Contact Time Mean ± SD		Contact Time Paired T-Test	Contact Time Effect Size (LL, UL)
	Baseline	ExFB	P-Value	ExFB - Baseline	Baseline	ExFB	P-Value	ExFB - Baseline
Medial Heel	22.5 ± 3.9	22.4 ± 3.8	0.64	−0.02 (−0.56, 0.52)	615.3 ± 129.6	592.4 ± 156.5	0.81	−0.18 (−0.72, 0.37)
Lateral Heel	20.5 ± 3.7	20.2 ± 3.5	0.15	−0.07 (−0.61, 0.48)	670.8 ± 141.4	663.4 ± 171.1	0.50	−0.05 (−0.60, 0.49)
Medial Midfoot	21.0 ± 6.9	23.1 ± 5.2	< 0.001	0.31 (−0.24, 0.85)	742.6 ± 135.4	743.0 ± 137.9	0.71	0.00 (−0.54, 0.55)
Lateral Midfoot	26.8 ± 4.5	26.4 ± 4.1	0.66	−0.09 (−0.63, 0.45)	797.1 ± 130.4	800.7 ± 124.2	0.70	0.03 (−0.52, 0.57)
Medial Forefoot	12.8 ± 2.5	12.9 ± 2.4	0.01	0.03 (−0.51, 0.57)	714.1 ± 116.3	703.8 ± 115.2	0.88	−0.09 (−0.63, 0.46)
Central Forefoot	15.1 ± 2.2	15.1 ± 2.2	0.27	−0.02 (−0.56, 0.53)	740.9 ± 127.3	718.2 ± c114.0	0.21	−0.18 (−0.72, 0.37)
Lateral Forefoot	14.5 ± 2.2	14.3 ± 2.1	0.08	−0.11 (−0.65, 0.44)	774.1 ± 134.7	744.9 ± 111.9	0.06	−0.22 (−0.76, 0.33)
Great Toe	11.0 ± 1.9	11.1 ± 1.8	0.03	0.05 (−0.50, 0.59)	733.7 ± 118.2	747.8 ± 122.6	0.53	0.12 (−0.42, 0.66)
Lesser Toes	18.7 ± 3.2	18.9 ± 3.0	0.31	0.04 (−0.50, 0.59)	734.8 ± 139.4	722.6 ± 123.6	0.81	−0.09 (−0.63, 0.46)

Abbreviations: ExFB = external feedback via laser; LL = lower limit of 95% confidence interval; MD = mean difference; SD = standard deviation; UL = upper limit of 95% confidence interval; negative effect size represents smaller contact area or contact time during the ExFB condition.

condition at the lateral heel (P = 0.029) and lateral midfoot (P = 0.018), while the great toe region displayed an increase (P = 0.001; Table 3). Both the lateral heel (moderate effect size) and great toe (large effect size) were associated with 95% CIs that did not cross 0.

3.5. Center of pressure

The ExFB condition significantly shifted the COP gait line medially during the first 80% of the stance phase (P < 0.002; Fig. 3). Phases 60–80% of the stance phase had moderate effect sizes with 95% CIs that did not cross 0.

4. Discussion

Real-time external visual feedback via a novel laser device reduced peak pressure on the lateral midfoot and lateral forefoot, which corresponded with an increase in peak pressure at the great toe. Furthermore, during the ExFB condition, the lateral heel had a decrease in pressure-time integral, while the great toe displayed an increase in pressure-time integral. These results indicate that participants demonstrated a lateral to medial shift in plantar pressure, which supports our original hypothesis. Although other significant changes (P ≤ 0.05) were observed, these differences were associated with trivial to small effect sizes with 95% CIs that crossed 0, implying limited clinical relevancy. The percent change observed in the current investigation exceeded those minimum detectable changes previously established. [27] Along with plantar pressure changes, we observed a medial shift in COP gait lines during the ExFB trial between 1.42 and 2.65 mm during the first 80% of the stance phase, with phases 60–80% being associated with moderate effect sizes with 95% CIs that did not cross 0. This measured difference in distance represents roughly 9–16.75% of the range within COP gait line. An individual's COP gait line only has the ability to shift a distance relative to the width of their foot. Therefore, a 16.5% change in COP would be considered a difference that is not typical of normal gait variation and a potentially meaningful clinical change. In addition, the greatest area of shift within this study corresponds to the region of the foot with the greatest differences in COP gait lines when comparing individuals with CAI to a healthy population. [7]

To the author's knowledge, this is the first paper to demonstrate and provide a method to implement external visual feedback in participants with CAI to improve plantar pressure measures during gait. Evidence suggests using an external focus of attention achieves greater motor learning than internal focus of attention which may constrain the natural motor learning process. [28] Furthermore, literature advocates that external feedback is more beneficial than utilizing an internal feedback strategy due to its ability to produce longer lasting improvements in motor function, [19] although this has yet to be established in individuals with CAI. When a skill was learned through external feedback there were greater retention and transfer skills while allowing automaticity of the motor skill. [28] When considering manipulating an automated skill such as walking, it seems the best strategy to employ is the use of external feedback which is supported the by results of the current study. The medial shift in plantar pressure and COP measures

Table 3
Peak pressure measured in kilopascals (kPa), pressure time integral measured in kilopascals times seconds (kPa*s), and the nine regions of the foot during treadmill walking during baseline and external visual feedback conditions.

Region of the foot	Peak Pressure Mean ± SD		Peak Pressure Paired T-Test	Peak Pressure Effect Size (LL, UL)	Pressure Time Integral Mean ± SD		Pressure Time Integral Paired T-Test	Pressure Time Integral Effect Size (LL, UL)
	Baseline	ExFB	P-Value	ExFB - Baseline	Baseline	ExFB	P-Value	ExFB - Baseline
Medial Heel	166.2 ± 39.1	164.1 ± 46.7	0.43	−0.05 (−0.60, 0.49)	56.8 ± 12.7	50.2 ± 13.5	0.07	−0.52 (−1.08, 0.03)
Lateral Heel	155.0 ± 26.4	149.9 ± 35.7	0.87	−0.19 (0.74, 0.35)	55.2 ± 13.1	47.8 ± 14.0	0.03*	−0.57 (−1.12, -0.01)
Medial Midfoot	112.3 ± 21.9	107.6 ± 18.7	0.79	−0.21 (−0.76, 0.33)	51.8 ± 12.3	49.2 ± 13.1	0.60	−0.21 (−0.75, 0.34)
Lateral Midfoot	117.3 ± 18.7	106.5 ± 19.1	0.004*	−0.58 (−1.13, −0.02)	61.5 ± 13.6	54.7 ± 14.7	0.02	−0.50 (−1.06, 0.05)
Medial Forefoot	187.3 ± 50.7	174.2 ± 45.5	0.07	−0.26 (−0.80, 0.29)	63.8 ± 17.6	66.0 ± 21.2	0.40	0.13 (−0.66, 0.43)
Central Forefoot	188.0 ± 40.7	169.4 ± 41.9	0.001	−0.46 (−1.01, 0.09)	63.1 ± 13.5	63.2 ± 18.3	0.65	0.01 (−0.54, 0.55)
Lateral Forefoot	161.7 ± 31.2	142.6 ± 37.7	0.002*	−0.61 (−1.17, −0.05)	59.0 ± 14.2	55.6 ± 17.5	0.12	−0.24 (−0.78, 0.31)
Great Toe	217.1 ± 45.1	256.3 ± 70.4	0.001*	0.87 (0.30, 1.44)	70.5 ± 17.7	89.1 ± 35.1	0.001*	1.05 (0.47, 1.63)
Lesser Toes	179.5 ± 43.5	174.0 ± 38.9	0.65	−0.13 (−0.67, 0.42)	58.4 ± 14.1	62.8 ± 19.1	0.12	0.32 (−0.23, 0.86)

Abbreviations: ExFB = external feedback via laser; LL = lower limit of 95% confidence interval; MD = mean difference; SD = standard deviation; UL = upper limit of 95% confidence interval.
*Indicates statistically significant difference between conditions (P ≤ 0.05) and moderate to large effect size with 95% confidence interval that does not cross 0; negative effect size represents a decrease in peak plantar pressure or pressure time integral during the ExFB condition.

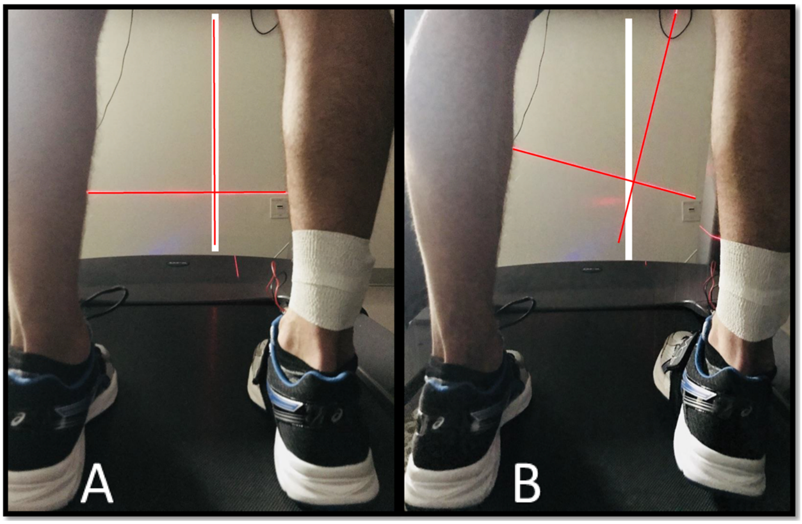

Fig. 3. Center of pressure during 10% intervals of stance phase with associated effect sizes and mean differences between baseline and external visual feedback condition.
Abbreviations: ESeffect size; ExFBexternal feedback vie laser; MDmean difference; mmmillimeters; * indicates statistically significant difference between conditions (P ≤ 0.05) and moderate to large effect size with 95% confidence interval that does not cross 0; Negative effect size represents a decrease in peak plantar pressure during the ExFB condition.

achieved in this study are consistent with previous suggestions to reduce laterally situated COP during walking which has prospectively been established as a risk factor for inversion ankle sprains. [29]

Despite being a risk factor, most ankle sprains do not occur during walking, which may be due to the established relationship between walking and other functional movements that are associated with higher rates of ankle sprains such as jumping. [14] With this in mind, typical rehabilitation programs begin with simple tasks and progress into more dynamic tasks, therefore incorporating walking gait re-training early in a rehabilitation program is important to restore simple function before introducing more complex movements. Indicating the potential for improvements of walking gait in the early phases of rehabilitation translating into better mechanics during more functional tasks incorporated later in rehabilitation. This is further supported considering real-time external visual feedback is more beneficial during early phases of task learning [14,30]. Therefore, it is our recommendation, based on the results of this study and evidence from motor learning strategies [24], to incorporate this novel laser device to deliver feedback during walking gait in the early phases of rehabilitation.

The moderate changes in plantar pressure measures over the lateral column and increased pressure at the great toe observed in the current study are in agreement with previous studies attempting to alter gait in patients with CAI. [15,16] In comparison to these studies, our baseline plantar pressure values were typically larger and our feedback changes smaller. Yet it is unknown if moderate-incremental or immediately-large changes will produce greater long-term benefits or prolonged gait alterations in patients with CAI. Furthermore, any disadvantageous kinematic modifications that may occur as a result of introducing a gait re-training protocol or possibility of overcorrection occurring have yet to be identified. In order to establish the appropriate dose of gait modification that will produce the greatest long-term patient benefit and retention, we must incorporate this external focus of attention device into an impairment-based intervention program to fully understand its potential to produce clinically-beneficial gait modifications. In addition, further investigation is warranted to determine which mode of external feedback (visual vs auditory), or a multimodal feedback approach (inclusion of a combination of haptic, auditory and visual) [24], is most appropriate for patients with CAI. Perhaps a combination of the two modes of external focus of feedback would provide the greatest and longest lasting changes.

4.1. Limitations

A limitation of the current investigation is we chose to make comparisons from the single involved limb only; thus, no conclusions can be made into what modifications, if any, occurred in the uninvolved limb during the ExFB condition. We chose to not include the contralateral limb within our analysis as our primary purpose was to first establish whether external focus feedback via laser is capable of modifying gait patterns in participants with CAI. Although this laser device can effectively alter gait in individuals with CAI, no conclusions can be drawn on the long-term effectiveness of this device.

5. Conclusion

The novel laser device used in our study was able to medially shift COP and reduce lateral plantar pressure while increasing great toe pressures in real-time. Incorporating gait retraining using an external visual feedback device into an impairment-based rehabilitation program may allow for a greater improvement in deficiencies associated with CAI. This is the first study to demonstrate that gait parameters can be positively modified using an external focus of attention visual feedback device in participants with CAI.

Conflict of interest

The authors have no conflict of interest to declare in relation to this article.

Ethical statement

This research was approved by the Institutional Review Board (#17-0077) at the University of North Carolina at Charlotte and all participants provided informed consent prior to any information being obtained.

Credit author statement

Danielle Torp: Validation, Formal Analysis, Investigation, Resources, Data Curation, Writing – Original Draft, Visualization. **Abbey Thomas:** Conceptualization, Methodology, Writing – Review and Editing. **Luke Donovan:** Conceptualization, Methodology, Writing – Review and Editing, Supervision, Project Administration, Funding Acquisition.

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