Received: 5 June 2020 | Revised: 17 August 2020 | Accepted: 3 September 2020

DOI: 10.1111/sms.13823

ORIGINAL ARTICLE

WILEY

Gait biofeedback and impairment-based rehabilitation for chronic ankle instability

Rachel M. Koldenhoven[1,2] | **Abbis H. Jaffri**[3] | **Alexandra F. DeJong**[2] | **Mark Abel**[4] | **Joseph Hart**[2] | **Susan Saliba**[2] | **Jay Hertel**[2,4]

[1]Department of Health and Human Performance, Texas State University, San Marcos, TX, USA

[2]Department of Kinesiology, University of Virginia, Charlottesville, VA, USA

[3]Department of Physical Therapy, Creighton University, Omaha, NE, USA

[4]Department of Orthopedic Surgery, University of Virginia, Charlottesville, VA, USA

Correspondence
Rachel M.Koldenhoven, Texas State University, Jowers Center, 601 University Drive, San Marcos, TX 78666, USA.
Email: rmr214@txstate.edu

Funding information
National Athletic Trainers' Association; University of Virginia Curry School of Education; Mid Atlantic Athletic Trainers' Association

Our purpose was to analyze the effects of 4 weeks of visual gait biofeedback (GBF) and impairment-based rehabilitation on gait biomechanics and patient-reported outcomes (PROs) in individuals with chronic ankle instability (CAI). Twenty-seven individuals with CAI participated in this randomized controlled trial (14 received no biofeedback (NBF), 13 received GBF). Both groups received 8 sessions of impairment-based rehabilitation. The GBF group received visual biofeedback to reduce ankle frontal plane angle at initial contact (IC) during treadmill walking. The NBF group walked for equal time during rehabilitation but without biofeedback. Dependent variables included three-dimensional kinematics and kinetics at the ankle, knee, and hip, electromyography amplitudes of 4 lower extremity muscles (tibialis anterior, fibularis longus, medial gastrocnemius, and gluteus medius), and PROs (Foot and Ankle Ability Measure Activities of Daily Living (FAAM-ADL), FAAM-Sport, Tampa Scale of Kinesiophobia (TSK), and Global Rating of Change (GROC)). The GBF group significantly decreased ankle inversion at IC (MD:-7.3°, $g = 1.6$) and throughout the entire stride cycle (peak inversion: MD:-5.9°, $g = 1.2$). The NBF group did not have significantly altered gait biomechanics. The groups were significantly different after rehabilitation for the FAAM-ADL (GBF: 97.1 ± 2.3%, NBF: 92.0 ± 5.7%), TSK (GBF: 29.7 ± 3.7, NBF: 34.9 ± 5.8), and GROC (GBF: 5.5 ± 1.0, NBF:3.9 ± 2.0) with the GBF group showing greater improvements than the NBF group. There were no significant differences between groups for kinetics or electromyography measures. The GBF group successfully decreased ankle inversion angle and had greater improvements in PROs after intervention compared to the NBF group. Impairment-based rehabilitation combined with visual biofeedback during gait training is recommended for individuals with CAI.

KEYWORDS
ankle sprain, electromyography, gait training, kinematics, kinetics

Trial registration number: NCT03507803

1 | INTRODUCTION

Following an initial lateral ankle sprain, 40% of individuals develop chronic ankle instability (CAI)[1] which involves feelings of instability, decreased self-reported function, and recurrent sprains.[2] Several deficits associated with CAI include diminished range of motion (ROM), postural control, and strength.[3] Rehabilitation protocols for intervention studies have typically focused on a single treatment domain such as balance, ROM, or strength and appear to improve the outcomes in that treatment domain specifically.[4-6] Impairment-based rehabilitation targets individualized patient deficits and has previously shown to improve a variety of patient-oriented and clinically oriented outcomes associated with CAI.[7,8]

Individuals with CAI have demonstrated a more inverted ankle position during walking compared to ankle sprain copers (4-6°)[9] and healthy controls (6-7°).[10] When the ankle is inverted during the swing phase just prior to initial contact (IC), it may be susceptible to incurring an inversion ankle injury. Video capture of lateral ankle sprains occurring in athletes has identified that excessive ankle inversion and internal rotation were consistent mechanisms of injury for lateral ankle sprains.[11,12] Gait deficits have been targeted with strength or balance training but such interventions have not successfully corrected the impaired frontal plane kinematics.[13] Davis and Futrell[14] suggested that strength training without neuromuscular reeducation rarely translates to changes in movement patterns. Therefore, targeted gait training strategies may be necessary to change gait mechanics.

Only two published studies have used biofeedback as a gait training method to address deficits associated with CAI.[15,16] Donovan et al[15] instructed participants to walk in a way that would not trigger an audible cue when lateral plantar pressure forces became too high. Torp et al[16] provided visual biofeedback using a shoe-mounted laser and instructed participants to keep the projection in a vertical position. When participants received biofeedback, pressure on the lateral aspect of the foot decreased[15,16] demonstrating that individuals with CAI can alter their gait mechanics while biofeedback is present. It is unknown how gait training may improve gait mechanics after several training sessions or when the biofeedback has been removed for individuals with CAI. Reducing ankle inversion during walking could potentially lower the risk of subsequent lateral ankle sprains for individuals with CAI. Adding gait training to an impairment-based rehabilitation program may further improve the patient's overall condition.

The purpose of this study was to analyze the effects of 4-weeks of a visual biofeedback intervention and impairment-based rehabilitation on gait biomechanics, clinically oriented measures, and patient-reported outcomes (PROs) between gait biofeedback (GBF) and no biofeedback (NBF) groups. We hypothesized that the GBF group would have a reduced ankle inversion angle at IC that would also translate to a less inverted position throughout the remainder of the stride cycle and that the NBF group would not change their gait kinematics from baseline to follow-up time points. Additionally, we hypothesized that the groups would have meaningful changes in patient-reported and clinically oriented outcome measures as measured by minimally important changes.

2 | MATERIALS AND METHODS

2.1 | Participants

Twenty-seven individuals with CAI completed this single-blinded randomized controlled trial (Figure 1). Inclusion criteria followed guidelines provided by the International Ankle Consortium.[2] All participants had history of significant lateral ankle sprain at least 12-months prior to study participation, self-reported dysfunction (Foot and Ankle Ability Measure (FAAM) Sport ≤ 85%), and feelings of perceived instability (Identification of Functional Ankle Instability (IdFAI) >10) (Table 1).

Exclusion criteria included any history of lower extremity fracture or surgery, ankle sprain within past 6-weeks, any conditions known to affect gait, pregnancy, and currently participating in rehabilitation. This study was approved by the university's Institutional Review Board and all participants provided written informed consent prior to participation.

2.2 | Instrumentation

Three-dimensional kinematics were collected using 12 motion capture cameras (VICON motion systems) at 250Hz. An instrumented treadmill (Bertec™) collected kinetic data at 1000Hz. Wireless sEMG sensors (Delsys) collected at 2000Hz and a 10-500Hz bandpass filter and 50-sample average moving window were applied. Data were synchronized using The MotionMonitor™ software (Innovative Sports Training, Inc). A custom program (WorldViz) integrated real-time kinematic data to generate the visual biofeedback for the GBF group. Participants wore standardized laboratory shoes for all gait assessments (Brooks Defyance; Brooks Sports, Inc).

Strength was assessed using a handheld dynamometer (MicroFET2, Hoggan Scientific). Static balance was assessed using a pressure mat (MatScan™ Pressure Mat, Tekscan Inc) sampling at 50 Hz.

2.3 | Procedures

Participants completed the following questionnaires prior to participation to provide an assessment of how our

FIGURE 1 Consort flowchart

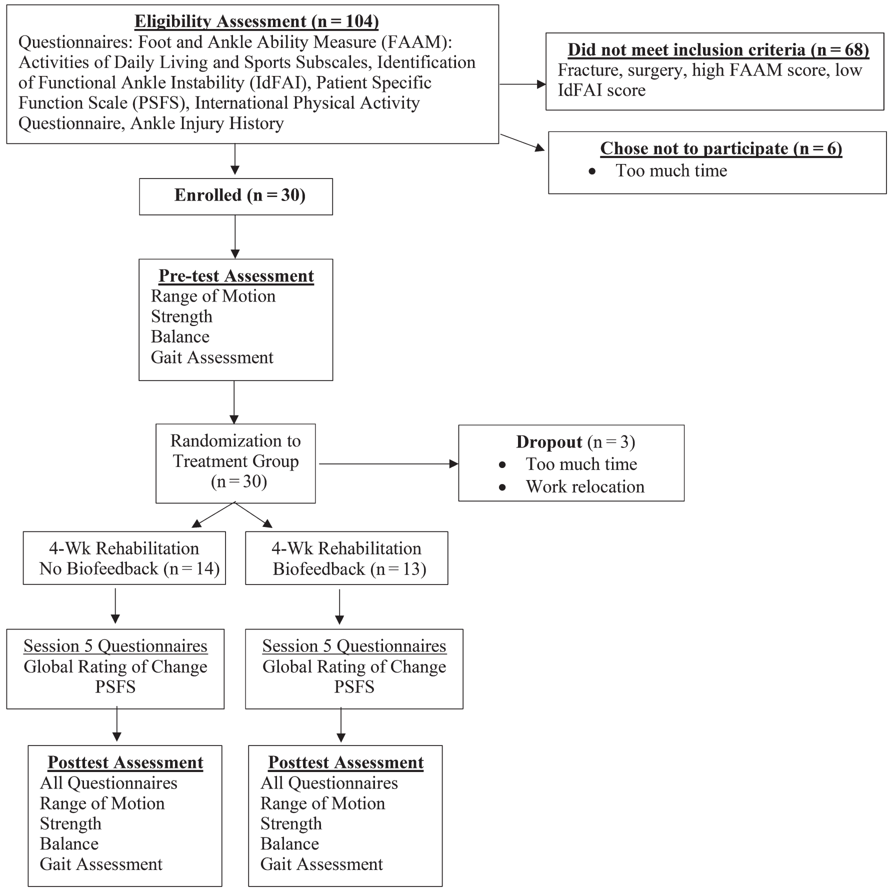

TABLE 1 Patient demographics for the no biofeedback and biofeedback groups (mean ± SD)

	No Biofeedback (n = 14)	Biofeedback (n = 13)
Sex (Male:Female)	5:9	3:10
Age (years)	21.5 ± 3.0	22.23 ± 3.8
Height (cm)	174.0 ± 10.7	167 ± 8.8
Mass (kg)	72.1 ± 13.9	69.2 ± 14.7
Total number of ankle sprains	4.6 ± 3.7	4.1 ± 2.0
Time since first sprain (months)	89.7 ± 53.8	98.8 ± 51.2
Time since last sprain (months)	15.0 ± 30.6	12.0 ± 8.9

participant's perceived their ankle function and physical activity: FAAM Activities of Daily Living (ADL),[17] FAAM-Sport Scale,[17] IdFAI,[18] Tampa Scale of Kinesiophobia (TSK),[19] International Physical Activity Questionnaire (IPAQ),[20] and the Patient Specific Functional Scale (PSFS) (Figure 1).[21] The Global Rating of Change (GROC)[22] and PSFS questionnaires were administered at the half-way (beginning of session 5/8) and post-rehabilitation time points (at follow-up visit) to provide an assessment of how our participant's perceived improvements or lack of improvements in ankle function during and after rehabilitation.

2.4 | Baseline & follow-up assessment

All assessments were performed by the clinicians that were blinded to the treatment condition. Our gait assessment procedures have been previously published.[9] Briefly, reflective markers were placed on the lower extremities and segments were digitized to identify the joint centers to assess the 3-D kinematics and kinetics of the ankle, knee, and hip joints. sEMG electrodes were placed over the muscle belly of the tibialis anterior (TA), fibularis longus (FL), medial gastrocnemius (MG), and gluteus medius (GMed) on the limb with CAI and placement was verified using a manual muscle test. Data were normalized to a 5-second quiet standing trial. Participants completed 5 minutes of walking warm-up prior to collecting kinematics, kinetics, and sEMG simultaneously for 60 seconds while walking at 1.3 m/s (3.0 mph). It has been established that walking at various speed significantly changes the kinematic motions and spatiotemporal aspects of gait.[9] Therefore, it was critical that the speed be standardized for this study as we compared gait biomechanics at two time points.

Clinical assessments consisted of ROM, balance, and strength. Passive ankle ROM was assessed using a standard plastic goniometer to measure dorsiflexion, plantarflexion, rearfoot inversion, and eversion.[23] Weightbearing dorsiflexion was also measured.[23]

Participants performed 3 10-second trials of single limb balancing on a force plate with their eyes open, and again with their eyes closed. The average center of pressure area (cm^2) and velocity (cm/s) of the 3 trials were calculated. Dynamic balance was assessed using the SEBT in the anterior, posteromedial, and posterolateral directions.[24] A composite SEBT score was calculated by combining the average score for 3 trials in each direction.[8]

Isometric strength was assessed using established methods for ankle dorsiflexion, plantarflexion, inversion, eversion, 1st toe flexion, toes 2-5 flexion,[23] hip abduction, and hip extension.[25]

2.5 | Randomization

After baseline data collection, participants were randomly assigned to treatment groups (GBF or NBF) using a random-number generator by an investigator not involved in participant screening, outcome measurements, or intervention administration (JH). Group assignments were placed in sealed envelopes to conceal allocations. The supervising clinicians (AFD, AHJ) for the impairment-based rehabilitation were blinded to group status. Participants were not blinded to group assignment, but were instructed not to discuss group allocation with the rehabilitation clinician.

Participants began supervised impairment-based rehabilitation sessions within 1-week of the baseline assessment. Follow-up assessments occurred 24-72 hours after completion of the last rehabilitation session.

2.6 | Impairment-based rehabilitation

Participants in the GBF and NBF groups performed 4-weeks of impairment-based rehabilitation (8 sessions) modified from Donovan et al[8] (Supplemental 1). Rehabilitation sessions lasted approximately 1 hour. All participants walked on the treadmill for the same amount of time at the end of the rehabilitation session regardless of group allocation.

2.7 | Visual biofeedback

The goal of the GBF intervention was to reduce ankle inversion at IC (Figure 2, Supplemental 2). The ankle inversion angle at IC was projected as an oval onto a screen directly in front of the treadmill and a maximum inversion threshold was progressively decreased each session. The threshold for ankle inversion angle at IC was set to reduce inversion by 20% for the first session. If participants did not exceed the threshold for 10 consecutive strides and confirmed that this walking pattern was not difficult, the threshold was increased for the next session. The

FIGURE 2 Participant setup for the GBF sessions

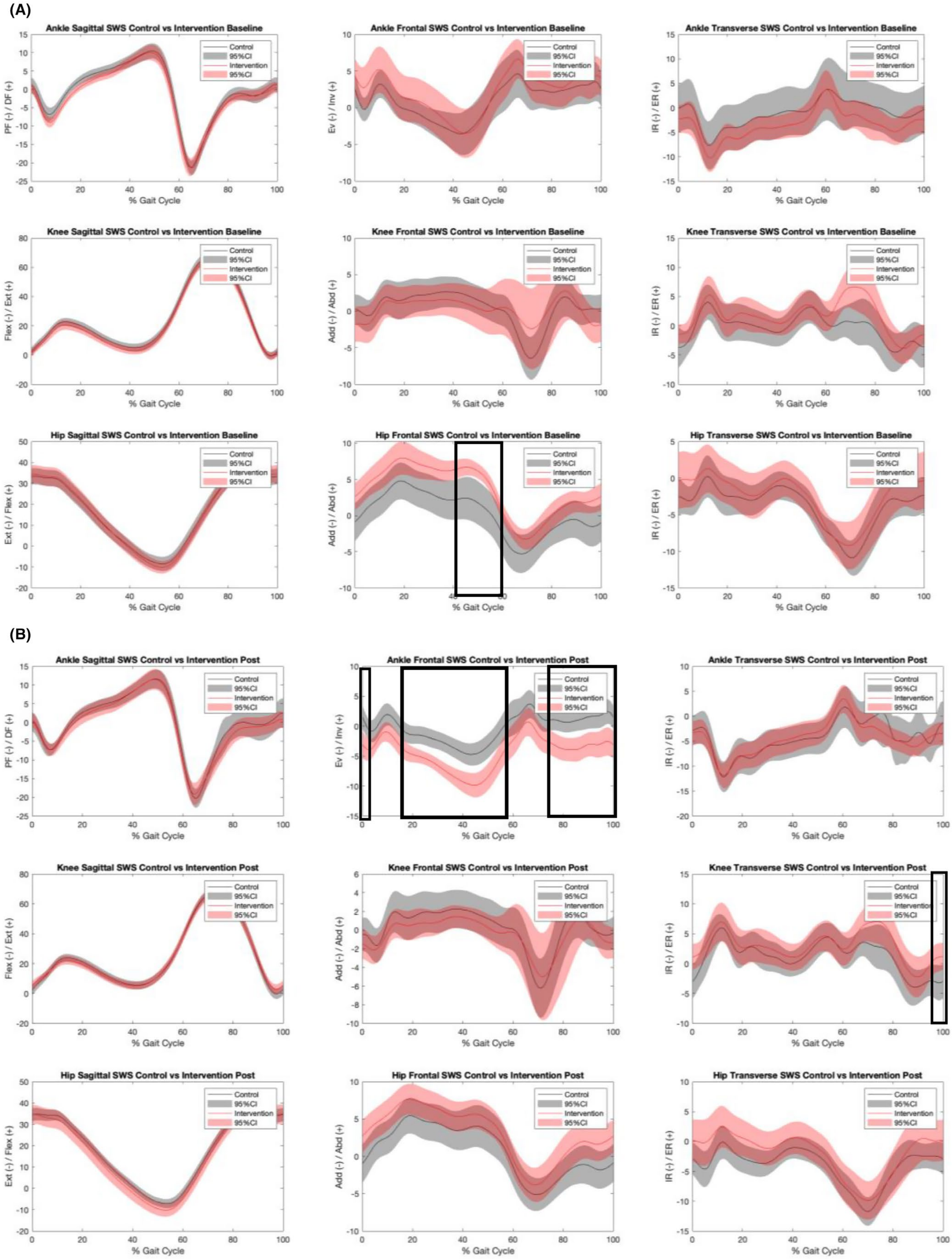

FIGURE 3 Kinematics for the GBF and NBF at baseline (A) and follow-up (B). Boxes indicate significant differences between the groups

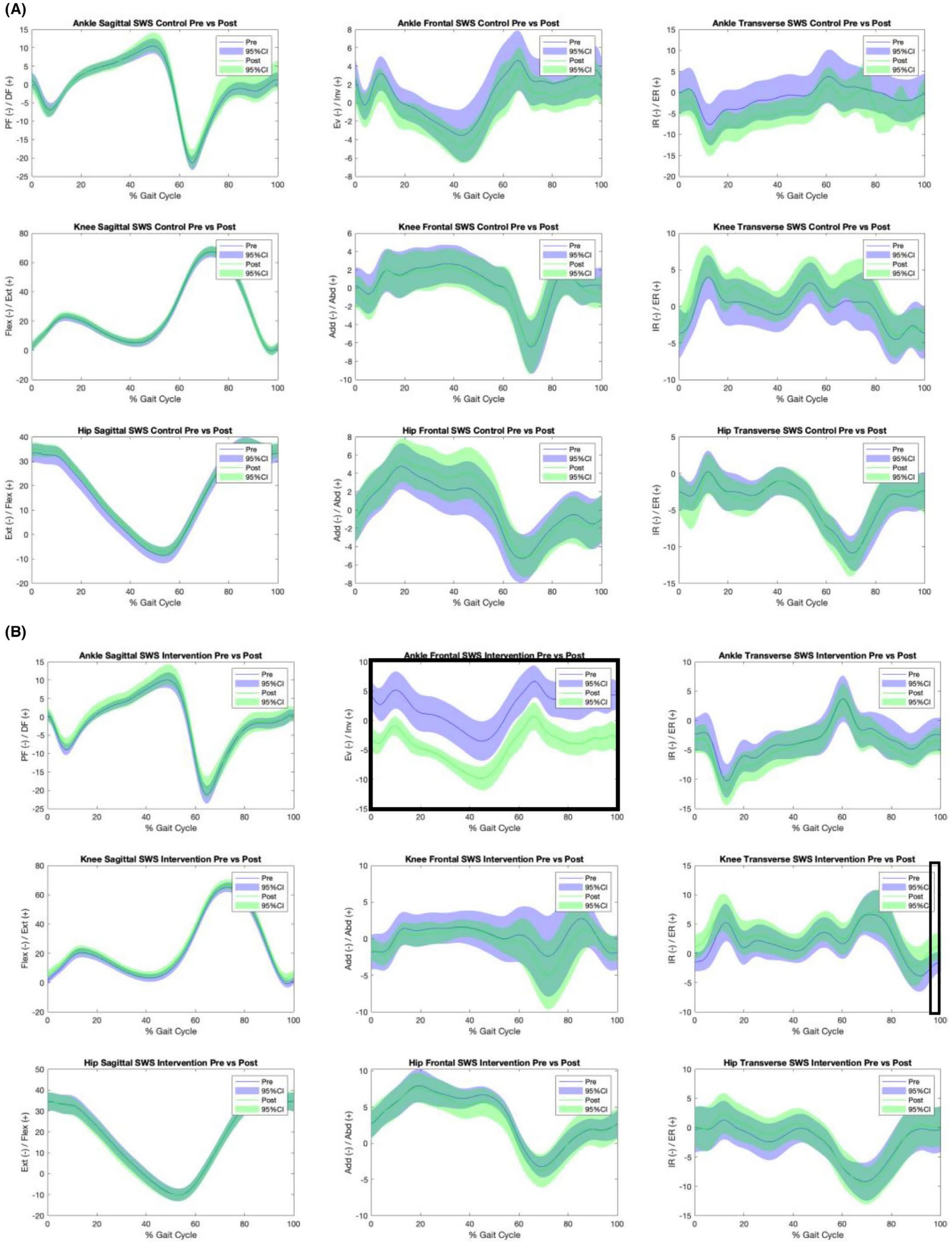

FIGURE 4 Kinematics for the NBF (A) and GBF groups (B) for the baseline and follow-up comparisons. Boxes indicate significant differences between baseline and follow-up

goal was to decrease the ankle inversion angle by up to 100% which would reflect a neutral foot position at IC. During the initial session, participants were instructed to avoid walking on the outside of their foot so as not to exceed the inversion threshold which was indicated when the biofeedback oval turned red. The biofeedback schedule was adapted from Noehren et al.[26] Participants received biofeedback for the entire walking exercise during the first 4 sessions for 8, 12, 16, and 20 minutes. Then biofeedback was decreased by 4 minutes per session of the 4 subsequent 20-minute walking sessions (supplemental 2). The maximum walking time was 20 minutes. All gait training sessions were supervised by one investigator (RMK) who was not involved in administering the rehabilitation protocol.

2.8 | Data processing

Ten consecutive strides from each walking trial were analyzed and reduced to 101 data points representing 0%-100% of the gait cycle.[9] sEMG data were normalized to quiet standing for each muscle.[9] All data processing was performed using Matlab version R2018a (MathWorks, Inc).

2.9 | Statistical analysis

The sample size estimate revealed that 13 participants per group were needed to identify large effects based on a between-group mean difference of 6.6º of inversion and standard deviation of 4.6º at IC during walking between control and CAI participants.[9]

Descriptive statistics were calculated for group demographics using Statistical Package for Social Sciences (SPSS) version 24.0 (SPSS, Inc). The gait measures were assessed using the spm1d Version 0.4 for one-dimensional statistical parametric mapping (SPM) package for Matlab.[9,27] A 2 × 2 group by time SPM repeated measures analysis of variance and post-hoc SPM t-tests were used to compare gait biomechanics between the GBF and NBF groups. The a priori level of significance was set at $P \leq .05$.

PROs, strength, balance, and ROM outcome measures at post-rehabilitation were analyzed using separate analyses of covariance with the baseline scores as the model covariate. Hedge's *g* effect sizes were calculated to determine the magnitude of difference. The effect sizes were interpreted as large (≥0.80), moderate (0.50-0.79), small (0.20-0.49), or trivial (≤0.19).[28]

Odds ratios (OR) were calculated between the groups for the change in ankle angle at IC and for PROs to determine the likelihood of incurring a good outcome. The upper limit of the 95% confidence interval for the coper group from our prior study[9] was determined to be a "desired" outcome for ankle angle at IC for the OR calculation. A score of >3 on the GROC, >8% increase on the FAAM-ADL,[17] >9% increase on the FAAM-Sport,[17] and >6-point decrease on TSK[29] was used as the "desired" outcome for the OR calculation for the PROs.

3 | RESULTS

There were no significant differences between the groups for patient demographics at baseline (Table 1). Three participants dropped out of the study. Two participants indicated that the study took too much time and 1 participant was relocated for work and could no longer travel to the study visits. The dropout participants were not included in any analyses.

TABLE 2 Patient-reported outcomes for the no biofeedback and biofeedback groups (mean ± SD) and Hedges *g* effect sizes with 95% confidence intervals

Variable	No Biofeedback Group: Pre-rehabilitation	No Biofeedback Group: Post-rehabilitation	Biofeedback Group: Pre-rehabilitation	Biofeedback Group: Post-rehabilitation	Group Main Effect *P* Value	Between Groups Hedges *g* Effect Size
FAAM-ADL (%)	85.6 (8.9)	92.0 (5.6)	89.8 (7.8)	97.1 (2.3)	**.016**	1.00
FAAM-Sport (%)	64.3 (15.0)	80.1 (11.9)	70.3 (16.0)	86.3 (8.4)	.170	0.53
IdFAI	21.8 (3.3)	20.9 (3.5)	21.8 (4.5)	19.2 (4.5)	.252	0.45
TSK	35.4 (5.8)	34.9 (5.7)	33.1 (5.1)	29.7 (3.7)	**.016**	1.00
IPAQ (MET)	4735.6 (1946.9)	4846.1 (1972.8)	5223.5 (3774.5)	5035.3 (2248.3)	.788	0.05
GROC Mid-Rehab	–	2.3 (2.0)	–	3.5 (1.2)	.076	0.69
GROC Post-Rehab	–	3.9 (2.0)	–	5.5 (1.1)	**.022**	0.92
PSFS Total Score	6.2 (0.9)	8.0 (1.3)	5.1 (1.8)	8.0 (1.2)	.644	0.19

Abbreviations: Foot and Ankle Ability Measure (FAAM), Activities of Daily Living (ADL), Identification of Functional Ankle Instability (IdFAI), Tampa Scale of Kinesiophobia (TSK), International Physical Activity Questionnaire (IPAQ), Minutes per week (MET), Global Rating of Change (GROC), Patient Specific Functional Scale (PSFS).

Bold indicates statistically significant difference between the groups.

TABLE 3 Results for strength, ROM, and balance for the no biofeedback and biofeedback groups (means ± SD) and between group Hedges *g* effect sizes.

Variable	No Biofeedback Group			Biofeedback Group			Group Main Effect	Between Group
	Pre-rehabilitation	Post-rehabilitation	% change at follow-up (95% CI)	Pre-rehabilitation	Post-rehabilitation	% change at follow-up (95% CI)	*P* Value	Hedges *g* Effect Size
Strength (N/kg)								
1st Toe Flexion	1.2 ± 0.3	1.8 ± 0.4	50.0 (23.7, 76.3)†	1.1 ± 0.3	2.1 ± 0.3	90.9 (59.0, 122.9)†	**0.025**	0.87
2-5 Toe Flexion	1.3 ± 0.3	1.7 ± 0.4	30.8 (8.2, 53.3)†	1.2 ± 0.4	2.0 ± 0.4	66.7 (31.4, 101.9)†	0.071	0.72
Dorsiflexion	3.6 ± 0.6	3.8 ± 0.6	5.6 (−7.1, 18.2)	2.9 ± 0.9	3.6 ± 0.4	24.1 (1.9, 46.4)†	0.112	0.37
Plantarflexion	6.5 ± 1.4	7.8 ± 1.4	20.0 (2.4, 37.6)†	6.6 ± 1.6	8.5 ± 1.1	28.8 (9.5, 48.0)†	0.169	0.55
Inversion	2.6 ± 0.4	3.1 ± 0.5	19.2 (5.3, 33.2)†	2.3 ± 0.6	3.4 ± 0.7	47.8 (21.1, 74.5)†	**0.049**	0.68
Eversion	2.5 ± 0.5	3.9 ± 3.0	56.0 (−8.9, 120.9)	2.0 ± 0.7	3.3 ± 0.5	65.0 (30.8, 99.2)†	0.716	0.13
Hip Abduction	2.3 ± 0.5	2.5 ± 0.5	8.7 (−8.1, 25.5)	1.9 ± 0.5	2.7 ± 0.5	42.1 (17.2, 67.0)†	**0.047**	0.86
Hip Extension	3.8 ± 0.7	4.0 ± 0.8	5.3 (−9.7, 20.3)	3.7 ± 0.8	4.2 ± 0.7	13.5 (−3.3, 30.4)	0.419	0.32
ROM								
Weightbearing Dorsiflexion (cm)	11.7 ± 3.1	13.9 ± 3.7	18.8 (−4.5, 42.2)	10.6 ± 3.9	12.7 ± 4.2	19.8 (−12.4, 52.0)	0.961	0.02
Dorsiflexion (°)	7.8 ± 8.2	11.6 ± 7.2	48.7 (−46.2, 143.8)	8.7 ± 9.9	13.8 ± 12.0	58.6 (−64.9, 182.1)	0.516	0.24
Plantarflexion (°)	72.3 ± 7.8	72.3 ± 10.0	0.0 (−9.2, 9.2)	74.1 ± 6.9	81.4 ± 5.7	9.8 (2.9, 16.8)†	**0.003**	0.92
Inversion (°)	31.6 ± 9.7	34.4 ± 9.9	8.9 (−15.1, 32.9)	34.7 ± 13.3	31.0 ± 11.3	-10.7 (−36.4, 15.0)	0.341	0.36
Eversion (°)	14.0 ± 8.4	13.0 ± 3.9	-7.1 (−39.8, 25.5)	9.6 ± 5.9	13.7 ± 8.3	42.7 (−24.2, 109.7)	0.616	0.19
Balance								
Static Balance								
Eyes Open								
Area (cm^2)	4.0 ± 2.1	3.8 ± 2.7	-5.0 (−48.9, 38.9)	4.6 ± 3.9	3.4 ± 1.3	-26.1 (−63.5, 11.3)	0.606	0.23
Velocity (cm/s)	3.3 ± 1.0	3.1 ± 1.2	-6.1 (−30.25, 18.1)	3.2 ± 1.2	2.6 ± 0.6	-18.5 (−38.2, 0.7)	0.208	0.54
Eyes Closed								
Area (cm^2)	17.6 ± 6.9	13.0 ± 4.7	-26.1 (−46.8, −5.5)†	20.4 ± 9.7	12.9 ± 7.1	-36.8 (−61.8, −11.8)†	0.606	0.19
Velocity (cm/s)	8.7 ± 2.2	6.9 ± 1.7	-20.7 (−35.4, −6.0)†	8.5 ± 2.9	6.6 ± 2.1	-22.4 (−42.0, −2.7)†	0.690	0.20
Dynamic Balance								
SEBT Composite Score (%)	71.7 ± 8.2	79.2 ± 5.6	7.5 (−0.3, 15.3)	72.6 ± 7.6	77.8 ± 5.5	5.2 (−2.2, 12.6)	0.292	0.41

Note: Positive effect sizes indicate greater improvements in the biofeedback group. Positive percent change indicates an increase, and negative percent change indicates a decrease. † indicates 95% confidence interval does not cross zero.

Bold indicates statistically significant difference between the groups.

3.1 | Gait

A significant time main effect was identified for ankle frontal plane motion ($P < .001$) and a group-by-time interaction was identified for knee transverse plane motion ($P = .039$). The groups were not significantly different at baseline for any variables (Figure 3). At the follow-up time point, the GBF group reduced their ankle inversion ankle at IC (pre: 4.2 ± 4.6º, post: −3.1 ± 4.1º, $g = 1.6$) and throughout the entire stride cycle (peak inversion ankle: pre: 6.7 ± 5.0º, post: 0.8 ± 4.3º, $g = 1.2$) (Figure 4). The GBF group was substantially more likely to have an improvement in ankle angle at IC at the conclusion of the 4-week intervention compared to the NBF group (OR = 6.0, 95% CI:1.11, 32.55; $P = .038$).

For knee transverse plane, the groups were not different at baseline, but at follow-up the GBF group demonstrated an externally rotated knee compared to an internally rotated knee at baseline during terminal swing (Peak transverse plane motion: pre: −2.0 ± 4.3º, post: 1.2 ± 4.2º, $g = 0.7$). There were no significant differences for any other kinematic or any kinetic or sEMG measures.

3.2 | PROs

The GBF had greater improvements following rehabilitation for FAAM-ADL, TSK, and GROC than the NBF group (Table 2).

Individuals in the GBF group were substantially more likely to report a score of 4 (moderately better) or higher on the GROC than were members of the NBF group (OR = 12.0, 95% CI: 1.21-118.9; $P = .034$) at the conclusion of 4-week intervention (Table 3). Although not statistically significant, members of the GBF group trended towards being more likely to have a decrease of 6 points or more on the TSK compared to the NBF group (OR = 18.8, 95% CI: 0.92-383.1; $P = .057$) (Table 2).

3.3 | Clinically oriented measures

The GBF group had greater improvements in ankle inversion, hip abduction, and 1st toe flexion strength, and for plantarflexion ROM compared to the NBF group (Table 2).

4 | DISCUSSION

Our primary hypothesis that the visual GBF group would have reduced ankle inversion at IC and throughout the entire stride cycle at follow-up compared to their baseline measures was confirmed. The NBF group did not significantly change their gait mechanics from baseline to follow-up; however, there was a small ($g = 0.3$) shift in decreased inversion throughout the stride cycle. Additionally, both groups demonstrated improvements in patient-reported and clinically oriented outcomes; however, the improvements were not equal between the groups which does not support our original hypothesis. Most importantly, the GBF group not only had meaningful improvements in gait mechanics, they also had significantly greater improvements for several patient-reported and clinically oriented outcomes than the NBF group.

4.1 | Gait biofeedback measures

The GBF intervention in this study specifically targeted ankle inversion during walking at IC. Participants in the GBF group decreased their ankle inversion angle at IC by 7.3º, throughout the gait cycle by 6º, and were 6 times more likely to have an improvement in their ankle position at IC compared to the NBF group. Our GBF group adopted a strategy that was similar to the ankle sprain copers from our prior study.[9] Participants were instructed to reduce ankle inversion by avoiding walking on the outside of their foot in order to receive positive biofeedback as indicated by the green oval. We did not provide any additional instructions on how to accomplish this task which is potentially why we did not identify additional changes for kinematics, kinetics, or sEMG. Participants utilized their own strategies to achieve positive feedback while reducing their ankle inversion angle at IC during walking.

Hertel and Corbett[30] recently proposed an updated model for CAI. Within the updated model, the authors suggest that heterogeneous patient impairments present uniquely through constructs of self-organization, perception-action cycles derived from the dynamic systems theory, and an individualized neurosignature.[30] The dynamic systems theory proposes that complex physiological systems can be self-organized in a variety of ways to achieve a specific task.[31] Task constraints in addition to unique organismic constraints may influence the participant's behaviors and movements.[30] Our study supports that theory in that participants received targeted biofeedback and displayed a consistent pattern of reduced ankle inversion throughout the gait cycle at follow-up as demonstrated by the tighter confidence intervals on the follow-up measures. The GBF technique used in this study placed a task constraint on participants by limiting how much ankle inversion could occur during gait training sessions. This is also likely why significant changes in kinematics in areas other than in ankle inversion were not observed.

The neurosignature within the context of the new CAI model signifies an individual's neural patterns that influence their motor function as well as sensory and emotional perceptions.[30] After an ankle sprain, an individual's neurosignature is negatively impacted as a result of the injury. Hertel and Corbett[30] propose that patients who recover quickly after an acute ankle sprain (copers) are able to restore their neurosignature to their preinjury status. Individuals with CAI are likely unable to fully restore their preinjury neurosignature which may contribute to the chronicity of their condition. While we are not able to compare our participants' gait mechanics to their preinjury gait mechanics, we were able to "restore" the participants' ankle inversion during walking to the level of those who are classified as ankle sprain copers.[9]

The NBF group did not significantly alter their ankle inversion mechanics from baseline to follow-up; however, there was a small 1-2° shift towards a less inverted foot position. Similarly, other studies have demonstrated small and non-significant shifts in ankle inversion kinematics after 4-weeks of balance training[13] and impairment-based rehabilitation without specific gait training[8] in CAI patients. Without gait training specifically addressing kinematic alterations, CAI patients do not substantially change their gait mechanics. Our study demonstrates that real-time GBF coupled with comprehensive impairment-based rehabilitation leads to greater improvements in self-reported function and a restoration of frontal plane ankle kinematics during walking.

Several gait training studies have been executed for individuals with CAI, yet none were designed specifically to reduce ankle inversion kinematics.[15,16,32] The studies resulted in a medial shift in plantar pressure while receiving audio or visual feedback[15,16] and after 5 training sessions using a novel gait training device.[32] It is likely that the medial shift in plantar pressure found in each of these studies may be the result of a less inverted foot position; however, kinematics were not directly assessed.[15,16]

While we were the first to focus specifically on reducing ankle inversion kinematics, our study methods would be difficult to implement in a clinical setting due to the instrumentation used. Individuals were instructed to avoid walking on the outside of their foot at the initial training session to understand how to achieve a "good" step in our study. Clinicians could potentially implement this verbal cue as a form of feedback during walking for individuals with CAI. The shoe-mounted laser technique[16] is most similar to ours and may be easier to implement in the clinical setting than our methods; however, this method has not been assessed over several sessions of gait training.

4.2 | Patient-reported outcome measures

In addition to improved gait biomechanics, we found greater improvements in several PROs in the GBF group compared to the NBF group. For the GROC, the GBF group reported an improvement of 3.5 points (somewhat better) at the half-way time point and 5.5 points (quite a bit better) at follow-up while the NBF group only had an improvement of 2.3 points (a little bit better) at the half-way time point and 3.9 points at follow-up. The GBF group was 12 times more likely to report "moderately better" or greater improvements than the NBF group for the GROC. Therefore, the GBF group felt better earlier during rehabilitation and had better outcomes at follow-up for the GROC compared to the NBF group.

The TSK measures fear of movement and reinjury. Individuals with CAI have demonstrated increased kinesiophobia compared to healthy controls.[33] Our study demonstrated that gait training in addition to rehabilitation reduced kinesiophobia more than rehabilitation alone. Although the results were not statistically significant, the GBF group was 18.8 times more likely to have improvements in kinesiophobia than the NBF group.

For the FAAM-ADL, the GBF group showed a 9.3% increase whereas the NBF group improved by only 6.4%. We identified that the GBF group had greater improvements in FAAM-ADL scores following rehabilitation, but there was not a significant difference in the proportion of individuals who exceeded the MCID for improvement. Both groups improved by 15%-16% for the FAAM-Sport; however, only the GBF group score improved enough to exceed the cut-off score to be classified as having CAI for our inclusion criteria (≤85%) prior to study enrollment. It appears the GBF facilitated a new gait strategy that was associated with a higher likelihood of having large meaning improvements in global self-reported outcome measures (GROC, TSK), but not for the region-specific outcome measures (FAAM-ADL, FAAM-Sport).

4.3 | Clinically oriented measures

For the clinically oriented outcomes, both groups improved from the initial assessment to the follow-up assessment in most of the strength measures and for eyes-closed balance. The GBF group improved significantly more than the NBF group for 1st toe flexion, ankle inversion, and hip abduction strength measures and for plantarflexion ROM which may be a result of adapting a new gait pattern over the course of the intervention. The substantial change in ankle position during walking gait may have contributed to the additional improvements in strength in several areas. The impairment-based rehabilitation program improved many of the outcome measures in both groups; however, the addition of gait training may be beneficial for added improvements in strength.

Our study had several limitations. We initially powered the study to identify pre- to post-intervention differences for ankle inversion angle at initial contact (the primary dependent variable) and not for kinetic or sEMG measures. This increases the risk for type 2 error for our secondary analyses. Due to the inherent variability of sEMG, we would need a much larger sample of participants to be able to detect differences between the groups or between time points. Our study had primarily female participants; however, this is reflective of the higher incidence rate of ankle sprains in females compared to males.[34] Additionally, the male to female ratio in our study is similar to other studies of individuals with CAI.[8,32,33] We elected to include young physically active individuals, and our results may not be generalizable to other groups of individuals with CAI. Lastly, we do not have long-term follow-up data on biomechanical, clinical, or patient-reported outcome measures and are unable to determine if there was a reduction in recurrent ankle sprains.

5 | PERSPECTIVE

The GBF intervention was successful at decreasing ankle inversion positioning during walking and had a greater impact on patient-reported and clinically oriented outcomes compared to the NBF group. This is the first study to substantially improve ankle frontal plane kinematics through the use of visual biofeedback. Other gait training studies have shifted plantar pressure medially which may be linked to changes in kinematics; however, those studies did not measure ankle inversion angles.[15,16,32] Similar to previous research,[13] the NBF group participated in rehabilitation but did change their gait biomechanics. This suggests that rehabilitation that does not include gait biofeedback is not successful at altering gait mechanics. The GBF group also had a significant decrease in kinesiophobia in comparison with the NBF group which is clinically meaningful. Fear of movement for activities of daily living could substantially decrease an individual's overall quality of life. Therefore, we recommend that gait training using visual biofeedback to reduce the ankle inversion angle should be added to traditional rehabilitation protocols for individuals with CAI.

ACKNOWLEDGMENTS

This study was funded in part by the University of Virginia's Curry School of Education Foundation, the Mid-Atlantic Athletic Trainers' Association District III Research Grant, and the National Athletic Trainers' Association Research and Education Foundation. The authors would also like to thank Andrea Baellow, MEd, ATC for her contributions to the rehabilitation program; Emily Dooley, MS for her assistance with data processing; Madison Howell for her contributions to data collection; and Marshall Tumperi for his assistance with statistical analysis.

CONFLICT OF INTEREST

There are no conflicts of interest to declare. This work was performed in partial fulfillment of the requirement for the doctor of philosophy degree and is archived in the Online Archive of University of Virginia Scholarship (https://doi.org/10.18130/v3-zv0r- mj47).

ORCID

Rachel M. Koldenhoven https://orcid.org/0000-0002-2569-9052
Abbis H. Jaffri https://orcid.org/0000-0003-4134-8540
Alexandra F. DeJong https://orcid.org/0000-0002-5702-9184
Mark Abel https://orcid.org/0000-0001-7869-2172
Joseph Hart https://orcid.org/0000-0002-0410-5112
Susan Saliba https://orcid.org/0000-0001-7179-8310
Jay Hertel https://orcid.org/0000-0003-0680-6534

REFERENCES

1. Doherty C, Bleakley C, Hertel J, Caulfield B, Ryan J, Delahunt E. Recovery from a first-time lateral ankle sprain and the predictors of chronic ankle instability a prospective cohort analysis. *Am J Sports Med*. 2016;44(4):995-1003.
2. Gribble PA, Delahunt E, Bleakley C, et al. Selection criteria for patients with chronic ankle instability in controlled research: a position statement of the International Ankle Consortium. *Br J Sports Med*. 2014;48(13):1014-1018.
3. Hertel J. Functional anatomy, pathomechanics, and pathophysiology of lateral ankle instability. *J Athl Train*. 2002;37(4):364.
4. Anguish B, Sandrey MA. Two 4-week balance-training programs for chronic ankle instability. *J Athl Train*. 2018;53(7):662-671.
5. Hall EA, Docherty CL, Simon J, Kingma JJ, Klossner JC. Strength-training protocols to improve deficits in participants with chronic ankle instability: a randomized controlled trial. *J Athl Train*. 2014;50:36-44.
6. Reid A, Birmingham TB, Alcock G. Efficacy of mobilization with movement for patients with limited dorsiflexion after ankle sprain: a crossover trial. *Physiotherapy Canada*. 2007;59:166–172.
7. Donovan L, Hart JM, Saliba S, et al. Effects of ankle destabilization devices and rehabilitation on gait biomechanics in chronic ankle instability patients: a randomized controlled trial. *Phys Ther Sport*. 2016;21:46-56.
8. Donovan L, Hart JM, Saliba SA, et al. Rehabilitation for chronic ankle instability with or without destabilization devices: a randomized controlled trial. *J Athl Train*. 2016;51(3):233-251.
9. Koldenhoven RM, Hart J, Saliba S, Abel MF, Hertel J. Gait kinematics & kinetics at three walking speeds in individuals with chronic ankle instability and ankle sprain copers. *Gait Posture*. 2019;74:169-175.
10. Delahunt E, Monaghan K, Caulfield B. Altered neuromuscular control and ankle joint kinematics during walking in subjects with functional instability of the ankle joint. *Am J Sports Med*. 2006;34(12):1970-1976.
11. Fong DT-P, Ha SC-W, Mok K-M, Chan CW-L, Chan K-M. Kinematics analysis of ankle inversion ligamentous sprain injuries in sports: five cases from televised tennis competitions. *Am J Sports Med*. 2012;40(11):2627-2632.
12. Mok K-M, Fong DT-P, Krosshaug T, et al. Kinematics analysis of ankle inversion ligamentous sprain injuries in sports: 2 cases during the 2008 Beijing Olympics. *Am J Sports Med*. 2011;39:1548-1552.
13. McKeon PO, Paolini G, Ingersoll CD, et al. Effects of balance training on gait parameters in patients with chronic

ankle instability: a randomized controlled trial. *Clin Rehabil*. 2009;23(7):609-621.
14. Davis IS, Futrell E. Gait retraining: altering the fingerprint of gait. *Phys Med Rehabil Clin N Am*. 2016;27(1):339-355.
15. Donovan L, Feger MA, Hart JM, Saliba S, Park J, Hertel J. Effects of an auditory biofeedback device on plantar pressure in patients with chronic ankle instability. *Gait Posture*. 2016;44:29-36.
16. Torp DM, Thomas AC, Donovan L. External feedback during walking improves measures of plantar pressure in individuals with chronic ankle instability. *Gait Posture*. 2019;67:236-241.
17. Martin RL, Irrgang JJ, Burdett RG, Conti SF, Swearingen JMV. Evidence of validity for the foot and ankle ability measure (FAAM). *Foot Ankle Int*. 2005;26(11):968-983.
18. Gurav RS, Ganu SS, Panhale VP. Reliability of the identification of functional ankle instability (IdFAI) scale across different age groups in adults. *North Am J Med Sci*. 2014;6(10):516-518.
19. Houston MN, Hoch JM, Hoch MC. Patient-reported outcome measures in individuals with chronic ankle instability: a systematic review. *J Athl Train*. 2015;50(10):1019-1033.
20. Booth M. Assessment of physical activity: an international perspective. *Res Q Exerc Sport*. 2000;71(sup2):114-120.
21. Horn KK, Jennings S, Richardson G, van Vliet D, Hefford C, Abbott JH. The patient-specific functional scale: psychometrics, clinimetrics, and application as a clinical outcome measure. *J Orthop Sports Phys Ther*. 2012;42(1):30-42.
22. Kamper SJ, Maher CG, Mackay G. Global rating of change scales: a review of strengths and weaknesses and considerations for design. *J Man Manip Ther*. 2009;17(3):163-170.
23. Fraser JJ, Koldenhoven RM, Saliba SA, Hertel J. Reliability of ankle-foot morphology, mobility, strength, and motor performance measures. *Int J Sports Phys Ther*. 2017;12(7):1134-1149.
24. Gribble PA, Hertel J, Denegar CR, Buckley WE. The effects of fatigue and chronic ankle instability on dynamic postural control. *J Athl Train*. 2004;39(4):321-329.
25. Thorborg K, Petersen J, Magnusson SP, Hölmich P. Clinical assessment of hip strength using a hand-held dynamometer is reliable. *Scand J Med Sci Sports*. 2010;20(3):493-501.
26. Noehren B, Scholz J, Davis I. The effect of real-time gait retraining on hip kinematics, pain and function in subjects with patellofemoral pain syndrome. *Br J Sports Med*. 2011;45(9):691-696.
27. Pataky TC. One-dimensional statistical parametric mapping in Python. *Comput Methods Biomech Biomed Engin*. 2012;15(3):295-301.
28. Cohen J. *Statistical Power Analysis for the Behavioral Sciences*, 2nd edn Mahwah, NJ: Lawrence Erlbaum Associates ; 1988.
29. Monticone M, Ambrosini E, Rocca B, Foti C, Ferrante S. Responsiveness and minimal clinically important changes for the Tampa Scale of Kinesiophobia after lumbar fusion during cognitive behavioral rehabilitation. *Eur J Phys Rehabil Med*. 2017;53(3):351-358.
30. Hertel J, Corbett RO. An updated model of chronic ankle instability. *J Athletic Train*. 2019;54:572–588.
31. Davids K, Glazier P, Araújo D, Bartlett R. Movement systems as dynamical systems. *Sports Med*. 2003;33(4):245-260.
32. Feger MA, Hart JM, Saliba S, Abel MF, Hertel J. Gait training for chronic ankle instability improves neuromechanics during walking. *J Orthop Res*. 2018;36(1):515-524.
33. Houston MN, Van Lunen BL, Hoch MC. Health-related quality of life in individuals with chronic ankle instability. *J Athl Train*. 2014;49(6):758-763.
34. Doherty C, Delahunt E, Caulfield B, Hertel J, Ryan J, Bleakley C. The incidence and prevalence of ankle sprain injury: a systematic review and meta-analysis of prospective epidemiological studies. *Sports Med*. 2014;44(1):123-140.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

How to cite this article: Koldenhoven RM, Jaffri AH, DeJong AF, et al. Gait biofeedback and impairment-based rehabilitation for chronic ankle instability. *Scand. J. Med. Sci. Sports*. 2021;31:193–204. https://doi.org/10.1111/sms.13823