EFFECTS OF EXTERNAL BIOFEEDBACK ON BIOMECHANICS AND ANKLE JOINT HEALTH IN INDIVIDUALS WITH CHRONIC ANKLE INSTABILITY

by

Danielle Marie Torp

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Approved by:

_____
Dr. Luke Donovan

_____
Dr. Abbey Thomas

_____
Dr. Tricia Hubbard-Turner

_____
Dr. Adam Reitzel

_____
Dr. Didier Dréau

_____
Dr. Harrison Campbell

ABSTRACT

DANIELLE M TORP. Effects of External Biofeedback on Biomechanics and Ankle Joint Health in Individuals with Chronic Ankle Instability. (Under the direction of LUKE DONOVAN)

Individuals with chronic ankle instability (CAI) often demonstrate abnormal biomechanical patterns which may be associated with the onset of posttraumatic osteoarthritis (PTOA). There is a lack of interventions capable of changing gait impairments and targeting the sensorimotor dysfunction in this population. The use of external focus of attention biofeedback during walking has shown to be capable of improving biomechanics in real-time, however the retention of these changes needs to be further explored prior to implementing into clinical practice. Further, technological advancements have shown ultrasonography of the talar articular cartilage is a plausible mechanism to monitor joint health, yet the associations of ultrasound-based images and biomechanical patterns in patients with CAI remains unknown. This dissertation focused on three main research questions: 1) Does incorporating an auditory biofeedback device during common rehabilitation exercises improve biomechanics during a single session, 2) Is there a relationship between abnormal walking biomechanics in patients with CAI and ultrasound-based measures of talar articular cartilage health, 3) Does incorporating an auditory biofeedback device into a 2-week gait training program improve biomechanics and ankle joint health in patients with CAI compared to a control condition. First, we identified auditory biofeedback is effective at improving biomechanics during functional exercises in addition to its improvements in gait. Next, we found significant correlations between abnormal walking biomechanics and talar cartilage thickness and echo intensity.

Finally, our 2-week gait training intervention has shown to be effective in improving walking gait in patients with CAI immediately and up to 1 week following the intervention. The findings of this dissertation highlight the relationship between biomechanical gait patterns and ankle joint health which will guide clinical practice in identifying modifiable factors to potentially mitigate the onset of PTOA after an ankle injury. This dissertation has also identified a clinically applicable mechanism to improve the abnormal biomechanics that are related to cartilage joint health.

DEDICATION

This is for all the athletes I've had the privilege of directly working with before pursuing this degree. You all will always be inspiration.

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LIST OF ABBREVIATIONS

CAI	Chronic Ankle Instability
LAS	Lateral Ankle Sprain
COP	Center of Pressure
PTOA	Posttraumatic Osteoarthritis
PRO	Patient Reported Outcome
HRQOL	Health Related Quality of Life
FAAM	Foot and Ankle Ability Measure
ADL	Activities of Daily Living
FAAM-S	Foot and Ankle Ability Measure – Sport
IdFAI	Identification of Functional Ankle Instability
IPAQ	International Physical Activity Questionnaire
CSA	Cross Sectional Area
DFROM	Dorsiflexion Range of Motion
WBLT	Weight Bearing Lunge Test
MDC	Minimal Detectable Chnage
TTB	Time to Boundary
MR	Magnetic Resonance
US	Ultrasonography

CHAPTER 1: INTRODUCTION

1.1 STATEMENT OF THE PROBLEM

Lateral ankle injuries continue to be the most common musculoskeletal injury among a wide range of populations[1-7] and have a high rate of developing chronic ankle instability (CAI).[8] Characterized by residual symptoms, feelings of instability, and recurrent injuries, CAI is a condition that develops in the months and years following an index sprain.[9] Compared to age-matched counterparts, those with CAI tend to be less physically active[10] and have a reduced health-related quality of life.[11,12] The most recent model of CAI development outlines the multifactorial influence of structural, biomechanical, and sensorimotor impairments contributing to the clinical- and patient-reported insufficiencies in this pathological population.[13] Recent evidence suggests that ankle sprains and recurrent injuries spark a reorganization of the central nervous system, leading to neuromechanical deviations and a constrained sensorimotor system.14-16 Sensorimotor alterations continue to develop as peripheral impairments months and years after the acute inflammation subsides. The most commonly reported impairments demonstrated by those with CAI compared to healthy controls to include poor postural control,[14,17-25] muscle weakness,[26-31] range of motion deficits,[32-34] and altered biomechanics during gait[35-46] and functional tasks.[47-51] The insufficient structural integrity and sensorimotor dysfunction lingering after an ankle sprain likely influence biomechanical alterations during movement. Specifically, altered biomechanical patterns commonly found are increased ankle inversion,[52] increased lateral plantar pressure[53] and a laterally deviated center of pressure (COP) gait line[45] which places the individual closer to the mechanism of ankle injury. In addition to these impairments, there is a high

probability that these patients will develop posttraumatic osteoarthritis (PTOA) in as early as ten years after their initial injury,[54] which causes further pain,[55] physical activity limitations,[56] and reductions in quality of life.[55]

It is hypothesized that the high rate of PTOA development after an ankle sprain to be associated with the aberrant biomechanical pattern of those with CAI.[57] Specifically, the medial talar cartilage undergoes excessive and unequal contact stresses[58,59] which promotes degeneration of the medial talar cartilage.[60-63] These findings have been confirmed with magnetic resonance (MR) imaging but are limited in their ability to measure acute deformational changes in the talar articular cartilage and are not a feasible imaging technique for repetitive monitoring. Thus, researchers have sought alternative approaches with more clinically applicable technologies, specifically diagnostic ultrasonography (US). While most of these advancements in US have been at the knee, there is promising evidence showing US of the talar articular cartilage can be a surrogate for MR imaging.[64] Furthermore, US is also sensitive enough to detect deformational changes after a loading protocol and has exposed the difference in deformational patterns between those with and without CAI.[65] However, it is unknown if US-based images of the talar cartilage are correlated with specific biomechanical patterns in patients with CAI. Considering the relationship between abnormal biomechanics in ankle sprain patients and cartilage stress, restoring proper ankle biomechanics may be imperative to maintaining long-term joint health in patients with CAI.

Most rehabilitation protocols for CAI center around restoring peripheral impairments and are not targeting the sensorimotor dysfunctions. Furthermore, there has been little attention placed on the impact of rehabilitation on talar articular cartilage

health which may provide direction to mitigate onset of PTOA. Several rehabilitation protocols are available for clinicians to specifically target modifiable impairments associated with CAI, including balance,66 strength,67 or range of motion68 deficits, and a few multimodal programs.[69,70] While these programs are efficient at improving the peripheral impairments they are targeting, there is a lack of focus on improving biomechanics during walking or functional exercises. To date, the only interventions capable of producing gait changes are those specifically targeting gait[71-74] and the few protocols that have examined multi-session effects are not readily available for clinicians.[72,75] Therefore, there is still a need for clinically applicable gait retraining programs for patients with CAI capable of targeting central and peripheral adaptations.

Motor learning theories and recent evidence suggest that external focus of attention biofeedback interventions can combat cortical dysfunction and enhance motor learning by allows an unconstrained pathway to reorganization.[76-78] Our research team has demonstrated a novel auditory external biofeedback instrument (AudFB) that causes real-time biomechanical changes during a single session in patients with CAI during walking[73] and other functional tasks.[79] Before suggesting this mode of gait training to clinicians and incorporating it into an impairment-based rehabilitation model,[80] we must first study the effects of a multi-session intervention on biomechanics and talar articular cartilage health in patients with CAI.

1.2 RESEARCH QUESTIONS

The overall purpose of this dissertation is to fill some critical gaps in the current literature and rehabilitation paradigm to improve patient and clinical outcomes in a CAI population. This dissertation focused on three main research questions:

1. Does incorporating an auditory biofeedback device during common rehabilitation exercises improve biomechanics during a single session?
2. Is there a relationship between abnormal walking biomechanics in patients with CAI and ultrasound-based talar articular cartilage health measures?
3. Does incorporating an auditory biofeedback device into a 2-week gait training program improve biomechanics and ankle joint health measures compared to a control condition?

1.3 SPECIFIC AIMS

Specific Aim 1: Identify the effects of a single-session using auditory feedback on real-time biomechanics during functional exercises and static postural control in individuals with CAI. We will accomplish this by comparing a baseline condition of each task to two conditions using external biofeedback during a forward lunge, lateral hop, step down, and single-limb balance. Plantar pressure will be compared between baseline and each intervention condition during the functional exercises. A force platform will be used to collect measures of postural control during each condition.

Hypothesis 1.1: We hypothesized that individuals with CAI would reduce their lateral plantar pressure during a step-down, forward lunge, and lateral hop while using the auditory biofeedback device. Further, we did not anticipate an overt increase in medial plantar pressure.

Hypothesis 1.2: We hypothesized individuals with CAI would worsen in traditional laboratory measures of static balance as they learned a new strategy to balance.

Specific Aim 2: Identify the relationship between the biomechanical profile and talar cartilage characteristics using ultrasonography in individuals with CAI. We

will accomplish this with B-mode ultrasonography measuring resting talar articular cartilage thickness and echo intensity after an unloading period and changes in thickness and echo intensity following 30-minutes of treadmill walking. Talar cartilage characteristics will be correlated with: 1) plantar pressure during treadmill walking, 2) plantar pressure during a step-down and lateral hop, 3) static postural control measured on a force platform, 3) weight-bearing dorsiflexion range of motion measuring through the weight-bearing lunge test (WBLT), and 4) patient-reported outcomes measures of the Foot and Ankle Ability Measure (FAAM) Activities of Daily Living (ADL) and Sport subscales.

Hypothesis 2.1: We hypothesize increased lateral plantar pressure and a laterally deviated COP gait line during treadmill walking will correlate with smaller resting thickness, larger deformation, and worse echo intensity in the medial talar cartilage.

Hypothesis 2.2: We hypothesize increased lateral plantar pressure step-down and lateral hopping will correlate with smaller resting thickness, larger deformation, and worse echo intensity in the medial talar cartilage.

Hypothesis 2.3: We hypothesize worse static postural control will correlate smaller resting thickness, larger deformation, and worse echo intensity in the medial talar cartilage.

Hypothesis 2.4: We hypothesize smaller distances on the WBLT will correlate smaller resting thickness, larger deformation, and worse echo intensity in the medial talar cartilage.

Hypothesis 2.3: We hypothesize worse scores on the FAAM ADL and Sport subscales will correlate smaller resting thickness, larger deformation, and worse echo intensity in the medial talar cartilage.

Specific Aim 3: Identify the effects of a two-week gait retraining program using auditory feedback on biomechanics during walking, functional tasks, static balance performance, talar cartilage characteristics, and patient-reported outcomes. To accomplish this we will utilize a randomized, single-blinded study of participants with CAI. All participants will complete 8 time-matched treadmill walking sessions over 2 weeks; however, the Control group will receive no biofeedback, while the AudFB group will receive auditory biofeedback during each session. We will evaluate biomechanics, ankle cartilage, and the FAAM before the intervention (baseline), 24-72 hours post-intervention (immediate-post), and 1-week after the intervention (1-week post). Between and within-group comparisons will be made across all time points for all dependent variables.

Hypothesis 3.1: We hypothesize that individuals who received the auditory biofeedback intervention would significantly reduce lateral plantar pressure during walking than those who do not receive auditory biofeedback immediately and 1-week following the intervention.

Hypothesis 3.2 We hypothesize individuals who receive the auditory biofeedback intervention would improve their talar cartilage deformation patterns compared to those who do not receive auditory biofeedback immediately and 1-week following the intervention.

Hypothesis 3.3 We hypothesize individuals who receive the auditory biofeedback intervention would improve scores on the FAAM ADL and Sport compared to those who do not receive auditory biofeedback immediately and 1-week following the intervention.

Hypothesis 3.4: We hypothesize individuals who receive the auditory biofeedback intervention would demonstrate a cross-over effect with improved biomechanics during a step down, lateral hop, and static balance task compared to those who do not receive auditory biofeedback immediately and 1-week following the intervention.

CHAPTER 2: BIOMECHANICAL RESPONSE TO EXTERNAL BIOFEEDBACK DURING FUNCTIONAL TASKS IN INDIVDUALS WITH CHRONIC ANKLE INSTABILITY

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2.1 CONTRIBUTIONS TO DISSERTATION

This chapter is adapted from Torp, Thomas, Hubbard-Turner, and Donovan. The previous research using external biofeedback in a CAI population was limited to treadmill walking, therefore the purpose of this investigation was to determine if individuals with CAI were capable of altering their movement patterns during functional tasks. In this study, we compared the effects of a baseline condition to two forms of external biofeedback: visual using a cross-line laser and auditory using a noise generating pressure sensor. The main findings of this study were 1) both forms of external biofeedback were able to produce beneficial changes in static balance; 2) the auditory biofeedback condition elicited changes in biomechanics during the step-down and forward lunge tasks; 3) the visual biofeedback condition produced biomechanical changes during the lateral hopping task. Collectively, the results of this study supported the use of external biofeedback in either capacity is beneficial for biomechanical improvements during rehabilitation tasks.

2.2 INTRODUCTION

Lateral ankle sprains are continually reported as the most common musculoskeletal injury with a large portion of cases developing into chronic ankle

instability (CAI) over the months and years following the acute incident.[1] CAI is categorized by the recurring sprains, episodes of ankle giving way, and feelings of instability that linger after the acute injury subsides.[2] Several long-term consequences have been associated with CAI, including reduced physical activity levels, a decreased quality of life,[3] and increased risk of ankle posttraumatic osteoarthritis (PTOA).[4] 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, decreased ankle strength, and altered biomechanics during functional activities.[2]

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.[5] Similarly, COP during static balance is also laterally shifted among individuals with CAI, whereas healthy counterparts tend to maintain a medially positioned COP.[6] Given that a relationship exists between kinematics across functional tasks,[7] it is likely that the altered biomechanics displayed during walking, is also present during other functional tasks or movements (stepping, jumping, lunging etc.).[8,9] It has been postulated that the CAI biomechanic profile contributes to repetitive sprains and ankle PTOA progression. Greater lateral plantar pressure and lateral COP trajectory places the individual closer to the mechanism of ankle injury and reduces cartilage stress on the lateral talus, which increases peak stress on the medial talar cartilage.[10,11] This unequal distribution of contact stress[11] promotes degeneration of the medial talar cartilage.[4,12,13] Moreover, not only is the foot mal-positioned during each step, but given the associated neuromuscular control and strength deficits, the individual

has a reduced ability to protect the joint from sudden perturbation, further exacerbating the risk of re-injury. Therefore, restoring proper ankle biomechanics is imperative to maintain long-term joint health in patients with CAI.

Previous studies[14-17] aimed to test the efficacy of rehabilitation programs comprised of exercises that target impairments associated with range of motion (ROM), strength, balance and/or functional exercises (stepping, jumping, cutting) in patients with CAI. Although the rehabilitation programs demonstrated to be effective at improving dorsiflexion ROM, balance and strength in patients with CAI, many of the patients continued to report deficits in self-reported function following the intervention.[18] One rationale as to why the previously mentioned rehabilitation programs did not fully restore patient function, is that not all impairments associated with CAI were improved. Specifically, COP location during static balance remained laterally positioned and ankle inversion and muscle activation during functional movements (walking, jogging, and jump-landing) remained unchanged.[14-17] We attribute the lack of change in balance strategy and biomechanics during functional movements not to the specific exercises, but rather the lack of feedback provided to the patient during the exercise. Including feedback that promotes a neutrally positioned ankle during functional exercises may cause the patient to adopt a movement strategy that is not linked to recurrent ankle sprains.

Recently, two novel biofeedback instruments have successfully increased muscle activation, reduced lateral plantar pressure, and medially shifted COP during a single-session of treadmill walking.[19,20] Both devices provide external focus of attention biofeedback; however, one device targets visual centers while the other targets auditory. The objective of external feedback is to direct attention of the individuals' movement to

the context of the environment[21] that is achieved by an external source.[22] Contrastingly, internal focus can be described as attention being directed to the individuals' body so that the patient is consciously aware of their movement.[21] External feedback has demonstrated to be the superior mode of feedback when altering movement strategies;[22] however, neither of the aforementioned external biofeedback instruments have been studied in individuals with CAI performing a range of tasks (balance, stepping, hopping). Prior to implementing these novel devices into rehabilitative programs for patients with CAI, we must first determine the patients' real-time response to each 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 to a baseline condition with no feedback instructions. We hypothesize both external biofeedback conditions will improve biomechanics compared to the baseline condition.

2.3 METHODS

Study Design

We performed a crossover study to compare 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 our 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-down, lateral hops, and forward lunges. To capture a complete biomechanic profile during each task, secondary

variables of postural control and plantar pressure were included. An a priori power analysis was calculated to determine sample size using pilot data from our lab. A sample size of 16 was needed to obtain an alpha of 0.05, power of 0.95, and an effect size of 1.

Participants

Nineteen physically active adults with CAI volunteered (23.95 ± 5.52 years; 168.87 ± 6.94 cm; 74.74 ± 15.41 kg, female = 12). Participants met standards for CAI determined by the International Ankle Consortium.[23] Briefly, they reported having at least 1 significant ankle sprain that occurred at least 12 months prior to enrollment and their most recent sprain occurred more than 3 months prior. Participants self-reported foot and ankle dysfunction by scoring ≤ 85% on the Foot and Ankle Ability Measure (FAAM) Sport subscale. Further, they reported having ankle instability by scoring a ≥ 11 on the Identification Functional Ankle Instability (IdFAI) questionnaire. Physical activity levels were determined by the International Physical Activity Questionnaire (IPAQ) short form which participants indicated engaging in a minimum of 30 minutes of physical activity 3 times per week. Participants were excluded if they did not meet aforementioned criteria or reported previous ankle fracture or surgery, any underlying condition that would influence plantar pressure, or ability to perform tasks. This study was approved by our university's institutional review board and participants provided written, informed consent prior to enrollment.

Instrumentation

Single-limb static balance was performed on an AccuSway Optimized force platform (AMTI, Watertown, MA) at a sampling rate of 50 Hz and processed in Balance Clinic software (AMTI). Plantar pressure was collected via the Pedar-X plantar pressure

system (Novel Inc., St. Paul, MN) at a sampling rate of 200 Hz. Calibration methods were performed to ensure plantar pressure was only recorded when the foot was in contact with the ground and excludes aerial phases.

Visual biofeedback was given through a class IIIA cross-line laser diode (Calpac Lasers, Steamboat Springs, CO, USA) powered by 2 AAA batteries and has previously been used and described in detail elsewhere.[20,24] Auditory biofeedback[19] was given through a thin (14 x 25.4 x 0.203 mm) FlexiForce Load Sensor (Tekscan, Inc. South Boston, MA).The pressure sensor was connected to a FlexiForce Quickstart Board (31.75 x 31.75 mm) and a potentiometer (Tekscan, Inc. South Boston, MA) with an attached buzzer, powered with a 9-volt battery. Set up of each biofeedback device can be viewed in Figure 2.

Procedures

After informed consent was obtained, participants performed four tasks: single-limb balance, step-down, forward lunge, and lateral hops under each of our three conditions. Balance trials were always performed first since it required participants to be barefoot; however, the remaining three tasks were randomized for each subject using a Latin-Square. After balance trials were completed, participants were fitted with standard, neutral athletic shoes (model M680V3, New Balance Inc., Boston, MA) with the plantar pressure insoles placed inside. Practice trials were given for each task under each condition and Each task was completed under each condition before starting another task. The baseline condition for all tasks were always performed first using standard instructions. The visual and auditory biofeedback conditions were randomly performed for each task using a Latin-Square. All data were captured on the involved limb reported

with CAI. If a participant reported a bilateral history of ankle sprains, the perceived worse limb was chosen for testing.

Balance and Functional Tasks

Static balance was performed while participants stood barefoot on a force plate with their uninvolved limb placed in 30° hip flexion and 45° knee flexion with hands placed on their hips.[25] Participants were instructed to "stand as still as possible while maintaining the test position" and given three practice trials. During the baseline condition, no other instructions were given. Participants performed 3 practice trials followed by 3 successful 10-second trials recorded with their eyes open and eyes closed. Failed trials, where 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, 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.[7] Three practice trials were given before 10 successful step-down trials were completed and used for analysis.

Participants performed lateral hops[25] over a piece of athletic tape that was placed along the floor and continued up onto the wall. Participants were asked to hop laterally over the tape while maintaining their vision forward onto the wall and to use the tape as a guide for making it over the tape on the ground. All participants started with the tape towards the outside of their involved limb so every beginning jump was lateral. A successful trial consisted of a lateral hop, balance maintained upon landing, and a hop back to the starting position without removing hands from the 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 three testing conditions, thus we chose to standardize the hopping distance rather than the hopping speed through a metronome. Participants were given 3 practice trials before recording 10 continuous successful trials which were used for analysis.

Forward lunges were performed from a neutral stance with hands on the hips.[25] The involved limb lunged forward into a 90°/90° position of the hip and knee and the back uninvolved knee touched the ground, then the participant returned to the starting position. Three practice trials were given then a total of 10 forward lunges were performed and used for analysis.

Biofeedback

Visual biofeedback was provided by the cross-line laser device that was secured to the dorsum of the foot using a strap (Figure 2).[20,24] During non-visual biofeedback trials, the laser was turned off, but remained fastened to the foot to eliminate differences in plantar pressure or COP data distribution during all trials. During the visual biofeedback conditions, the cross-line laser was turned on and visible to the participant on a wall directly in front of them. Before each task, the laser was adjusted to find neutral stance/starting position. A piece of white athletic tape was used as a reference point 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 to limit the amount of rotation of the cross-line." Participants performed 3 practice trials with the visual biofeedback prior to collection of 10 trials used for analysis.

Auditory external focus of attention biofeedback was by provided by the auditory device and was calibrated for each participant prior to each task (Figure 2). During single-limb balance, the sensor was taped to the forceplate underneath the head of the fifth metatarsal which ensured consistent placement of the foot on the forceplate. Laboratory shoes were cut to allow the sensor be taped to the insole of the shoe under the fifth metatarsal but still maintained integrity of the shoe.[19] 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 where noise was heard. During non-auditory biofeedback trials, the auditory instrument 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 with the auditory biofeedback prior to collection of 10 trials used for analysis.

Data Processing

Primary Outcomes

During each static balance trial, a time series of 500 COP data points (10s x 50Hz) were generated and a custom MATLAB code (version R2019a, MathWorks, Natick, MA) was used to determine location of each data point in four quadrants of the foot (anteromedial, anterolateral, posteromedial, posterolateral).[17] More data points equate to more loading in the respective quadrant.

Peak pressure (kPa) and pressure-time integral (kPa*s) were calculated from the 10 steps performed during each task using Novel Database Pro (Novel Inc., St. Paul,

MN). A standard mask was applied to divide the foot into 9 regions, of which our primary regions of interest were the lateral heel, lateral midfoot, and lateral forefoot.

Secondary Outcomes

The COP 95% confidence eclipse area (centimeters squared [cm^2]) and mean velocity (cm/s) were calculated using Balance Clinic software (AMTI, Watertown, MA) using a fourth-order, zero-lag, low pass filter with a cutoff frequency of 5 Hz. Time to boundary (TTB) variables (absolute minima and standard deviation of the minima) were calculated in the anteroposterior (AP) and mediolateral (ML) directions using a custom MATLAB code. Smaller area, velocity, and TTB values indicate worse postural control.

Additional plantar pressure measures were extracted including contact area (cm^2), contact time (ms), maximum force (N), and force-time integral (N*s). The remaining regions created from the applied mask include: medial heel, medial midfoot, medial forefoot, central forefoot, lesser toes, and the great toe. Additionally, we included a total foot region.

Statistical Analysis

Separate within-factor repeated-measures analysis of variance tests were used (SPSS v26, SPSS Inc., Chicago, IL) to compare means for each dependent variable across the three conditions (Baseline, Visual, Auditory). Only results comparing baseline to each biofeedback condition is reported and no comparisons between are the biofeedback conditions are reported. Alpha levels were set *a priori* at $p < 0.05$. In accordance with modern statistical recommendations,[26] we did not control for multiple comparisons. Rather, we calculated Hedges *g* effect sizes (ES) and associated 95% confidence intervals (CIs) and interpreted results as significant if $p \leq 0.05$ and ES were

moderate to large with 95% CIs that do not cross 0. Effect sizes were considered large (≥0.80), moderate (0.50-0.79) and small (0.20-0.49) and were calculated in Microsoft Excel 2016 (Microsoft Corporation, Redmond, WA).

2.4 RESULTS

All demographic information can be found in Table 1. Results for primary outcomes are presented in Figure 1, Tables 2 and 3. Results for all secondary outcomes are presented as supplementary data in Tables S1-4.

Static Balance

Results for primary outcomes during eyes open and eyes closed balance are presented in Figure 1 and Table 2. Results for secondary outcomes are presented in Supplemental Table S1.

The auditory (ES=0.86) and visual (ES=0.80) biofeedback conditions during eyes open static balance reduced the number of COP data points in the anterolateral quadrant (p=0.002) while simultaneously increasing COP data points in the posteromedial quadrant (p=0.010; ES= -0.89 and -0.74, respectively) compared to baseline condition. Further, the auditory biofeedback condition reduced the number of COP data points in the posterolateral quadrant (p=0.003; ES=0.72) compared to baseline (Figure 1 and Table 2)..

During eyes closed trials, we observed a significant decrease in COP data points in the anterolateral quadrant (p<0.001; ES=0.95) and an increase in data points in the posteromedial quadrant (p=0.006; ES=-0.97) during the auditory biofeedback condition compared to baseline (Figure 1 and Table 2).

Step-Down

Results for variables during the step-down task are presented in Table 3 with secondary variable in Supplementary Tables S2-S4. Compared to baseline, the auditory biofeedback condition significantly increased lateral heel peak pressure ($p=0.029$; ES=-0.68) and pressure-time integral ($p=0.003$; ES=-0.75) (Table 3). The auditory condition reduced pressure-time integral of the lateral forefoot compared to baseline ($p=0.001$; ES=0.70).

Lateral Hop

Results for all variables during the lateral hop are presented in Table 3 with secondary variables in Supplementary Tables S2-S4. Visual biofeedback increased peak pressure ($p=0.002$; ES=-0.73) and pressure-time integral ($p=0.001$; ES=-1.01) in the lateral heel region as well as increased pressure-time integral ($p=0.001$; ES=-0.78) of the lateral midfoot region (Table 3). Auditory biofeedback did not change plantar pressure from baseline.

Forward Lunges

Results for all variables during the forward hop are presented in Table 3 with secondary variables presented in Supplementary Tables S2-S4. The Auditory biofeedback condition significantly decreased pressure-time integral ($p<0.001$; ES=0.78) in the lateral forefoot (Table 3). Visual biofeedback did not change plantar pressure during the forward lunge task.

2.5 DISCUSSION

The purpose of our study was to determine real-time effects of two novel external focus of attention biofeedback devices on static balance and functional task biomechanics in a cohort of individuals with CAI. Our results partially support 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 begins to provide evidence of the utility of harnessing various external biofeedback media to target multiple rehabilitation exercises to maximize 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 quadrant. The visual biofeedback condition produced similar changes in COP location in the eyes open trails. According to previous research, healthy individuals have more COP data points in the posteromedial quadrant, whereas individuals with CAI have more in the anterolateral quadrant.[6] Despite a real-time advantageous shift in COP location, our secondary TTB outcomes (Table S1) indicate an initial worsening in postural control during these trials. The development of balance training programs through the perspective of dynamic systems theory[27] is to manipulate the task in such a way to allow patients to explore new avenues to handle a changing environment. We speculate it is natural to have less stability as these individuals are discovering a new COP location and evidence suggests postural control continues to improve over time when balance training is coupled with an external focus of attention.[28] Furthermore, individuals with CAI have a heightened reliance on visual information and traditional balance training programs are unable to alter that visual reliance.[29] In the current study, our auditory biofeedback condition produced parallel changes in eyes open and eyes closed balance trials indicating potential for improved balance without relying on visual stimulus. Perhaps as patients continue to use external biofeedback to maintain a

posteromedial COP their overall stability will also improve, but more research is needed to determine the long-term effects of our external biofeedback devices on postural control.

The efficacy of our visual and auditory biofeedback devices differed between our chosen functional tasks. The step-down and forward lunge were more responsive to auditory feedback whereas the visual biofeedback was effective during the lateral hopping task. During the step-down task, auditory biofeedback caused participants to adopt a more dorsiflexed, closed-packed position during initial contact and throughout the loading phase of the step-down. This strategy may benefit patients with CAI as landing in a more plantarflexed and inverted ankle position is considered to cause giving way or recurrent ankle sprain episodes.[9,30] Auditory biofeedback provided during the forward lunge caused participants to reduce primary and secondary plantar pressure measures on the lateral midfoot, lateral forefoot, and lesser toes. There were no observed increases in plantar pressure measures in the medial foot column which indicates participants did not adopt an overly unnatural tactic when performing these tasks. While COP trajectory was not measured in this study, previous studies analyzing walking gait retraining observed reductions in lateral plantar pressure is accompanied with a medial shift in COP trajectory which is a beneficial strategy for those with CAI.[20] The visual biofeedback in the lateral hops produced a more closed-packed landing strategy by increased plantar pressure measures in the heel and midfoot regions. As previously mentioned with the step-down task, this appears to be a beneficial strategy for individuals to adopt to reduce the inherent risk of sustaining another inversion ankle sprain.

Our results illustrate auditory biofeedback was beneficial during tasks performed in the sagittal plane whereas visual biofeedback was advantageous in targeting tasks in the frontal plane. Evidence of motor learning supports the use of visual biofeedback during complex tasks (e.g. lateral hops) compared to auditory biofeedback during less complex tasks (e.g. step-down and lunge).[22] Even though our auditory device was designed to only provide feedback when the lateral forefoot applied excessive pressure to the sensor and no feedback was given during the aerial phases our participants were able to adjust their foot upon initial contact to adhere to the cues given. However, during the lateral hopping tasks the placement of the auditory sensor may have prohibited them to alter their landing strategy in a way to follow to the cue and still perform the task correctly. Contrastingly, the constant visualization of the cross-line laser during the lateral hops may have allowed participants to determine a proper biomechanical strategy in order to adjust their performance to adhere to the feedback. Our visual biofeedback instructions during all tasks were to keep the vertical line of the laser parallel to a piece of tape (i.e. transverse plane motion) but also to reduce the amount of rotation of the cross-line (i.e. frontal plane motion).

Collectively the tasks chosen in this investigation were to mimic common exercises used during ankle rehabilitation and the primary focus in previous research.[14,15,25] While both these devices have been shown as beneficial in targeting aberrant walking gait biomechanics,[19,20] this study does not support one media over the other. In order to optimize motor learning, Guadagnoli and Lee[31] proposed protocols incorporating feedback should be flexible and cognizant of the demands of the task being performed. Although this framework is primarily built around healthy individuals

learning a new motor tasks, results from our study add to this existing framework to include a pathological population re-learning a skill with ideal biomechanics. There may be more utility in these novice external biofeedback devices to be used congruently during an impairment-based rehabilitation model to improve biomechanics across various tasks.

Limitations

Our study was not without limitations. Primarily, the nature of this study was to determine a real-time, single dose effect; therefore, we cannot make conclusions about their long-term ability to improve biomechanics. Further, our study lacked a neuromuscular perspective and future research is needed to determine the full biomechanical changes occurring while using these novice biofeedback devices. Our results warrant more research of these external biofeedback devices included into a full impairment-based rehabilitation program to determine their overall benefit to patients with CAI.

Conclusions

Both visual and auditory biofeedback devices improved static balance and functional task biomechanics differently depending on the exercise. Our study begins to extrapolate the use of external focus of attention biofeedback during rehabilitation after an ankle sprain injury. Clinicians should consider using low cost, user-friendly external focus of attention devices to improve biomechanics and balance during already established rehabilitation protocols.

2.6 Tables

Table 2.1. Participant Demographics (mean ± standard deviation)

	Chronic Ankle Instability (n=19)
Sex (males : females), No.	7 : 12
Age, y	23.95 ± 5.52
Height, cm	168.87 ± 6.94
Weight, kg	74.74 ± 15.41
Ankle sprains, No.	2.57 ± 1.07
Time since last sprain, mo	86.65 ± 64.04
Foot and Ankle Ability Measure, %	81.03 ± 13.46
Foot and Ankle Ability Measure-Sport Scale, %	65.28 ± 14.17
Identification of Functional Ankle Instability score	20.63 ± 3.87

Table 2.2 Center of Pressure Data Points (Mean (Standard Deviation)) During Eyes Open and Closed Static Balance During Baseline, Visual and Auditory Biofeedback Conditions.

	Eyes Open				Effect Size (95% Confidence Interval)		Eyes Closed				Effect Size (95% Confidence Interval)	
	Baseline (n=19)	Visual (n=19)	Auditory (n=19)	P Value	Baseline – Visual	Baseline – Auditory	Baseline (n=18)	Visual (n=19)	Auditory (n=18)	P Value	Baseline – Visual	Baseline – Auditory
AM	75.1 (89.0)	117.9 (144.4)	143.2 (144.4)	0.034	-0.35 (-0.99,0.29)	-0.56 (-1.20,0.09)	125.9 (80.2)	108.2 (77.6)	109.3 (93.9)	0.452	0.22 (-0.44,0.88)	0.19 (-0.47,0.84)
AL	138.7 (124.2)	**58.0 (64.1)**	**53.0 (60.8)**	0.002	**0.80 (0.14,1.46)**	**0.86 (0.19,1.52)**	148.1 (73.4)	116.5 (99.2)	**82.9 (60.9)**	0.003	0.35 (-0.30,1.01)	**0.95 (0.26,1.64)**
PM	97.5 (85.6)	**173.7 (113.2)**	**198.9 (132.5)**	0.010	**-0.74 (-1.40, -0.09)**	**-0.89 (-1.56, -0.22)**	94.4 (48.0)	132.9 (91.7)	**164.8 (87.8)**	0.032	-0.51 (-1.18,0.15)	**-0.97 (-1.66,-0.28)**
PL	189.4 (127.8)	150.7 (113.9)	**105.1 (98.1)**	0.003	0.31 (-0.33,0.95)	**0.72 (0.07, 1.38)**	131.8 (94.9)	142.7 (107.4)	144.0 (89.6)	0.676	-0.10 (0-.76,0.55)	-0.13 (-0.78,0.52)

AM: anteromedial; AL: anterolateral; PM: posteromedial; PL: posteromedial; Bold numbers indicates a significant difference from baseline; P values from repeated measures analysis of variance

Table 2.3 Peak Pressure (kPa) and Pressure Time Integral (kPa*S) (Mean (Standard Deviation)) in the Lateral Column of the Foot During Baseline, Visual and Auditory Biofeedback Conditions During Each Functional Task.

		Peak Pressure				Effect Size (95% Confidence Interval)		Pressure time integral				Effect Size (95% Confidence Interval)	
		Baseline	Visual	Auditory	P value	Baseline-Visual	Baseline-Auditory	Baseline	Visual	Auditory	P value	Baseline-Visual	Baseline-auditory
Step Down	LH	106.7 (34.7)	135.3 (89.1)	**156.1 (94.1)**	0.038	-0.41 (-1.06,0.23)	**-0.68 (-1.34,-0.03)**	16.5 (8.1)	22.9 (15.0)	**26.7 (17.1)**	0.003	-0.52 (-1.16,0.13)	**-0.75 (-1.41,-0.09)**
	LM	135.9 (31.7)	134.3 (34.8)	125.8 (37.2)	0.086	0.05 (-0.59,0.68)	0.29 (-0.35,0.93)	48.8 (20.7)	52.5 (23.6)	45.1 (25.3)	0.023	-0.16 (-0.80,0.47)	0.16 (-0.48,0.80)
	LF	191.4 (38.1)	185.4 (45.1)	168.2 (38.2)	<0.001	0.14 (-0.50,0.78)	0.60 (-0.05,1.25)	89.4 (18.8)	90.4 (27.0)	**74.2 (23.8)**	<0.001	-0.04 (-0.68,0.60)	**0.70 (0.04,1.35)**
Lateral Hop	LH	106.2 (41.8)	**139.7 (47.5)**	114.8 (47.2)	0.001	**-0.73 (-1.39,-0.08)**	-0.19 (-0.83,0.45)	31.8 (18.4)	**61.4 (36.3)**	40.8 (32.1)	0.001	**-1.01 (-1.68,-0.33)**	-0.33 (-0.98,0.31)
	LM	159.4 (34.3)	165.5 (28.8)	156.5 (40.3)	0.083	-0.19 (-0.82,0.45)	0.08 (-0.56,0.71)	60.7 (27.0)	**88.0 (40.6)**	70.0 (40.5)	0.001	**-0.78 (-1.44,-0.12)**	-0.26 (-0.90,0.37)
	LF	214.1 (54.8)	203.6 (43.4)	210.7 (60.3)	0.274	0.21 (-0.43,0.84)	0.06 (-0.58,0.69)	83.4 (28.5)	102.2 (38.8)	94.1 (38.9)	0.011	-0.54 (-1.19,0.11)	-0.31 (-0.95,0.33)
Forward Lunge	LH	193.1 (35.0)	188.3 (42.7)	201.4 (45.4)	0.029	0.12 (-0.52,0.76)	-0.20 (-0.84,0.44)	119.5 (29.0)	125.9 (37.5)	125.1 (37.1)	0.545	-0.19 (-0.82,0.45)	-0.17 (-0.80,0.47)
	LM	105.1 (22.2)	103.1 (23.3)	96.9 (18.3)	0.005	0.09 (-0.55,0.73)	0.40 (-0.24,1.04)	102.5 (26.0)	104.8 (34.1)	86.4 (22.5)	<0.001	-0.08 (-0.71,0.56)	0.64 (-0.01,1.30)
	LF	99.1 (28.0)	100.9 (27.8)	85.4 (22.7)	<0.001	-0.07 (-0.70,0.57)	0.52 (-0.12,1.17)	94.9 (33.3)	98.6 (35.1)	**71.3 (25.6)**	<0.001	-0.11 (-0.74,0.53)	**0.78 (0.12,1.44)**

LH=Lateral Heel; LM= Lateral Midfoot; LF= Lateral Forefoot; Bolded numbers indicate a statistically significant difference from baseline with moderate to large effect sizes and 95% confidence intervals that do not cross 0; P values from repeated measures analysis of variance; A negative effect size represents an increase in the biofeedback condition from baseline; A positive effect size represents a decrease in the biofeedback condition from baseline.

2.7 Figures

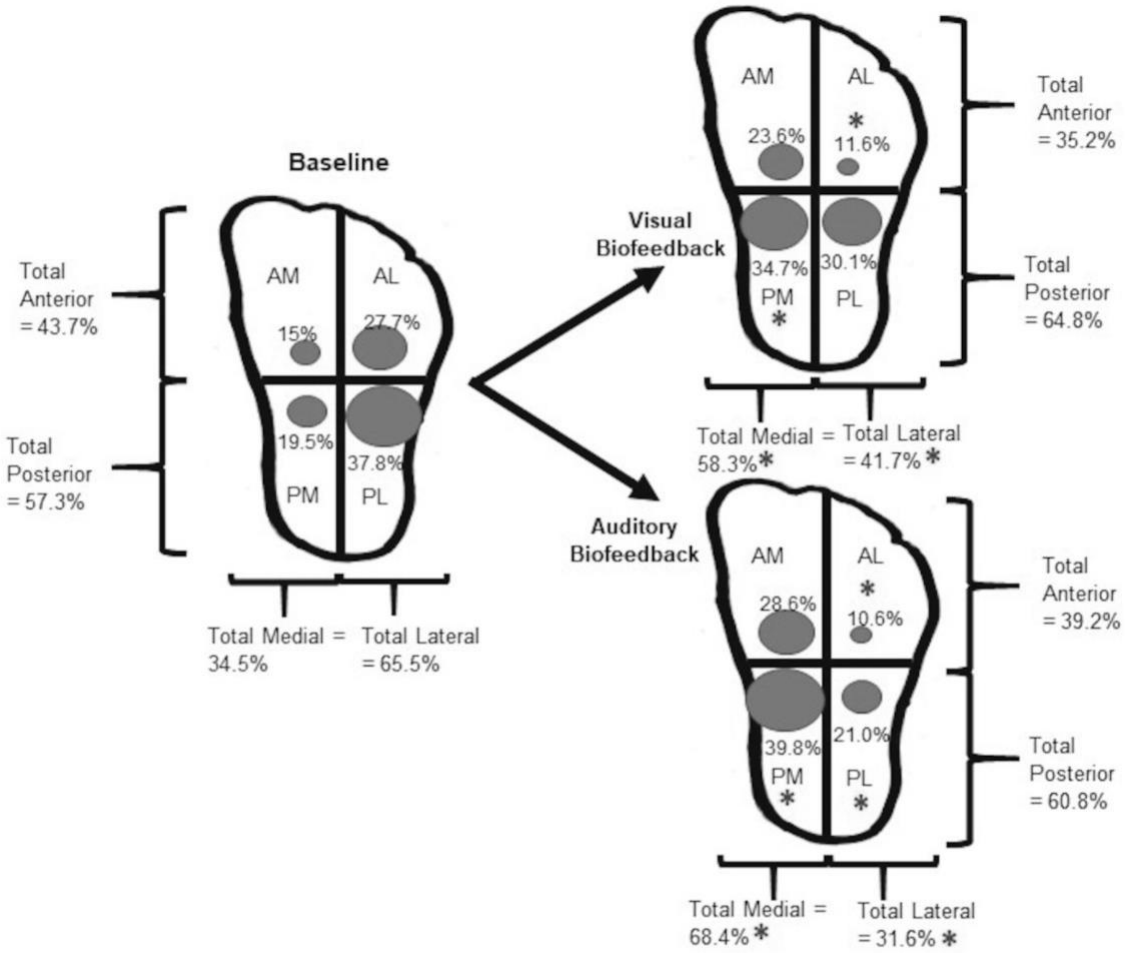

Figure 1. Percent of Center of Pressure Data Points in Each Quadrant During Eyes Open Balance During Baseline, Visual and Auditory Biofeedback Conditions.
AM: anteromedial; AL: anterolateral; PM: posteromedial; PL: posterolateral; * indicates a significant shift in COP data points from baseline.

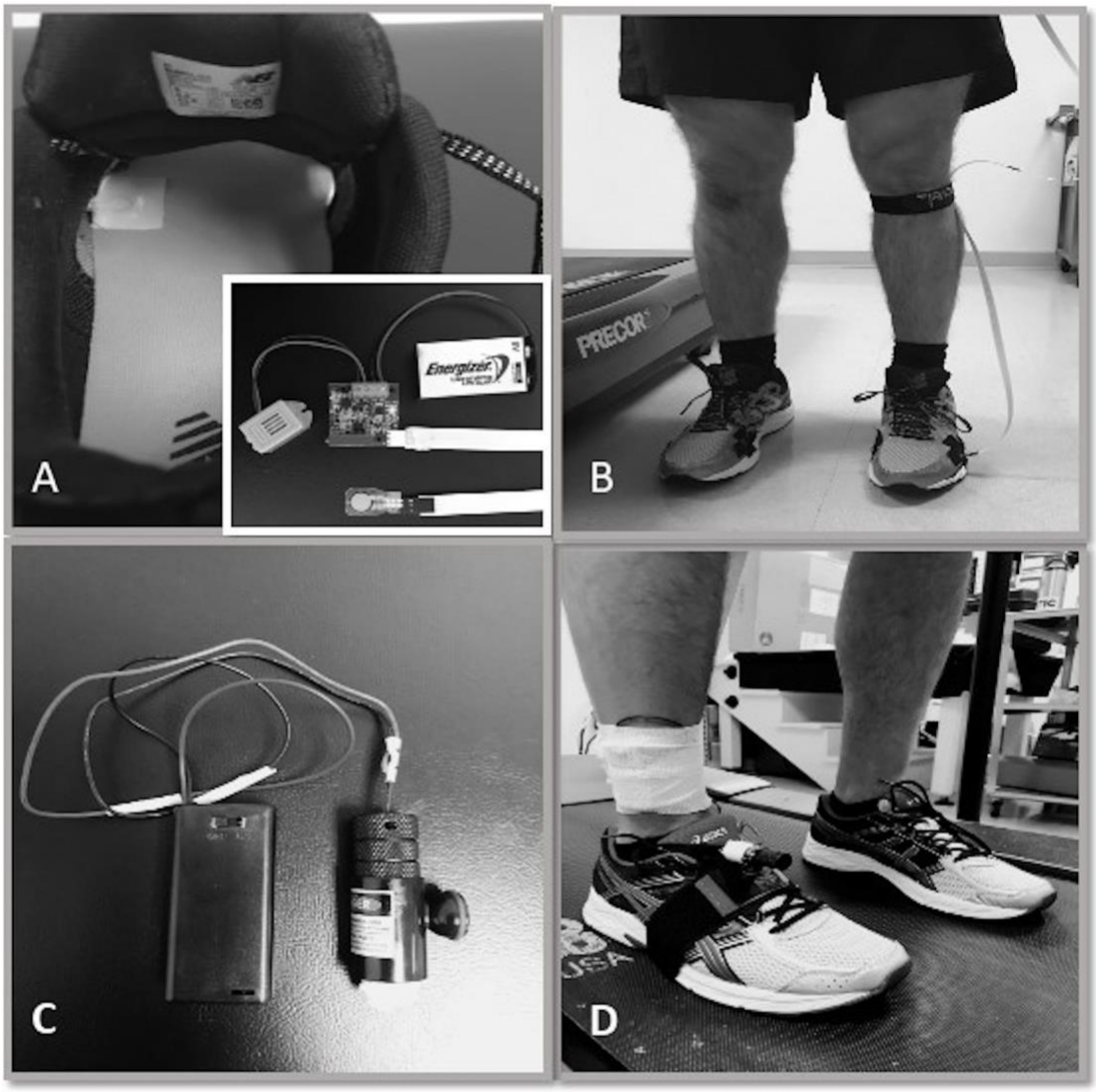

Figure 2. Auditory and Visual Biofeedback Devices and Set Up.
A: Auditory device includes a pressure sensor placed inside laboratory shoes. The sensor is connected to a potentiometer powered by a 9V battery and attached with a buzzer; B: Participant set up of the auditory biofeedback device; C: The cross-line laser and 2 AA battery pack; D: Participants set up of the visual biofeedback device.

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CHAPTER 3: RELATIONSHIP BETWEEN PLANTAR PRESSURE PROFILE AND TALAR CARTILAGE CHARACTERISTICS IN INDIVIDUALS WITH CHRONIC ANKLE INSTABILITY

3.1 INTRODUCTION

An estimated 2 million ankle sprains occur annually in the United States[1] and nearly two thirds of those sprains will develop chronic symptoms, recurring sprains, and functional limitations.[2] Collectively, these poor outcomes are known as chronic ankle instability (CAI) which is associated with a multitude of biomechanical, sensorimotor, and structural impairments.[3] In addition to individuals with CAI having a less physically active lifestyle[4] and impacted health-related quality of life,[5] an ankle sprain increases the likelihood of developing posttraumatic osteoarthritis (PTOA) compared to individuals with no ankle sprain history.[6] The development of PTOA in patients with CAI can occur in as early as 10 years after their initial injury[7] and without an effective conservative treatment option for OA, it is imperative to mitigate modifiable risk factors of PTOA following ankle sprains through the rehabilitation process.

While it is likely all physical and functional impairments have an influence on ankle PTOA progression in individuals with CAI, the proposed mechanism of development is mechanically driven.[8-11] The most common biomechanical alteration in patients with CAI present as increased ankle inversion,[12] increased lateral plantar pressure,[13] and a laterally deviated center of pressure (COP) gait line.[14] This pattern places the individual closer to the mechanism of injury[15,16] and creates a disproportionate pattern of contact stress on the talar cartilage.[17,18] Specifically, the unequal distribution of contact stress[18] promotes degeneration of the medial talar cartilage[8-11] coinciding with the

most common site of ankle PTOA development.[7] Early markers of degenerative changes in cartilage include compositional fluctuations (e.g. proteoglycan density and collagen orientation)[19] which have been identified in individuals with CAI compared to healthy adults via magnetic resonance (MR) analysis.[20,21] Unfortunately, MR imaging is inaccessible to most patients and not a cost effective method for continued assessment of cartilage composition.

Assessing cartilage characteristics in pathological populations is becoming more common as imaging technologies continue to advance. Since the current standard in assessing cartilage health is with MR imaging, there is a need to validate the use of ultrasonography (US) as a surrogate measurement of cartilage health. A recent report provided support for the relationship between US-based images of the talar articular cartilage thickness and MR-based volume measures at rest.[22] In addition to measuring cartilage thickness, there are association between B-mode US echo intensity (i.e. brightness of an image) and arthroscopic cartilage damage at the knee.[23] Cartilage echo intensity may provide an additional quantitative analysis of cartilage health (e.g. water content).[24,25] While compositional changes provide early signs of OA, the overall health of cartilage is dependent on the applied loading patterns it endures.[19,26] Therefore, a suitable method to determine the resiliency of human cartilage is by assessing deformational behavior.

A study by Song et al.,[27] was the first to distinguish that US of the talar articular cartilage is sensitive enough to detect cartilage deformation patterns after loading. The results of this study provide insight that patients with and without CAI have different rates of cartilage deformation following both a static (i.e. single-limb standing) and

dynamic (i.e. hopping) loading protocol.[27] However, this investigation did not assess deformation following walking, quantify the magnitude of loading, or assess other characteristics of cartilage health (e.g. echo intensity); therefore, the association of walking biomechanics and talar cartilage characteristics remain unknown. Considering the connection between walking gait and talar cartilage contact strain patterns, understanding the relationship between walking biomechanics and US-based talar cartilage characteristics is crucial in guiding impairment-based rehabilitation protocols for patients with CAI. Therefore, the purpose of this study was to investigate the relationship between biomechanical loading patterns during walking and characteristics of talar articular cartilage measured via ultrasonography. We hypothesize, larger lateral plantar pressure will correlate with more medial cartilage deformation and overall water content loss after 30 minutes of treadmill walking.

A secondary purpose was to explore the relationship between other commonly observed clinical impairments in-patients with CAI such as biomechanics during a step-down, lateral hop, static balance, and dorsiflexion range of motion.

3.2 METHODS

Participants

Twenty-three adults with CAI were recruited from a university setting and local community. Inclusion criteria for participant was to be between the age of 18 and 35 and meeting the recommended criteria set forth by the International Ankle Consortium[28]: 1) History of ≥ 1 significant ankle sprain 12 months prior to study enrollment 2) most recent ankle sprain occurred greater than 3 months prior 3) history of "giving way" established by scoring ≥11 on the Identification of Functional Ankle Instability (IdFAI)

4) self-reported ankle function determined by scoring ≤95% and ≤85% on the Foot and Ankle Ability Measure (FAAM) Activities of Daily living (-ADL) and Sport (-S) subscales, respectively. Potential participants also completed the International Physical Activity Questionnaire (IPAQ) indicating they were physically active. Individuals were excluded from participating if they did not meet the aforementioned criteria or disclosed any of the following: 1) history of ankle surgery 2) history of lower extremity fracture which required realignment 3) any acute lower extremity musculoskeletal injury within the previous 6 weeks of enrollment 4) any other known pathologies that would cause an alteration in plantar pressure during gait. In the event an eligible participant reported a history of bilateral ankle sprains, the worst perceived unstable ankle was chosen as the involved limb.

Informed consent was obtained upon arrival to the laboratory (Figure 3.1). Participants were immediately placed in a long-sitting position on a treatment table to begin a 30-minute offloading period. After the offloading period, participants were positioned with their back flat against the wall, the involved limb was positioned with the knee at 90°, verified via goniometer, and the foot flat on the table. The distance of the heel from the wall was measured and used to standardize participant position between measurements. A LOGIQe B-mode ultrasound system (General Electric, Fairfield, CT, USA) and a 12-MHz linear probe was used to collect talar cartilage images (Figure 3.2). The measurement depth was independently set for each participant allowing for the best view of the cartilage and was kept constant for all measurements. The probe was positioned transversely between the medial and lateral malleoli and adjusted until the talar cartilage appeared to be maximally reflected. A transparent grid was placed over the

ultrasound screen to ensure image consistency within sessions. Three images were before (unloaded) and immediately after (loaded) 30 minutes of treadmill walking. The aforementioned US procedures have been shown to have a within-session test-retest reliability of 0.982.[22]

Before walking, participants were fitted with the Pedar-X insole system (Novel, St. Paul, MN) with 1-mm thick pressure insoles placed into neutral laboratory shoes (model M680V3, New Balance Inc., Boston, MA). Pressure insoles were connected to a transmitter that was worn around the waist in a belt. The transmitter was connected via Bluetooth to a computer database.

Participants then walked on a treadmill (Precor, Inc. Woodinville, WA) at a self-selected pace for 30 minutes. A thirty second recording of plantar pressure was collected at 30 seconds and every 5 minutes thereafter. Immediately following the 30-minute walking period, participants returned to the treatment table and US process was repeated. No more than 2-3 steps were taken from the treadmill to the treatment table after walking and all images were taken within 1 minute of ending the walking trial.

Following the loaded US image acquisition, participants completed 4 tasks which were block randomized. First, they randomly completed two tasks with the Pedar-X system: a step-down and lateral hopping task. The step-down task was performed with the participant standing on a 30cm tall box, was instructed to step-down with their involved limb and continue their forward momentum with a few more steps. The lateral hopping was performed with their hands on the hips, gaze forward at a wall in front of them, and instructed to hop laterally over a piece of tape on the ground and return to the starting position.

The plantar pressure in-shoe insole system was removed, and participants randomly performed either the single-limb static balance with their eyes opened and closed or the weight-bearing lunge task (WBLT). Single-Limb static balance was performed as participants stood barefoot on an AccuSway Optimized force platform (Advanced Medical Technology, Inc, Watertown, MA) sampled at a rate of 50Hz, with their uninvolved limb placed in 30° hip flexion and 45° knee flexion with hands placed on their hips.[25] Participants were instructed to "stand as still as possible while maintaining the test position" and given three practice trials. Three successful 10-second trials were recorded with their eyes open and eyes closed. Failed trials, where the participant moved out of the test position, were repeated. A maximum of 10 total attempts were allowed for each condition.

The WBLT was performed as participants stood barefoot with their involved foot on tape measure secured to the ground. They were instructed to flex their knee to wall while keeping their heel flat on the ground. All subjects performed three practice trials followed by three testing trials. Each participant started at 2cm away from the wall and progressed away from the wall by 1 cm, until a failed lunge was performed. They were then progressed forward by 0.1 cm until they could successfully flex their knee to the wall while maintaining their heel on the ground.[29] The maximum distance was recorded and averaged across the three successful trials.

Data Processing

Biomechanical Outcomes

A total of seven 30-second measurements (minutes 0, 5, 10, 15, 20, 25, 30) were recorded with the Pedar-X system throughout the 30-minute treadmill walking task. The

middle 10 steps from each of these 30-second trials were used for data analysis. To create a plantar pressure profile to represent the average loading over the entire 30-minute walking trial, variables were averaged across the 7 trials. Plantar pressure primary variables of interest included: peak pressure (kPa) and maximum force (N, normalized to bodyweight). Secondary plantar pressure variables were: contact area (cm^2), contact time(ms), pressure-time integral (kPa*s), and force-time integral (N*s). Each plantar pressure variable was calculated in 10 regions of the foot (total foot, medial and lateral heel, medial and lateral midfoot, medial, central, and lateral forefoot, great toe, and lesser toes).

The same middle 10 steps from each of the 7 trials described above were used to calculate the COP gait line during walking using a custom MATLAB (version R2019b, MathWorks, Natick, MA) code using previously reported methods.[30-32] Briefly, COP gait line was calculated by taking the distance (mm) of the COP location from the medial border of the foot during and averaged in 10% increments producing 10 discrete data points representing 100% of the stance phase of gait. For example, 1-10% of the COP data points were averaged and represent the first 10% of stance, likewise 11-20% of the COP data points represent 11-20% of stance and so forth.

The same primary and secondary plantar pressure variables and regions as described above were calculated for the step down and lateral hopping tasks. Each of the ten step down trials were averaged and used for analysis. Similarly, only the ten hops in the lateral direction during the hopping task were selected and averaged for analysis.

Ultrasound Image Processing

Blinding during image processing was achieved by images being removed of any identifying information using a custom MATLAB code. The assessor was aware each block of images was associated with an individual participant but was unaware of the specific participant or session each image was taken.

Normalized talar cartilage cross-sectional area (CSA),[27] and echo intensity in three regions of interest were measured using ImageJ (National Institute for Health, Bethesda, MD). First, the total length of the cartilage was measured, from the midline, the length of the lateral and medial regions was measured in mm. Each region was then outlined using the polygon feature to obtain CSA (mm^2), and then divided by the length of that region to obtain a total, medial, and lateral normalized thickness. Cartilage deformation of the normalized thickness was calculated as a percent to determine the change of loading response after 30-minutes of treadmill walking using the following formula: $\%\Delta = [(Mean_{Loaded} - Mean_{Unloaded}) / Mean_{Loaded}] * 100$. Regional echo intensity was calculated as the average grey-scale pixel value ranging between 0 (black) and 255 (white). Larger grey-scale value indicates less water content, while smaller values indicate more water content.[24,25] Resting echo intensity values are averaged from unloaded US images and change in echo intensity values were calculated as the mean difference (Loaded – Unloaded) US images in the total, medial, and lateral regions of interest.

Balance Outcomes

The average of the three successful EO and EC balance trials were used for analysis. Area and 95% eclipse and velocity were extracted from Balance Clinic (Advanced Medical Technology, Inc) software. A custom MATLAB code was used to

calculate the time-to-boundary (TTB)[33] and COP data point location[34] during each balance trial in each condition. TTB is the time (ms) it would take the COP to reach the nearest border of the foot if it were to travel in the same direction and velocity. The TTB mean minima and standard deviation of the mean minima in the anteroposterior and mediolateral directions were used for analysis. The location of each COP data point was calculated based on its appearance in one of the four quadrants of the foot: anteromedial, anterolateral, posteromedial, posterolateral.

Statistical Analysis

Pearson Correlations Coefficients were used to determine the relationship between talar cartilage characteristics (resting thickness, deformation, echo intensity) and plantar pressure profile during 30-minute treadmill walking, step down, and lateral hop. Correlation Coefficients were also calculated between cartilage measures and demographics, PROs, balance measures, and DRFOM. Any variable that violated the Shapiro-Wilk test for normality were tested using Spearman's rho correlations. Significance was set *a priori* at $p \leq 0.05$. Interpretation of correlation coefficients (r or ρ) were interpreted as weak (0.00 – 0.40), moderate (0.41 - 0.69), and strong (0.70 to 1.00).

3.3 RESULTS

Demographic information can be found in Table 3.1. A total of 20 individuals with CAI (11 females, 21.8 ± 2.60 years, 169.11 ± 10.14 cm, 77.35 ± 14.94 kg) were included in the final analysis. Three participants were excluded from the analysis as they disclosed disqualifying information following the informed consent process. Means and standard deviations for all cartilage characteristic variable scan be found in Table 3.2

Demographics, PROs, and Ankle History

Age was moderately and positively correlated with total echo intensity after walking (r=0.478, p=0.033). No other associations were found between cartilage measures and demographics, PRO's, or previous ankle history (p>0.05, Table 3.3).

Plantar Pressure Profile

Results for primary plantar pressure variables, peak pressure and maximum force, can be found in Table 3.4 and Table 3.5, respectively. All results for secondary variables and tasks can be found in Tables A3.5 – A3.15.

Walking

Greater medial talar cartilage deformation was significantly correlated with greater peak pressure (kPa) in the lateral midfoot (r=0.482, p=0.031) and lateral forefoot (r=0.451, p=0.046). Greater peak pressure in the medial midfoot was correlated with larger resting echo intensity values in the medial cartilage (r=0.448, p=0.048) (Table 3.4).

Greater max force (N) in the medial forefoot was positively correlated with greater resting thickness in the total (r=0.539, p=0.014), medial (r=0.544, p=0.013), and lateral (r=0.484, p=0.031) regions. Less medial forefoot maximum force was correlated with greater total (r=0.0.468, p=0.037) medial (r=0.491, p=0.028) echo intensity values at rest. Greater lateral midfoot max force was correlated with and greater total (r=0.450, p=0.047) and lateral (r=0.458, p=0.044) deformation. Similarly, greater max force in the central forefoot was correlated with greater total (r=0.508, p=0.022) and lateral (r=0.614, p=0.004) deformation. Additionally, greater lateral forefoot max force was correlated with greater total (r=0.492, p=0.027) and lateral (r=0.532, p=0.016) deformation. Maximum force in the total foot was correlated with lateral echo intensity after walking

(r=0.473, p=0.035), indicating greater force over the entire foot relates to a greater change in echo intensity (Table 3.5).

COP gait line

A greater total cartilage deformation was correlated with a more lateral COP gait line at 15% (r=0.500, p=0.025), 25% (r=0.508, p=0.022), 35% (r=0.457, p=0.043) of stance. A greater lateral cartilage deformation was correlated with a more lateral COP gait line at 15% (r=0.587, p=0.007), 25% (r=0.594, p=0.006), 35% (r=0.522, p=0.0418) of stance (Table 3.6).

Dorsiflexion Range of Motion

A greater distance on the WBLT was positively correlated with a greater positive change in lateral echo intensity (r=0.539, p=0.021). No other cartilage measure was correlated with WBLT (p>0.05) (Table A3.9).

Static Balance

Area and Velocity

There were no significant correlations between cartilage measures and traditional measures of static balance (e.g. area and velocity) during EO or EC trials (Table A3.10).

Time-to-Boundary

Eyes Open

A smaller TTB standard deviation of the mean minima in the M-L direction during eyes open static balance correlates with smaller lateral resting thickness (r=0.468, p=0.038), and with larger resting echo intensity values in the total (r=0.543, p=0.013), medial (r=0.470, p=0.037), and lateral (r=0.580, p=0.007) regions (Table A3.10). More COP data points in the posterolateral region of the foot during eyes open balance

correlates with smaller echo intensity values after walking in the total (r=0.517, p=0.019) and lateral (r=0.460, p=0.041) regions (Table A3.11).

Eyes Closed

A smaller TTB standard deviation of the mean minima in the M-L direction during eyes closed static balance correlates with smaller resting cartilage thickness in the total (r=0.445, p=0.050) and medial (r=0.464, p=0.039) regions and also correlated with larger resting echo intensity values in the total (r=0.476, p=0.034) and lateral (r=0.473, p=0.035) regions (Table A3.10). More COP data points in the posterolateral region of the foot during EC balance correlated with greater lateral deformation (r=0.474, p=0.035) during walking (Table A3.11).

Lateral Hop

Plantar pressure

Greater lateral midfoot plantar pressure during a lateral hop correlated with a larger resting echo intensity value in the total (r=0.625, p=0.003), medial (r=0.622, p=0.003), and lateral (r=0.558, p=0.011) regions. Central forefoot peak pressure during a lateral hop negatively correlated with changes in echo intensity values in the lateral cartilage (r=0.450, p=0.047) after walking. Greater lateral forefoot plantar pressure during a lateral hop was correlated with a smaller resting thickness in the lateral region (r=0.458, p=0.042). Less plantar pressure in the lesser toes is correlated with greater lateral deformation after walking (r=0.463, p=0.040) (Table A3.12).

Maximum Force

Medial midfoot maximum force during a lateral hop was negatively correlated with total (r=0.477, p=0.033) and lateral (r=0.563, p=0.010) cartilage deformation.

Greater maximum force in lateral midfoot is correlated with smaller resting thickness in the total (r=0.459, p=0.042) and medial (r=0.527, p=0.017) regions, and correlated with larger resting echo intensity values in the total (r=0.551, p=0.012) and medial (r=0.598, p=0.005) regions. Maximum force in the medial forefoot during a lateral hop was positively correlated with medial (r=0.523, p=0.018) cartilage thickness at rest. Maximum force in the lateral forefoot during a lateral hop was negatively correlated with total (r=0.474, p=0.035), medial (r=0.463, p=0.040), and lateral (r=0.460, p=0.041) resting cartilage thickness, and positively correlated with resting echo intensity in the total (r=0.542, p=0.014), medial (r=0.525, p=0.017), and lateral (r=0.502, p=0.024) regions (Table A3.13).

Step Down

Peak Pressure

Greater plantar pressure in the lateral midfoot during step-down was positively correlated with larger resting echo intensity values in the total (r=0.535, p=0.018), medial (r=0.546, p=0.016), and lateral (r=0.460, p=0.047) regions. Greater plantar pressure in the lateral forefoot correlated with smaller resting thickness in the total (r=0.465, p=0.045) and medial (r=0.480, p=0.038) regions and larger resting echo intensity values in the total (r=0.460, p=0.047) and lateral (r=0.465, p=0.045) regions (Table A3.14).

Maximum Force

Total foot was negatively correlated with medial resting thickness (r=0.509, p=0.026), and positively correlated with total (r=0.486, p=0.035) and medial (r=0.537, p=0.018) resting echo intensity values. A greater max force in the lateral midfoot (r=0.457, p=0.049) and forefoot (r=0.488p=0.034) during step down task is correlated

with smaller medial cartilage thickness at rest. Greater maximum force in the lateral midfoot is correlated with larger resting echo intensity values in the total ($r=0.467$, $p=0.044$) and medial ($r=0.531$, $p=0.019$) cartilage regions. Greater maximum force in the medial forefoot correlated with a larger reduction in echo intensity values in the lateral region ($r=0.505$, $p=0.028$) before and after walking (Table A3.15).

3.4 DISCUSSION

The primary purpose of this study was to explore the relationship between biomechanical loading patterns during walking and US-based talar cartilage characteristics. Our central hypothesis was greater lateral plantar pressure measures would correlate with worse US characteristics in the medial talar cartilage. While some of our results support this hypothesis, there were several findings which add to our overall understanding regarding biomechanical patterns and ankle joint health in patients with CAI.

This is the first study to examine the relationship between plantar pressure patterns during walking and cartilage characteristics measured with ultrasonography. An increased lateral plantar pressure is common in patients with CAI and this altered biomechanical pattern is associated with larger cartilage deformation in the medial cartilage. A greater deformation after loading has been theorized to indicate less healthy tissue as it is unable to withstand tensile forces. This finding contributes to the growing body of literature supporting abnormal biomechanics contribute to degeneration of talar cartilage.[7,17,35,36]

Not every abnormal gait pattern in our sample was associated with worse medial cartilage characteristics. For example, a more laterally displaced COP gait line between

10 and 40% of stance was moderately correlated with greater deformation in the total and lateral regions, but not the medial. The first 40% of stance corresponds to initial contact and loading response and corresponds to contact in the heel and midfoot region of the foot. During this early phase, the foot transitions from a supinated position at initial contact to pronated during first half of midstance.[37] As the COP progresses during late midstance to toe-off, the foot begins to supinate once again. It is during this transition, in which individuals with CAI tend to be more supinated and place more pressure in the lateral forefoot.[38] The abnormal medial shift in talar cartilage strain observed in unstable ankles does not occur until 100% of body weight load is applied during gait,[17] which occurs in the single-limb support of mid- to terminal stance phases. Therefore, it is plausible the relationship between lateral forefoot peak pressures is more important in cartilage deformation than the patterns observed in the early stance phase.

Some biomechanical patterns demonstrated by our participants were related to better cartilage characteristics at rest. Specifically, more force applied in the medial forefoot (i.e. typical gait pattern for healthy adults) was associated with smaller echo intensity values and larger cartilage thickness in all regions. Cartilage strain patterns in healthy ankles present more laterally during full weight bearing stance,[39] likely due to healthy ankles typically demonstrating more eversion during loading whereas ankle instability tends to cause a more inverted/supinated foot position and thus increased medial cartilage strain. Our sample had an average of -2.34% cartilage deformation in the medial region, where some individuals demonstrated an increase in thickness (Maximum Δ: 30%) after loading rather than a reduction (Maximum Δ: -44%). It is plausible participants in this cohort who meet standard recommendations for CAI have other

impairments leading to their condition rather than abnormal biomechanical walking patterns. For example, some authors[17,36] theorized the altered contact strain was due to the lack of ligamentous integrity following an inversion sprain, which leads to an anteriorly translated and internally rotated talus. Our primary objective was not to assess joint laxity in relation to cartilage health, but it may be an important component for researchers to consider. Future studies should separate participants by clinical impairments[40] to determine if relationship to talar cartilage characteristics differ between domains.

A static loading protocol elicited greater deformation in the talar cartilage compared to dynamic loading.[27] Walking does not apply as much stress on the cartilage as constant static loading which may explain the wide range of deformational behaviors of this study sample. However, our secondary results indicate altered plantar pressure distributions during a step-down and lateral hopping are associated with a thinner articular cartilage and larger echo intensity values in an unloaded state. If patients have abnormal plantar pressure patterns during normal daily activities (e.g. walking, stepping of a curb, going down stairs, etc.), then perhaps the constant irregular stresses may explain the associated thinner cartilage and worse composition (e.g. water/collagen) presented at rest. Thus, it is likely a 30-minute walking protocol was not enough loading to fully identify the deformational patterns these patients exhibit on a daily basis. Future studies should quantify the daily or weekly loading in order to better understand how activities of daily life influence cartilage behavior.

Although traditional measures of balance (area and velocity) were not associated with any cartilage measure, a smaller TTB minima SD (e.g., more constrained

sensorimotor system) in the mediolateral direction was correlated with larger echo intensity values. The TTB measurement is more sensitive to balance impairments compared to 95% area and velocity measures. It is the time in which the COP would reach the boundary of the base of support thus causing a loss of balance. The SD of the TTB minima provides insight into the amount of variation in the COP and an individual's ability to respond to changes in COP location. When the sensorimotor system has less variability when exposed to an unstable environment, an individual has less degrees of freedom to make a correction to avoid injury. Instability, episodes of the ankle giving way, and recurring injuries are common complaints of those with CAI. The constrained sensorimotor system, expressed by smaller TTB SD is moderately correlated with larger echo intensity values at rest (i.e. worse cartilage feature). Similar to the potential abnormal daily biomechanical patterns and resting thickness, a worse overall postural control system during daily activities may explain this relationship.

We acknowledge some limitations of this investigation. First, our sample was comprised of young adults (mean age 21 years) who are physically active whom may not be exhibiting early signs of PTOA. The relationship between PRO measures such as the Ankle Osteoarthritis Scale and cartilage characteristics may provide a better indicate of which clinical signs and symptoms are important for ankle joint health. Another limitation of this study was a lack of a healthy group which may have strengthened the associated between abnormal gait patterns and cartilage features. Further, we did not control for or quantify the amount of activity our participants were involved in the days leading up to our data collection session. Perhaps the amount of resting thickness and echo intensity is related to the amount stress from the day prior.

Conclusion

Overall, this study adds to the existing literature that US imaging of talar articular cartilage features are associated with biomechanical patterns during walking and other tasks. More lateral peak pressure during walking is associated with increased medial cartilage deformation whereas better resting cartilage characteristics are associated with a more medial gait pattern. Better knowledge surrounding deformational patterns in talar cartilage using clinically accessible imagining techniques will continue to advance researchers and clinicians understanding surrounding the influence of rehabilitation after an ankle sprain and the influence of long-term joint health.

3.5 Tables

Table 3.1. Participant Demographics (mean ± standard deviation)

	Chronic Ankle Instability (n=20)
Sex (males : females), No.	9 : 11
Age, y	21.85 ± 2.60
Height, cm	169.11 ± 10.14
Weight, kg	77.35 ± 14.94
Ankle sprains, No.	2.85 ± 1.75
Time since first ankle sprain, mo	75.6 ± 39.91
Time since most recent ankle sprain, mo	29.05 ± 33.80
Foot and Ankle Ability Measure, %	85.52 ± 7.01
Foot and Ankle Ability Measure-Sport Scale, %	66.16 ± 11.77
Identification of Functional Ankle Instability score	21.90 ± 4.36

Table 3.2. Talar Cartilage Characteristics

Resting Thickness	Mean ± Standard Deviation (mm)	Deformation (% Change)
Total	0.68 ± 0.15	-4.57 ± 15.88
Medial	0.67 ± 0.17	-2.34 ± 19.87
Lateral	0.67 ± 0.15	-6.02 ± 16.16
Resting Echo Intensity	Mean ± Standard Deviation (grey scale)	Raw Difference (Post – Pre)
Total	142.72 ± 10.95	0.24 ± 5.32
Medial	144.02 ± 13.35	-0.43 ± 7.84
Lateral	141.42 ± 9.67	0.91 ± 4.82

Table 3.3 Correlation Coefficients Between Talar Cartilage Characteristics, Demographics, Patient-Reported Outcomes, And Ankle Sprain History

	Age (years)	Height (cm)	Weight (kg)	BMI	IdFAI	FAAM ADL	FAAM Sport	No. Previous LAS	Time since first LAS (mo)	Time since most recent LAS (mo)
Resting Thickness										
Total	0.175	0.378	0.220	0.080	0.262	-0.099	0.153	-0.014	0.066	-0.276
Medial	0.097	0.271	0.192	0.137	0.239	-0.078	0.080	0.035	0.177	-0.240
Lateral	0.322	0.421	0.198	0.053	0.255	-0.139	0.200	0.106	-0.08	-0.368
Deformation										
Total	0.149	-0.106	-0.180	-0.045	0.009	-0.028	-0.157	-0.018	0.325	0.175
Medial	-0.095	-0.210	-0.323	-0.146	-0.013	-0.021	-0.090	-0.059	0.257	0.163
Lateral	0.246	-0.120	-0.064	0.065	0.056	-0.021	-0.174	0.014	0.254	0.096
Resting Echo Intensity										
Total	-0.140	-0.070	0.086	0.032	-0.272	0.029	-0.075	0.186	0.023	0.065
Medial	-0.124	-0.118	0.051	-0.005	-0.343	0.058	-0.114	0.152	0.058	0.093
Lateral	-0.250	-0.038	0.009	-0.030	-0.142	-0.015	-0.012	0.081	-0.05	0.075
Change Echo Intensity										
Total	.478*	0.194	0.008	0.033	-0.083	-0.254	0.083	-0.002	-0.03	0.023
Medial	0.273	0.027	0.005	0.083	-0.193	-0.335	-0.066	-0.008	-0.01	0.073
Lateral	0.414	0.372	0.055	0.011	0.130	-0.015	0.289	-0.067	-0.25	-0.225

*. Correlation is significant at the 0.05 level (2-tailed).

Table 3.4 Pearson Product Correlations Between Talar Cartilage Characteristics and Plantar Pressure during 30-minute treadmill walking

	Total	Medial Heel	Lateral Heel	Medial Midfoot	Lateral midfoot	Medial Forefoot	Central Forefoot	Lateral Forefoot	Great Toe	Lesser Toes
Resting Thickness										
Total	0.040	-0.086	-0.095	-0.256	-0.291	0.124	0.018	-0.073	0.146	0.115
Medial	0.005	-0.114	-0.108	-0.210	-0.253	0.096	-0.026	-0.099	0.082	0.027
Lateral	0.061	-0.071	-0.096	-0.288	-0.331	0.124	0.044	-0.064	0.190	0.182
Deformation										
Total	-0.202	-0.022	0.010	-0.091	-0.298	-0.143	-0.325	-0.331	-0.214	-0.182
Medial	-0.279	-0.094	-0.062	-0.167	-0.482*	-0.242	-0.374	-0.451*	-0.283	-0.218
Lateral	-0.051	0.076	0.102	0.008	-0.059	0.024	-0.168	-0.129	-0.072	-0.079
Resting Echo Intensity										
Total	0.147	0.165	0.197	0.310	0.361	0.094	0.214	0.185	0.009	0.102
Medial	0.032	0.025	0.048	0.448*	0.315	0.014	0.131	0.126	-0.110	-0.005
Lateral	0.290	0.339	0.379	0.271	0.382	0.193	0.304	0.245	0.173	0.238
Change Echo Intensity										
Total	0.076	-0.042	-0.133	-0.056	0.049	0.038	0.067	0.162	0.142	-0.067
Medial	0.090	0.005	-0.047	0.019	0.156	0.045	0.047	0.122	0.083	-0.148
Lateral	0.022	-0.100	-0.218	-0.154	-0.144	0.012	0.071	0.159	0.178	0.093

*. Correlation is significant at the 0.05 level (2-tailed)

Table 3.5 Correlation Coefficients Between Talar Cartilage Characteristics and Maximum Force during 30-minute treadmill walking

	Total	Medial Heel	Lateral Heel	Medial Midfoot	Lateral midfoot	Medial Forefoot	Central Forefoot	Lateral Forefoot	Great Toe	Lesser Toes
Resting Thickness										
Total	0.113	-0.035	-0.138	0.083	0.006	.539*	0.080	0.084	0.359	0.231
Medial	-0.014	-0.037	-0.112	0.014	-0.083	.544*	-0.003	0.072	0.325	0.141
Lateral	0.225	-0.037	-0.177	0.191	0.095	.484*	0.105	0.078	0.379	0.297
Deformation										
Total	-0.144	-0.135	-0.192	-0.340	-.450*	-0.266	-.508*	-.492*	-0.171	-0.276
Medial	-0.031	-0.093	-0.126	-0.220	-0.349	-0.176	-0.347	-0.353	-0.260	-0.252
Lateral	-0.239	-0.170	-0.228	-0.424	-.458*	-0.318	-.614**	-.532*	-0.128	-0.240
Resting Echo Intensity										
Total	-0.028	0.023	0.095	-0.051	0.060	-.468*	-0.069	-0.131	-0.083	-0.222
Medial	-0.109	-0.042	-0.022	-0.062	0.094	-.491*	-0.119	-0.153	-0.253	-0.288
Lateral	0.088	0.111	0.246	-0.087	0.005	-0.381	-0.038	-0.085	0.074	-0.105
Change Echo Intensity										
Total	0.282	0.048	-0.209	-0.126	-0.064	0.006	0.119	0.225	0.096	0.190
Medial	0.092	0.081	-0.133	-0.295	-0.157	-0.152	-0.054	0.129	-0.119	0.031
Lateral	.473*	-0.026	-0.244	0.254	0.113	0.261	0.292	0.286	0.302	0.368

**. Correlation is significant at the 0.01 level (2-tailed). *. Correlation is significant at the 0.05 level (2-tailed).

Table 3.6 Correlation Coefficients Between Talar Cartilage Characteristics and COP Gait Line during 30-minute treadmill

	5%	15%	25%	35%	45%	55%	65%	75%	85%	95%
Resting Thickness										
Total	0.281	0.177	-0.006	-0.085	-0.122	-0.139	-0.180	-0.232	-0.202	-0.136
Medial	0.232	0.096	-0.095	-0.182	-0.222	-0.231	-0.273	-0.323	-0.281	-0.217
Lateral	0.286	0.233	0.080	0.013	-0.018	-0.042	-0.071	-0.112	-0.087	-0.023
Deformation										
Total	-0.447	-0.500*	-0.508*	-0.457*	-0.403	-0.413	-0.307	-0.242	-0.185	-0.059
Medial	-0.316	-0.390	-0.400	-0.373	-0.371	-0.344	-0.242	-0.176	-0.108	0.019
Lateral	-0.435	-.587**	-0.594**	-0.522*	-0.427	-0.384	-0.302	-0.253	-0.216	-0.118
Resting Echo Intensity										
Total	-0.034	0.034	0.103	0.181	0.195	0.143	0.101	0.105	0.089	0.095
Medial	-0.089	0.030	0.122	0.195	0.206	0.175	0.160	0.195	0.215	0.214
Lateral	0.046	0.034	0.065	0.141	0.157	0.082	0.009	-0.031	-0.096	-0.080
Change Echo Intensity										
Total	0.016	0.033	-0.046	-0.040	-0.005	0.073	0.135	0.189	0.222	0.170
Medial	-0.087	-0.067	-0.124	-0.094	-0.053	0.015	0.067	0.141	0.212	0.182
Lateral	0.176	0.181	0.099	0.064	0.075	0.139	0.191	0.190	0.151	0.082

**. Correlation is significant at the 0.01 level (2-tailed). *. Correlation is significant at the 0.05 level (2-tailed)

3.6 FIGURES

Figure 3.1. Procedures for Testing Sessions

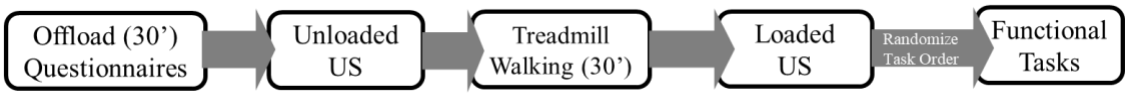
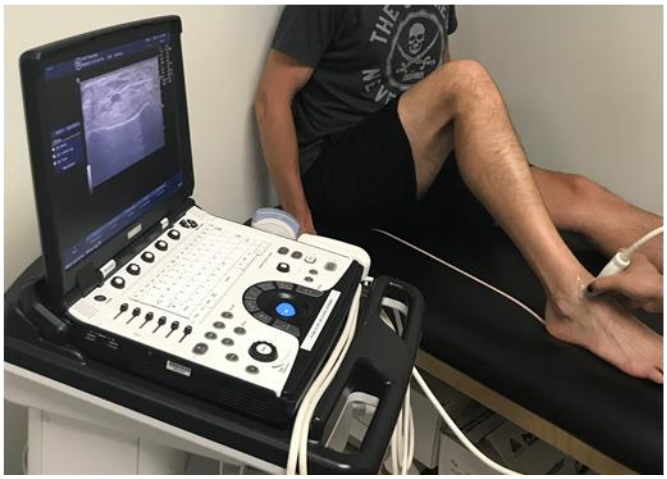


Figure 3.3 Ultrasound Acquisition



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CHAPTER 4: EFFECTS OF 2 WEEK GAIT TRAINING WITH EXTERNAL BIOFEEDBACK ON BIOMECHANICS AND TALAR ARTICULAR CARTILAGE CHARACTERISTICS AMONG INDIVIDUALS WITH CHRONIC ANKLE INSTABILITY

4.1 INTRODUCTION

Chronic ankle instability (CAI) is the culmination of poor outcomes following an acute lateral ankle sprain often described by feelings of instability, giving way episodes, and recurring sprains.[1] In addition, individuals with CAI demonstrate declines in physical activity levels[2] and health-related quality of life.[3] Generally perceived by patients as an insignificant injury with minor consequences and a swift recovery, the lack of proper attention to treatment sparks a cycle of disability in 40% to upwards of 70% of individuals.[4] Moreover, posttraumatic osteoarthritis (PTOA) at the ankle has been documented to develop in 78% of patients within 10 years of their initial ankle injury,[5] which causes further pain, physical limitations, and reductions in quality of life.[6] It is imperative to break the continuum of dysfunction through effective rehabilitation for patients with CAI to mitigate the life-long effects.

CAI is a complex clinical pathology with an assortment of possible sensorimotor impairments that can remain present for >18 months following an index ankle sprain.[7] Abnormal biomechanical patterns, poor postural control, and restricted range of motion are some of the more common impairments and often the target of rehabilitation in this patient population.[8] Specific gait impairments include greater ankle inversion,[9] increased lateral plantar pressure,[10,11] and a laterally deviated center of pressure (COP).[11] This aberrant biomechanical profile not only places the foot closer to the mechanism of

injury,[12] but it is also likely leads to early-onset PTOA by altering the contact strain patterns of the talar articular cartilage.[13,14]

Current rehabilitation protocols after an ankle sprain focus on treating balance deficits,[15] range of motion restrictions,[16] and muscle weakness.[17] While these programs have demonstrated beneficial improvements in the targeted impairments, they have not been able to alter gait biomechanics.[18] A handful of recent studies using various interventions have been shown to be capable of altering gait.[19-22] However, there is limited research regarding the retention or the effects of isolated gait retraining on other impairments (e.g., measures of joint health, postural control, functional task biomechanics). Therefore, it is unknown if patients with CAI can adopt improved gait patterns after a gait training intervention has ceased and the potential for a cross-over effect into other tasks.

Considering the sensorimotor involvement in a CAI population, researchers have utilized an external focus of attention during gait training which has shown early promise in correcting abnormal biomechanical patterns in individuals with CAI. One of these gait training protocols utilizes an auditory biofeedback device which has improved biomechanics during treadmill walking[23] and functional tasks.[24] However, this device has only been examined for real-time alterations and has yet to been studied for long-term use as a gait retraining tool. In addition to studying the effects of a multisession of gait training, quantifying and monitoring the health of the talar articular cartilage is crucial in understanding the impact of intervention techniques on long-term joint health outcomes.

Early markers of degenerative changes in cartilage include overall compositional changes and occurs through mechanobiological factors.[25] Changes in structural integrity

reduce the resiliency of articular cartilage to absorb forces during loading.[26] Overall health of cartilage is dependent on the applied loading patterns it endures[25,27] and its ability to absorb forces that cause deformation.[26] A suitable method to determine the resiliency of human cartilage is by assessing deformational behavior. The standard for assessing cartilage deformation is through magnetic resonance imaging (MRI) and has been previously used to quantify talar cartilage deformation after loading.[26] The downside to these expensive techniques is the inaccessibility of most clinicians and patients. Recently, a novel ultrasound method assessing cartilage deformation has been established at the knee[28] and ankle[29] but has yet to be applied in the context of a gait retaining intervention. Ultrasonography is an inexpensive and speedier alternative imaging technique that is more accessible to clinicians and patients. We intend to use these novel methods to assess cartilage deformation at the ankle after loading and determine if cartilage deformation is responsive to gait retraining.

The purpose of this study was to examine the effects of a 2-week gait training program using auditory biofeedback compared to a control condition on biomechanical patterns, ankle joint health, and patient reported function. A secondary purpose was to reveal the potential for this gait training program to influence other impairment domains such as: biomechanics during functional activities, static postural control, and dorsiflexion range of motion. We hypothesize the AudFB group will significantly improve in all impairment domains compared to a control group.

4.2 METHODS

Participants

Twenty adults with CAI were recruited from the University and local community. Inclusion criteria for participant was to be between the age of 18 and 35 and meeting the recommended criteria set forth by the International Ankle Consortium[30]: 1) History of ≥ 1 significant ankle sprain 12 months prior to study enrollment 2) most recent ankle sprain occurred greater than 3 months prior 3) history of "giving way" established by scoring ≥11 on the Identification of Functional Ankle Instability (IdFAI) 4) self-reported ankle function determined by scoring ≤95% and ≤85% on the Foot and Ankle Ability Measure (FAAM) Activities of Daily living (-ADL) and Sport (-S) subscales, respectively. Potential participants also completed the International Physical Activity Questionnaire (IPAQ) indicating they were physically active. Individuals were excluded from participating if they did not meet the aforementioned criteria or disclosed any of the following: 1) history of ankle surgery 2) history of lower extremity fracture which required realignment 3) any acute lower extremity musculoskeletal injury within the previous 6 weeks of enrollment 4) any other known pathologies that would cause an alteration in plantar pressure during gait. In the event an eligible participant reported a history of bilateral ankle sprains, the worst perceived unstable ankle was chosen as the involved limb.

Study Design

Once eligibility was established, written informed consent was obtained prior to any data collection. All testing and intervention sessions were performed in the Biodynamics Laboratory at UNC Charlotte. A randomized controlled trial was conducted using a single-blind design. A single researcher conducted each of the testing sessions: Baseline (Baseline), 24-48 hours after the final intervention session (Immediate-Post),

and 7 days after the final intervention session (1-Week Post). A second researcher supervised the 8 intervention sessions, which began 48-72 hours after baseline testing and was completed over a 2-week period (Figure 4.1).

Testing Sessions

Participants began sessions in a long-sit position for 30-minutes[31] before ultrasound images were taken of their ankle cartilage to unload the joint cartilage (unloaded). During ultrasound imaging, participants were positioned with their back flat against a wall with their hip and knee flexed to 90° and their foot flat against the table.[32] The distance of the heel from the wall was measured and used to standardize subject position between measurements. Three ultrasound images were taken with a 12-MHz linear transducer (LOGIQe, General Electric, Fairfield, CT, USA) positioned transversely between the medial and lateral malleoli while being adjusted until the talar cartilage appears to be maximally reflected. The measurement depth was independently set for each participant allowing for the best view of the cartilage and was kept constant for all measurements. Three separate images were taken and stored.

Next, participants were fitted with neutral athletic shoes (model M680V3, New Balance Inc., Boston, MA) and Pedar-X pressure in-shoe insoles (Novel Electronics, Inc., St. Paul, MN). They were then instructed to walk on a treadmill (Precor, Inc. Woodinville, WA) at a comfortable self-selected pace for a total of 30 minutes. This pace was used for all testing and intervention session. Thirty seconds of plantar pressure data were collected (100 Hz) at 30-seconds and every 5 minutes thereafter of the involved limb. Immediately following the 30-minute walking period, participants returned to the treatment table and US process was repeated (loaded). No more than 2-3 steps were taken

from the treadmill to the treatment table after walking and all images were taken within 1 minute of ending the walking trial.

Next, participants completed 4 tasks which were block randomized. First, they randomly completed two tasks with the Pedar insole system: a step-down and lateral hopping task.[24] Ten trials of the step-down task were performed with the participant standing on a 30-cm tall box. They were then instructed to step-down with their involved limb and continue their forward momentum with a few more steps. Next, ten consecutive lateral hops were performed with their hands on the hips, gaze forward at a wall in front of them, and instructed to hop laterally over a piece of tape on the ground and return to the starting position. Plantar pressure data was collected for the involved limb only during these two tasks.

The next block of tasks was performed barefoot and also randomized. Single-limb static balance was measured while participants stood on an AccuSway Optimized force platform (50 Hz) (AMTI, Watertown, MA) with their uninvolved limb placed in 30° hip flexion and 45° knee flexion with hands placed on their hips.[33] Participants were instructed to "stand as still as possible while maintaining the test position" and were given 3 practice trials followed by 3 successful 10-second trials. Balance was performed in both an eyes-open and eyes-closed conditions. Failed trials, where the participant moved out of the test position, were repeated. A maximum of 10 total attempts were allowed for each condition. The weight bearing lunge test (WBLT) was performed to quantify ankle dorsiflexion range of motion. It was performed using previously described procedures[34] where participants placed their involved limb on a tape measure on the floor beginning at a wall. With their hands flat against the wall, they were instructed to lunge

forward so their knee touched the wall, but their heel remained flat on the ground. The furthest distance (cm) was recorded to the nearest 0.10 cm.

Intervention Sessions

Within 48-72 hours of their baseline session, participants reported back to the laboratory to begin their 8-session gait training program. Before beginning the first intervention session began, pre-loaded ultrasound images were repeated to determine minimal detectable change scores (MDC). After ultrasound images were taken, participants were randomly assigned into either the control group (Control) or the intervention group (AudFB) via sealed, opaque envelopes with separate allocation schedules for males and females to improve the likelihood of equal distribution between groups. The gait training protocol was designed from previous studies using gait re-training,[35] auditory feedback instructions,[23] and best practices from motor learning research.[36] Each group (AudFB, Control) performed perform 8 intervention sessions (over 2 weeks) each consisting of 30-minutes of treadmill walking at the pace selected during Baseline. The Control group spent the same amount of time walking (minutes) as the AudFB group to account for any possible effects of the additional physical activity and steps taken per day; however, they were simply instructed to walk naturally and comfortably. The Control group was also never introduced to the auditory feedback.

Auditory Biofeedback

The AudFB group received the auditory feedback and were instructed to follow the cue to "walk in a manner where you do not hear a noise, but that is still as natural and comfortable as possible." It is recommended regular exposure to an external focus enriches the motor learning and performance effects[36]; therefore, participants were

exposed to the auditory feedback and instructed to follow our cue during the entire gait retraining session. The auditory biofeedback was given through a thin (14 x 25.4 x 0.203 mm) FlexiForce Load Sensor (Tekscan, Inc. South Boston, MA) placed on the sole of the shoe under the head of the 5th metatarsal for each participant. The pressure sensor connects to a FlexiForce Quickstart Board (31.75 x 31.75 mm) and a potentiometer (Tekscan, Inc. South Boston, MA) with an attached buzzer, powered with a 9-volt battery. The auditory instrument was calibrated for each participant prior to each intervention session by having them place their weight on the sensor and adjusting the potentiometer to the first point in which the buzzer produced a loud and sustainable noise.

Data Processing

Primary Biomechanical Outcomes

All plantar pressure data was processed in Novel Database Pro (Novel Electronics, Inc., St. Paul, MN). The average of the middle 10 steps during each time point while walking, the average of the 10 step downs and lateral hops were used for analysis. The primary variables of interest were peak pressure (kPa) and max force (N). The foot was divided into 10 regions: total object, medial heel, lateral heel, medial midfoot, lateral midfoot, medial forefoot, central forefoot, lateral forefoot, lesser toes, and great toe. Each plantar pressure variable was calculated for each region. The same middle 10 steps were used to calculate the COP gait line during walking using a custom MATLAB (version R2019b, MathWorks, Natick, MA) code using previously reported methods.[11,19,37] Briefly, COP trajectory was calculated by taking the distance (mm) of the COP location from the medial border of the foot and averaged in 10% increments

producing 10 data points representing 100% of the stance phase of gait. For example, 1-10% COP data points were averaged and are represented at 5% of stance likewise, 11-20% COP data points represent 15% of stance and so forth.

Ultrasound Image Processing

All images were stripped of any identifying information using a custom MATLAB code performed by a third member of the research team prior to processing. The assessor was aware each block of images was associated with an individual participant but was unaware of the actual participant or session of any image.

Normalized talar cartilage cross-sectional area (CSA),[29] and echo intensity in three regions of interest (total, medial, lateral) were measured using ImageJ (National Institute for Health, Bethesda, MD). First, the total length of the cartilage was measured. From the midline of the total length, the length of the lateral and medial regions was measured in mm. Each region was then outlined using the polygon feature to obtain CSA (mm^2) and then divided by the length of that region to obtain a total, medial, and lateral normalized thickness. Cartilage deformation of the normalized thickness was calculated as a percent to determine the change of loading response after 30-minutes of treadmill walking using the following formula: $\%\Delta = (Mean_{Loaded} - Mean_{Unloaded}) / Mean_{Unloaded.}$ A more positive percent change represents greater cartilage deformation. Echo intensity was calculated in each region (total, medial, lateral) as the average grey-scale pixel value ranging between 0 (black) and 255 (white). Resting echo intensity values are averaged from unloaded US images and change in echo intensity values were calculated as the mean difference (loaded - unloaded) US images in the total, medial, and lateral regions of interest.

In order to determine if changes in cartilage deformation exceed measurement error, MDC scores were calculated from unloaded images at Baseline and first intervention. The MDC was calculated using the following formula: SEM * √2 * 1.96, where SEM = SD √1-ICC.

4.2.6.3 Patient-Reported Outcome Measures

The FAAM-ADL and Sport were collected at Baseline, first intervention, Immediate-Post and 1-Week Post. In order to determine clinically meaningful changes in patient outcomes, MDC's were calculated between combined group scores at Baseline and first intervention, using the same formula previously mentioned.

Secondary Outcomes

Additional plantar pressure measures were extracted, including contact area (cm^2), contact time (ms), pressure-time integral (kPa*s) and force-time integral (N*s) during walking, step-down, and lateral hops.

The COP 95% confidence ellipse area (centimeters squared [cm^2]) and mean velocity (cm/s) were calculated using Balance Clinic software (AMTI, Watertown, MA) using a fourth-order, zero-lag, low pass filter with a cutoff frequency of 5 Hz. Time to boundary (TTB) variables (absolute minima, mean minima, and standard deviation of the minima) were calculated in the anteroposterior (AP) and mediolateral (ML) directions using a custom MATLAB code. TTB is the time (ms) it would take the COP to reach the nearest border of the foot if it were to travel in the same direction and velocity. Smaller area, velocity, and TTB values indicate worse postural control. Additionally, during each static balance trial, a time series of 500 COP data points (10s x 50Hz) were generated and a custom MATLAB code was used to determine location of each data point in four

quadrants of the foot (anteromedial, anterolateral, posteromedial, posterolateral).[38] More data points equate to more time their COP spent in the respective quadrant.

Statistical Analysis

Separate 2 x 3 (group by time) mixed-methods analysis of variances were applied to each dependent variable (plantar pressure measures, COP gait line, ultrasound measures, and PROs). The between-subject factor is group (AudFB, Control) and the within-subject factor is time (Baseline, Immediate-Post, 1-Week Post). Significant interactions and main effects will be evaluated using posthoc pairwise comparisons of Least Significant Difference correction. Alpha was set *a priori* as $p \leq 0.05$ for all analysis and following recommendations for statistical testing in sports medicine studies,[39] we did not control for multiple comparisons. Results will be reported as those with $p \leq 0.05$ or Hedges *g* effect sizes of moderate to large scales with 95% confidence intervals that did not cross 0. Effect sizes were interpreted as large (≥0.80), moderate (0.50-0.79) and small (0.20-0.49). Statistical analyses were conducted in SPSS v26 (SPSS, Inc., Chicago, IL) and Excel (Microsoft Office 2019, Microsoft, Redmond, WA).

4.3 RESULTS

A total of 20 participants consented to participate in this study between March 2020 and May 2021. Two individuals ceased participation due to the beginning of the COVID-19 pandemic. One participant completed all intervention sessions but became ill and was unable to return for follow-up sessions. Four participants discontinued the study after one or more intervention sessions, indicating they could not commit to the time. Complete datasets were collected for 13 participants (Control = 7, AudFB = 6). Demographic information can be found in Table 4.1.

Box's test of equality of covariance and Mauchly's test of sphericity were verified before interpretation and Huynh-Feldt corrections were applied to all effects when necessary.

Walking Biomechanical Data

Results for primary walking biomechanical outcomes are presented in Tables 4.2 - 4.6 with secondary variables in Appendix 3 Tables A3.16 – A3.19.

Peak Pressure

The AudFB group significantly decreased peak pressure (kPa) from Baseline at Immediate-Post in the lateral midfoot (MD: -23.21, p=0.018) and lateral forefoot (MD: -28.09, p=0.016). Reductions in the lateral midfoot were retained at 1-Week Post (MD: -21.03, p=0.004). Changes in the lateral midfoot were associated with large effect sizes and 95% CI that crossed 0 at Immediate-Post, and small to moderate effect sizes and 95% CI that cross 0 at 1-Week Post.

The AudFB group significantly increased peak pressure at Immediate-Post in the total foot (mean difference (MD): 45.70, p=0.021), medial forefoot (MD: 37.61 kPa, p=0.004), and great toe (MD: 57.23, p=0.008) compared to Baseline. These changes were associated with small and large effect sizes with 95% CI that crossed 0. The AudFB group significantly increased peak pressure at 1-Week Post in the total foot (MD: 25.06, p=0.029), medial forefoot (MD:33.63, p=0.010), and great toe (MD: 32.54, p=0.033) compared to Baseline. These changes were associated with small to large effect sizes and 95% CI that crossed 0.

There were no significant main effects or interactions for peak pressure in the medial and lateral heel, medial midfoot, central forefoot, or lesser toes. Means, standard

deviations, and p-values for peak pressure can be seen in Table 4.2 and pairwise comparisons in Table 4.3

Maximum Force

The AudFB group significant reduced maximum force (N) in the lateral midfoot (MD: -6.50, p=0.005) and lateral forefoot (MD: -6.20, p=0.007) at Immediate-Post compared to Baseline. Reductions at the lateral midfoot (MD: -5.79, p=0.008) and lateral forefoot (MD: -4.41, p=0.019) were retained at 1-Week post. Changes in both regions were associated with large effect sizes and 95% CI that crossed 0, expect in the lateral forefoot at Immediate-Post (g=1.13 (0.08, 2.58).

At Immediate-Post (MD: 6.67, p=0.004) and 1-Week post (MD: 5.38, p=0.014) the AudFB group significantly increased maximum force at the medial forefoot compared to Baseline. The effect size for the AudFB group at Immediate-Post is large with 95% CI that do not cross 0 (g=-1.28, (-2.52, -0.04) and large effects at 1-Week Post but with 95% CI that cross 0 (g=-1.06, (-2.52, 0.15)

At Immediate-Post, the AudFB group significantly increased maximum force at the great toes (MD: 2.91, p=0.037) while decreasing force at the lesser toes (MD: -3.70, p=0.031) compared to Baseline. These changes were associated with small and large effect sizes with 95% CI that crossed 0.

In the central forefoot, the AudFB group demonstrated significantly more maximum force compared to the Control group across all time points (p=0.034). However, the Control group reduced maximum force in the central forefoot at Immediate-Post (MD:-1.97, p=0.033) 1-Week Post (MD: -2.43, p=0.002). These changes were associated with small to moderate effect sizes with 95% CI that crossed 0.

Means, standard deviations, and p-values for maximum can be seen in Table 4.4 and pairwise comparisons in Table 4.5

COP Gait Line

One subject was excluded from the COP gait line analysis because they demonstrated a toe-walk pattern at Baseline. Since the heel did not contact the ground at initial contact, their COP gait line is a significant outlier. The COP gait line analysis was compared between Control (n=6) and AudFB (n=6). The groups did not display significant differences in COP location at Baseline.

At Immediate-Post, the AudFB group significantly shifted their COP gait line (mm) more medially at the 45% (MD: 2.42, p=0.033), 55% (MD:3.54,p=0.019), 65% (MD: 4.66, p=0.015), 75% (MD: 5.64, p=0.012), 85% (MD: 6.27, p=0.007), and 95% (MD: 7.05, p=0.003) intervals compared to Baseline. The same medial shift was observed at 1-Week Post in the AudFB group compared to Baseline. The effect sizes at Immediate-Post and 1-Week Post ranged from moderate to large but all 95% CI crossed 0. The control group did not demonstrate any changes in COP gait line location across time. Means, standard deviations, and p-values for COP gait line can be seen in Table 4.6. The COP gait line across time in the AudFB and Control groups can be viewed in Figures 4.1 and 4.2, respectively.

Patient-Reported Outcomes

There were no significant interactions or main effects for either the FAAM ADL or Sport questionnaires. Change in PRO's between Baseline, Immediate-Post, and 1-Week Post did not exceed MDC. Means, standard deviations, and p-values for contact area can be seen in Table 4.7

Ultrasound Measures

The groups did not demonstrate any significant differences between any ultrasound measure at Baseline. Neither group demonstrated significant changes in deformation at either follow up. Additionally, there no differences in echo intensity between groups or across time. Mean differences between pre and post walking in deformation or echo intensity during any session do not exceed MDC scores. Means, standard deviations, and p-values for ultrasound measures can be seen in Table 4.8

Secondary Outcomes

Static Balance

There were no observed significant changes in either traditional, TTB, or COP location during static balance between or within groups. Means, standard deviations, and p-values for eyes open and eyes closed balance measures can be seen in Table A3.20 and Table A3.20, respectively.

Step Down

At Immediate-Post, the AudFB group increased peak pressure in the total foot (MD:62.71, p=0.042), medial forefoot MD: 40.13, p=0.008), and great toe (MD: 75.92, p=0.017) compared to Baseline. At 1-Week Post, similar changes were observed in the total foot (MD:56.67, p=0.033), medial forefoot (MD: 41.04, p=0.002), great toe (MD: 80.79, p=0.006) and lesser toes (MD: 30.83, p=0.050). The Control group did not exhibit any changes in peak pressure during the step down across time.

The AudFB group significantly increased maximum force at the medial forefoot (MD: 5.87, p=0.008) and great toe (MD: 5.73, p=0.002) at Immediate-Post from

Baseline. These changes were also observed at 1-Week post in the medial forefoot (MD: 6.31, p=0.008) and great toe (MD: 6.25, p=0.011).

The Control group demonstrated a significant decrease in maximum force in the medial midfoot at Immediate-Post (MD: 4.16, p=0.036) and 1-Week Post (MD: 4.12, p=0.037) compared to Baseline. Means, standard deviations, and p-values for peak pressure (Table A3.22), maximum force (Table A3.23), pressure-time integral (Table A3.24), and force-time integral (Table A3.25) during the step down are in Appendix 3.

Lateral Hop

The groups were significantly different at Baseline for peak pressure in the lateral midfoot during the lateral hop, with the AudFB group presenting significantly lower than the Control group (MD: -29.50, p<0.001). There were no other significant within or between group differences in any region of the foot for peak pressure or maximum force during the lateral hop. Means, standard deviations, and p-values for peak pressure (Table A3.26), maximum force (Table A3.27), pressure-time integral (Table A3.28), and force-time integral (Table A3.29) during the lateral hop are in Appendix 3.

4.4 DISCUSSION

The objective of this study was to test the effectiveness of an AudFB device during a multisession gait training protocol compared to a control condition on improving walking biomechanics in individuals with CAI. The results of this single-blinded study support our primary hypothesis that the use of an AudFB device significantly improved biomechanics immediately following and up to 1 week after the intervention. Although this is not the first study to implement a gait training tool for patients with CAI,[20,21,40] it is the first that used a device readily accessible to clinicians[20,21] and demonstrated retention

effects of improved gait.[40] The use of auditory biofeedback while walking produced significant reductions in lateral plantar pressure and concomitant medial shifts in COP gait line immediately following the intervention, more importantly those same shifts were also seen 1-week afterwards.

A laterally deviated COP and increases in lateral plantar pressure are common gait deviation and have been associated with increased risk of re-injury in individuals with a history of ankle sprains.[41,42] We speculate by moving COP away from the lateral border, these individuals will be less likely to sustain reinjury or episodes of giving way which would improve patients' quality of life; however, a longer post observational period would be needed to validate this claim. Our changes in gait did not coincide with improvements in PRO's of perceived dysfunction and instability within or between groups. We attribute this to our intervention only targeting gait without attention to other impairment domains (e.g. strength, range of motion, balance) and believe it provides further support for an impairment-based rehabilitation protocol.[43] For instance, Koldenhoven et al.[20]compared an impairment-based program with and without visual gait biofeedback. Improvements were found in ankle frontal plane motion and PRO's in the group receiving visual biofeedback. Even though our auditory biofeedback device is more readily available to clinicians, the effects of this protocol should be established in a full impairment-based program with a longer follow-up period to further support our current results.

The retention effects at 1-Week Post were not as clinically meaningful (small to moderate effect sizes) for which there are a few possible explanations. First, motor learning using external feedback suggests more exposure to the feedback is going to

enhance learning and retention.[36] Our study design attempted to follow this suggestion by using continuous exposure to the AudFB without a fading protocol. However, in many of our AudFB group participants, once they were able to walk without hearing the device, they may have never heard the buzzer during the remainder of the session. Perhaps since they were not truly continuously exposed to hearing the biofeedback, the retention effect was not as beneficial as it might have been using continuous visual[20] or tactile stimulus.[21] Although this is speculative since neither of the previous studies conducted follow-up testing to determine retention. Nonetheless, the observed retention of this newly learned biomechanical pattern is supported by the literature on external focus of attention.[44]

Our secondary aim was to explore the potential cross-over effects of gait retraining into improving biomechanics during functional tasks. Previous evidence suggest ankle frontal plane biomechanics are reserved across tasks,[45] which drove our hypothesis shifting lateral plantar pressure would elicit similar shifts during a step-down task. Our AudFB group demonstrated increased in medial peak pressure and force, however this was not in conjunctions with reductions in the lateral column. The step down tasks has also been used to identify biomechanical alterations using video inspection of a "lateral" landing.[46] Perhaps the increases in medial pressure signifies our participants are moving away from a lateral landing. Although we did not find improvements in static postural control following gait training, we have previously identified the benefits of using auditory biofeedback during balance.[24] Patients may benefit from AudFB being applied during all intervention exercises.

Talar cartilage deformation and echo intensity values did not change between or within groups from baseline. A two-to-three-week period may not be a sufficient amount

of time to reverse improper cartilage stress patterns that have been developing over the years since their first (~7 years) or most recent sprain (~3 years). Although we did observe gait changes in our AudFB group, we cannot verify these changes were adopted during everyday walking which may also explain the lack of significant improvements in measures of cartilage health. However, since there is an association between increased lateral plantar pressure medial cartilage deformation (Chapter 2) and an unstable ankle alters the cartilage contact stress patterns,[47] clinicians should still consider addressing biomechanical deficits and monitoring ankle joint health.

This study was not without its limitation. We did not measure muscle activity in our participants; thus, we cannot conclude if changes in biomechanics are related to neuromechanics. Another limitation is the lack of observation of contralateral limb biomechanics which would provide us with information the observed improvements in the involved limb are not causing negative effects in the opposite limb. Future studies should consider collecting information bilaterally.

Conclusions

The use of an auditory biofeedback device during 8 sessions of gait retaining had a positive impact on waking biomechanics in patients with CAI. The observed improvements were identified immediately following the intervention and were retained up to 1-week. Gait retraining alone did not have a significant impact on talar articular cartilage characteristics. We recommend clinicals incorporate auditory biofeedback during gait training in their intervention program in patients with CAI.

4.5 TABLES

Table 4.1. Participant Demographics (mean ± standard deviation)

	Control (n=7)	AudFB (n=6)	P-value
Sex (males:females), No.	2:5	2:4	0.751
Age, y	22.25 ± 3.33	22.33 ± 2.50	0.891
Height, cm	168.93 ± 14.03	166.92 ± 8.99	0.66
Weight, kg	80.48 ± 21.08	74.20 ± 11.56	0.636
Ankle sprains, No.	3.13 ± 2.32	2.33 ± 1.63	0.804
Time since first ankle sprain, mo	96.00 ± 31.42	72.00 ± 46.78	0.301
Time since most recent ankle sprain, mo	35.25 ± 40.33	41.83 ± 35.57	0.756
Foot and Ankle Ability Measure, %	87.13 ± 7.01	86.55 ± 6.48	0.913
Foot and Ankle Ability Measure-Sport Scale, %	67.58 ± 7.07	71.06 ± 14.87	0.533
Identification of Functional Ankle Instability score	20.63 ± 4.93	21.67 ± 4.27	0.490

Table 4.2 . Peak Pressure (mean ± standard deviation) in each region of the foot within each group across time

	Control			AudFB			Time Main Effect	Group Main Effect	Group x Time Interaction
	Baseline	Immediate	1-week Post	Baseline	Immediate	1-week Post	P Value	P Value	P Value
Total	197.17 ± 39.85	191.94 ± 32.26	191.39 ± 38.46	246.63 ± 61.67	292.33 ± 96.34	271.69 ± 71.53	.105	.033*	.041*
Medial Heel	143.58 ± 34.29	154.47 ± 24.61	152.18 ± 28.41	172.73 ± 28.24	185.61 ± 47.56	177.19 ± 34.01	.136	.131	.775
Lateral Heel	141.11 ± 32.5	149.48 ± 24.05	147.55 ± 27.27	166.45 ± 30.48	169.95 ± 31.67	165.27 ± 26.29	.332	.196	.620
Medial Midfoot	92.51 ± 18.78	94.18 ± 17.95	93.59 ± 20.76	107.51 ± 21.57	99.21 ± 16.34	105.29 ± 19.19	.577	.311	.332
Lateral Midfoot	118.93 ± 19.29	122.3 ± 17.02	118.64 ± 27.68	125.55 ± 17.61	102.33 ± 19.86	104.52 ± 21.07	.011*	.415	.003*
Medial Forefoot	172.68 ± 41.69	154.88 ± 52.65	152.44 ± 54.12	189.24 ± 30.41	226.85 ± 36.13	222.87 ± 27.51	.335	.036*	.004*
Central Forefoot	177.37 ± 48.79	162.15 ± 52.61	162.09 ± 56.91	203.68 ± 26.63	200.92 ± 33.58	205.09 ± 27.12	.098	.160	.132
Lateral Forefoot	165.59 ± 43.01	158.99 ± 38.93	160.98 ± 48.54	197.49 ± 29.27	169.4 ± 43.73	180.56 ± 41.21	.017*	.371	.176

Table 4.3 Pairwise comparisons, Hedge's g effect sizes and 95% confidence intervals for peak pressure

	Control				AudFB		
	MD	P-value	ES (UL, LL)		MD	P-value	ES (UL, LL)
Total							
Imm-Base	5.23	0.745	0.13 (-0.91, 1.18)	Imm-Base	-45.70	0.021	-0.44 (-1.58, 0.71)
1wk-Base	5.77	0.545	0.15 (-0.9, 1.2)	1wk-Base	-25.06	0.029	-0.27 (-1.41, 0.86)
Medial Heel							
Imm-Base	-10.88	.293	-0.34 (-1.39, 0.72)	Imm-Base	-12.88	.251	-0.25 (-1.39, 0.89)
1wk-Base	-8.60	.219	-0.3 (-1.35, 0.75)	1wk-Base	-4.46	.544	-0.10 (-1.23, 1.03)
Lateral Heel							
Imm-Base	-8.37	.231	-0.27 (-1.32, 0.78)	Imm-Base	-3.50	.633	-0.10 (-1.23, 1.03)
1wk-Base	-6.44	.223	-0.23 (-1.28, 0.82)	1wk-Base	1.17	.831	0.04 (-1.09, 1.17)
Medial Midfoot							
Imm-Base	-1.67	.698	-0.08 (-1.13, 0.96)	Imm-Base	8.29	.095	0.47 (-0.68, 1.62)
1wk-Base	-1.08	.846	-0.05 (-1.1, 1)	1wk-Base	2.22	.713	0.12 (-1.02, 1.25)
Lateral Midfoot							
Imm-Base	-3.37	0.520	-0.17 (-1.22, 0.88)	Imm-Base	23.21	0.001	1.08 (-0.13, 2.29)
1wk-Base	0.28	0.959	0.01 (-1.04, 1.06)	1wk-Base	21.03	0.004	0.95 (-0.25, 2.14)
Medial Forefoot							
Imm-Base	17.80	0.177	0.35 (-0.71, 1.4)	Imm-Base	-37.61	0.017	-0.96 (-2.16, 0.23)
1wk-Base	20.24	0.071	0.35 (-0.7, 1.41)	1wk-Base	-33.63	0.010	-0.97 (-2.16, 0.23)
Central Forefoot							
Imm-Base	15.21	.054	0.28 (-0.77, 1.33)	Imm-Base	2.76	.723	0.08 (-1.06, 1.21)
1wk-Base	15.27	.008	0.26 (-0.79, 1.31)	1wk-Base	-1.41	.785	-0.04 (-1.17, 1.09)
Lateral Forefoot							
Imm-Base	6.60	0.485	0.15 (-0.9, 1.2)	Imm-Base	28.09	0.016	0.59 (-0.56, 1.75)
1wk-Base	4.61	0.579	0.10 (-0.95, 1.15)	1wk-Base	16.93	0.078	0.37 (-0.77, 1.51)
Great Toe							
Imm-Base	16.54	0.334	0.26 (-0.79, 1.32)	Imm-Base	-57.23	0.008	-0.46 (-1.61, 0.69)

1wk-Base	15.84	0226	0.25 (-0.8, 1.3)	1wk-Base	-32.45	0.033	-0.29 (-1.42, 0.85)
Lesser Toes							
Imm-Base	17.95	.152	0.26 (-0.79, 1.31)	Imm-Base	-4.57	.724	-0.15 (-1.28, 0.98)
1wk-Base	10.72	.323	0.15 (-0.90, 1.20)	1wk-Base	-8.52	.463	-0.27 (-1.4, 0.87)

MD: Mean Difference; ES: Hedges *g* effect size; UL: 95% confidence interval upper limit; LL: 95% confidence interval lower limit.

Table 4.4 Maximum Force (mean ± standard deviation) in each region of the foot within each group across time

	Control			AudFB			Time Main Effect	Group Main Effect	Group x Time Interaction
	Baseline	Immediate	1-week Post	Baseline	Immediate	1-week Post	P Value	P Value	P Value
Total	105.18 ± 5.16	99.86 ± 6.81	95.78 ± 10.92	113.12 ± 10.76	102.82 ± 10.71	105.83 ± 9.97	.015*	.229	.066
Medial Heel	30.16 ± 7.47	31.96 ± 5.11	31.62 ± 5.55	33.57 ± 6.17	37.2 ± 10.01	35.85 ± 7.74	.059	.279	.622
Lateral Heel	27.72 ± 6.59	29.07 ± 4.99	28.79 ± 5.33	29.48 ± 5.74	30.83 ± 7.72	29.45 ± 6.93	.296	.682	.707
Medial Midfoot	6.29 ± 3.55	4.98 ± 3.12	5.26 ± 3.50	8.11 ± 3.30	6.96 ± 4.00	7.63 ± 4.68	.226	.303	.853
Lateral Midfoot	20.16 ± 3.48	20.22 ± 2.99	19.16 ± 5.78	21.25 ± 4.08	14.74 ± 6.65	15.46 ± 5.65	.008*	.287	.019*
Medial Forefoot	17.57 ± 3.03	15.85 ± 5.61	15.14 ± 5.9	18.00 ± 2.30	24.67 ± 4.82	23.38 ± 4.54	.106	.025*	.004*
Central Forefoot	22.37 ± 3.58	20.4 ± 4.74	19.58 ± 5.06	26.02 ± 3.05	26.01 ± 4.37	26.59 ± 3.72	.101	.034*	.018*
Lateral Forefoot	19.26 ± 1.94	18.17 ± 2.87	17.91 ± 3.47	21.37 ± 4.37	15.18 ± 4.3	16.96 ± 2.86	.008*	.683	.077
Great Toe	10.6 ± 3.79	8.95 ± 3.55	9.22 ± 3.59	17.03 ± 5.37	19.94 ± 8.63	19.32 ± 7.4	.648	.011*	.008*
Lesser Toes	10.77 ± 3.94	9.49 ± 4.57	9.47 ± 5.20	17.73 ± 6.16	14.03 ± 3.71	15.05 ± 3.9	.022*	.038*	.342

*Indicates significance at $p \leq 0.050$.

Table 4.5 Pairwise comparisons, Hedge's g effect sizes and 95% confidence intervals for maximum force

	Control				AudFB		
	MD	P-value	ES (UL, LL)		MD	P-value	ES (UL, LL)
Total							
Imm-Base	5.32	.275	0.82 (-0.27, 1.91)	Imm-Base	10.30	.064	0.89 (-0.30, 2.07)
1wk- Base	9.40	.052	0.96 (-0.15, 2.07)	1wk- Base	7.29	.146	0.65 (-0.51, 1.81)
Medial Heel							
Imm-Base	-1.80	.335	-0.26 (-1.31, 0.79)	Imm-Base	-3.62	.087	-0.33 (-1.47, 0.81)
1wk- Base	-1.45	.326	-0.25 (-1.30, 0.80)	1wk- Base	-2.28	.164	-0.23 (-1.37, 0.9)
Lateral Heel							
Imm-Base	-1.35	0.391	-0.21 (-1.27, 0.84)	Imm-Base	-1.35	0.424	-0.16 (-1.3, 0.97)
1wk- Base	-1.07	0.340	-0.19 (-1.24, 0.86)	1wk- Base	0.03	0.981	0.00 (-1.13, 1.14)
Medial Midfoot							
Imm-Base	1.30	.230	0.36 (-0.69, 1.42)	Imm-Base	1.15	.322	0.27 (-0.87, 1.4)
1wk- Base	1.02	.398	0.29 (-0.77, 1.34)	1wk- Base	0.47	.713	0.10 (-1.03, 1.23)
Lateral Midfoot							
Imm-Base	-0.06	0.973	-0.02 (-1.06, 1.03)	Imm-Base	6.50	0.005*	0.90 (-0.29, 2.09)
1wk- Base	0.99	0.565	0.20 (-0.85, 1.25)	1wk- Base	5.79	0.008*	0.87 (-0.32, 2.05)
Medial Forefoot							
Imm-Base	1.72	0.224	0.36 (-0.70, 1.41)	Imm-Base	-6.67	0.004*	-1.28 (-2.52, -0.04)
1wk- Base	2.43	0.135	0.39 (-0.66, 1.45)	1wk- Base	-5.38	0.014*	-1.06 (-2.27, 0.15)
Central Forefoot							
Imm-Base	1.97	0.033*	0.44 (-0.62, 1.5)	Imm-Base	0.01	0.990	0.00 (-1.13, 1.13)
1wk- Base	2.79	0.002*	0.53 (-0.54, 1.59)	1wk- Base	-0.57	0.108	-0.13 (-1.26, 1.00)
Lateral Forefoot							
Imm-Base	1.09	0.539	0.41 (-0.65, 1.47)	Imm-Base	6.20	0.007*	1.33 (0.08, 2.58)
1wk- Base	1.36	0.383	0.40 (-0.66, 1.45)	1wk- Base	4.41	0.019*	1.11 (-0.1, 2.33)
Great Toe							
Imm-Base	1.66	0.173	0.42 (-0.64, 1.48)	Imm-Base	-2.91	0.037*	-0.31 (-1.45, 0.83)
1wk- Base	1.38	0.189	0.36 (-0.7, 1.41)	1wk- Base	-2.29	0.054	-0.26 (-1.4, 0.87)
Lesser Toes							
Imm-Base	1.29	0.372	0.28 (-0.77, 1.33)	Imm-Base	3.70	0.031*	0.92 (-0.27, 2.11)
1wk- Base	1.31	0.287	0.25 (-0.80, 1.30)	1wk- Base	2.69	0.057	0.65 (-0.51, 1.81)

Table 4.6 COP gait line (mean ± standard deviation) during each interval of stance within each group across time

	Control			AudFB			Time Main Effect	Group Main Effect	Group x Time Interaction
	Baseline	Immediate	1-week Post	Baseline	Immediate	1-week Post	P Value	P Value	P Value
5%	52.76 ± 2.82	51.75 ± 2.03	51.54 ± 2.22	51.21 ± 0.83	51.59 ± 1.58	51.39 ± 1.58	.359	.563	.147
15%	52.74 ± 2.41	52.8 ± 1.56	52.89 ± 1.84	52.4 ± 1.39	52.05 ± 1.81	51.72 ± 1.58	.636	.246	.405
25%	51.9 ± 2.22	52.76 ± 1.64	52.93 ± 2.08	51.87 ± 1.98	51.47 ± 2.5	50.77 ± 2.24	.702	.336	.053
35%	50.71 ± 1.76	51.99 ± 1.27	52.39 ± 2.05	51.06 ± 2.25	49.89 ± 2.71	49.18 ± 2.44	.903	.099	.008*
45%	49.11 ± 1.35	50.77 ± 1.24	51.32 ± 2.22	49.61 ± 2.54	47.18 ± 3.07	46.87 ± 2.71	.742	.046*	.007*
55%	47.53 ± 1.01	49.4 ± 1.65	50.08 ± 2.61	47.61 ± 3.22	44.07 ± 3.92	44.13 ± 3.56	.508	.022*	.007*
65%	46.12 ± 1.49	48.2 ± 2.59	48.95 ± 3.41	45.67 ± 3.83	41.01 ± 5.00	41.84 ± 3.99	.356	.019*	.007*
75%	44.34 ± 2.28	46.48 ± 3.44	47.26 ± 4.13	43.61 ± 4.19	37.97 ± 5.64	39.53 ± 3.83	.246	.019*	.006*
85%	41.61 ± 2.77	43.29 ± 3.86	43.74 ± 4.13	41.01 ± 5.29	34.74 ± 6.04	36.42 ± 3.96	.127	.037*	.006*
95%	38.96 ± 2.88	39.52 ± 4.28	39.49 ± 3.79	38.91 ± 7.56	31.86 ± 7.71	33.45 ± 5.98	.025*	.165	.009*

*Indicates significance at $p \leq 0.05$

Table 4.7 Patient reported outcomes (mean ± standard deviation) for groups across time

	Control			AudFB			Time Main Effect	Group Main Effect	Group x Time Interaction
	Baseline	Immediate	1-week Post	Baseline	Immediate	1-week Post	P-Value	P-Value	P-Value
FAAM ADL (%)	86.99 ± 7.56	87.66 ± 5.25	89.59 ± 5.08	86.55 ± 6.46	85.52 ± 11.94	86.90 ± 10.46	.429	.682	.699
FAAM Sport (%)	66.96 ± 7.41	69.64 ± 12.85	69.64 ± 14.06	71.06 ± 14.87	76.56 ± 18.93	75.00 ± 15.93	.363	.587	.894

Table 4.8. Talar cartilage thickness and echo intensity mean difference and minimal detectable change scores in each group across time.

		Mean Difference (Loaded - Unloaded)				Time main effect	Group Main Effect	Group by Time Interaction
		Baseline	Immediate	1-week	MDC (mm)	P Value	P Value	P Value
Thickness								
Total	Control	-0.028 ± 0.14	-0.004 ± 0.037	-0.015 ± 0.056	0.08	.986	.739	.730
	AudFB	-0.013 ± 0.096	-0.042 ± 0.094	-0.019 ± 0.03				
Medial	Control	-0.003 ± 0.18	0.022 ± 0.046	-0.008 ± 0.054	0.09	.958	.292	.602
	AudFB	-0.029 ± 0.137	-0.066 ± 0.112	-0.011 ± 0.061				
Lateral	Control	-0.051 ± 0.105	-0.029 ± 0.035	-0.021 ± 0.076	0.10	.994	.463	.637
	AudFB	0.002 ± 0.085	-0.015 ± 0.115	-0.029 ± 0.041				
Echo Intensity					MDC (greyscale)	P Value	P Value	P Value
Total	Control	0.64 ± 6.12	-0.84 ± 6.56	1.13 ± 3.86	6.47	.592	.941	.403
	AudFB	2.50 ± 6.71	0.73 ± 6.73	-2.77 ± 6.85				
Medial	Control	0.892 ± 7.567	-1.583 ± 6.246	1.778 ± 5.778	7.86	.221	.727	.655
	AudFB	1.393 ± 11.092	-2.739 ± 3.847	-1.253 ± 7.774				
Lateral	Control	0.393 ± 6.036	-0.84 ± 6.557	0.491 ± 3.951	9.12	.282	.997	.231
	AudFB	3.614 ± 4.213	0.726 ± 6.731	-4.277 ± 7.776				

4.6 FIGURES

Figure 4.1 Consort flow chart of procedures

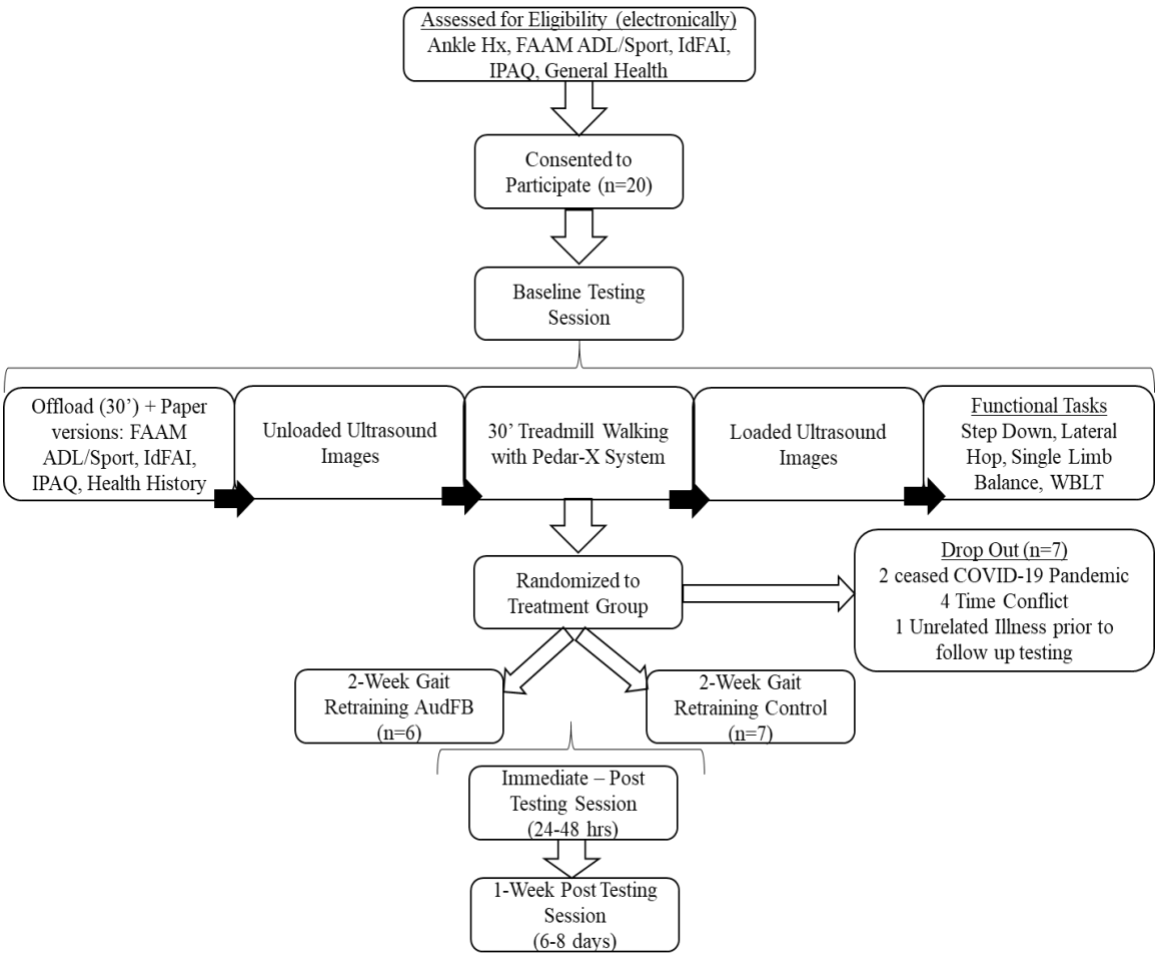


Figure 4.2 Auditory biofeedback device and participant set up

Figure 4.3 Ultrasound Acquisition

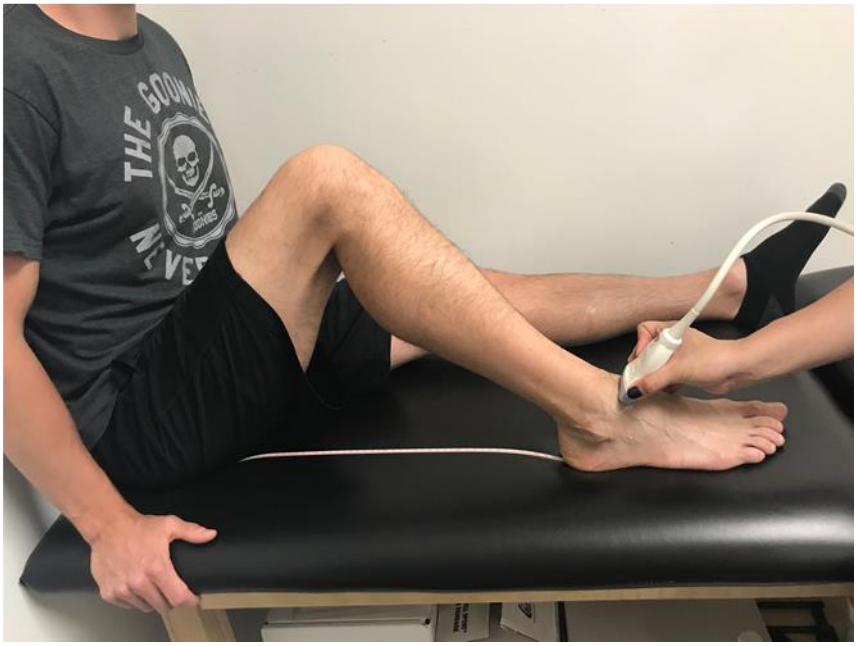


Figure 4.4 Auditory group COP gait line

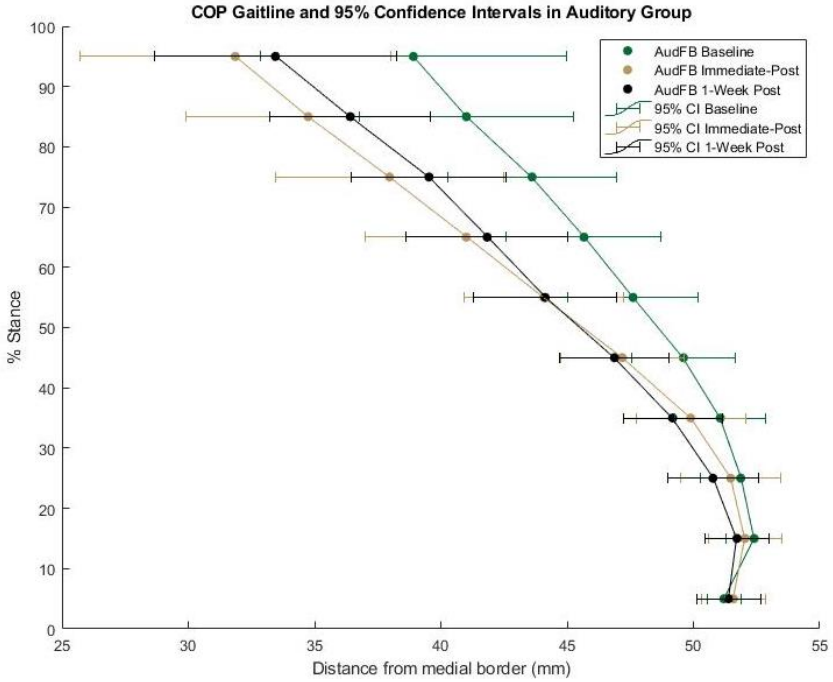
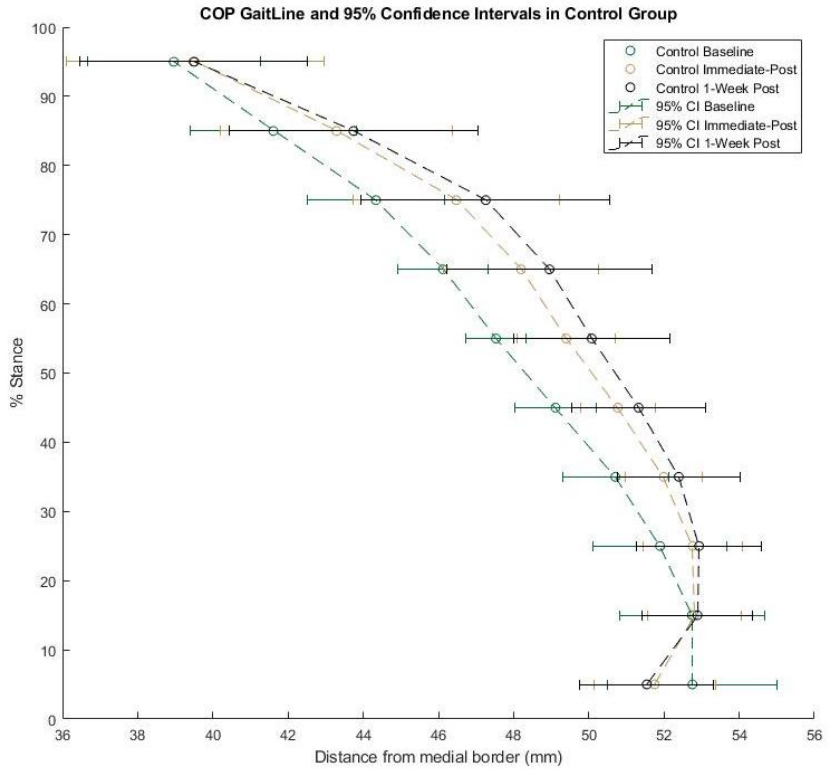


Figure 4.5 Control group COP gait line



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CHAPTER 5: CONCLUSIONS

5.1 SUMMARY

CAI is a complex clinical pathology with several associated impairments.[13] Traditional rehabilitation has shown to be moderately effective in improving deficits in postural control, range of motion, and strength. However, aberrant biomechanical patterns are among the most common impairments in patients with CAI, and there is a lack of effective treatment strategies to correct movement patterns. Several studies have concluded that the abnormal joint loading leading to early degradation of the tibiotalar articular cartilage is driven by the biomechanical alternations that arise after an ankle sprain,[58] which may be adding to the high rate of PTOA development in this population.[81] Therefore, it is essential first to develop clinical tools that effectively improve biomechanics and then determine the influence on ankle joint health.

The overall purpose of this dissertation was to address gaps in the rehabilitation paradigm and joint health evaluation in patients with CAI. First, we aimed to build upon previous research using an auditory biofeedback device to improve biomechanics in real-time.[73] CAI is associated with an impaired sensorimotor system which presents as the altered patient-, clinical-, and laboratory-outcomes. The use of an external focus of attention has been shown to be effective in creating automaticity and retention of newly learned biomechanical patterns. We concluded in Chapter 2 that an auditory biofeedback device is capable of improving mechanics during common rehabilitation tasks[82] and may be helpful to clinicians targeting this domain of the impairment-based rehabilitation paradigm.[80] Before making a strong recommendation for this device to be used in clinical

practice, the effectiveness of this device should be evaluated through a gait training program. However, understanding that the biomechanics we aim to improve are associated with talar articular cartilage loading patterns, we theorized that changing walking gait in patients with CAI may also elicit changes in talar articular loading patterns. Therefore, in Chapter 3 we set out to add to the lack of knowledge surrounding clinical measures of articular cartilage and biomechanics in patients with CAI.

Much of the evidence linking altered joint contact stress and PTOA development is through MR imaging,[58] which is an expensive and clinically inaccessible modality. Diagnostic B-mode US has been identified as a valuable surrogate for MR imaging[64] and may provide clinicians with an inexpensive, real-time assessment of ankle joint health. Our second study evaluated the relationship between resting and changes in talar cartilage thickness and echo intensity and biomechanics during walking in patients with CAI. Articular cartilage thickness and echo intensity have both been identified as important features in the early evaluation of PTOA development.[83] Additionally, a recent study reported the deformation of cartilage after loading varies between healthy adults and those with CAI.[65] Our aim was to assess cartilage deformation following a 30-minute walking session and assess the relationship with plantar pressure in individuals with CAI. Our primary finding was increase in lateral planar pressure was associated with larger medial cartilage deformation. This finding is supported by the evidence surrounding abnormal biomechanics and contact stress patterns in unstable ankles. Further, abnormal plantar pressure patterns during common tasks (step-down and lateral hop) were associated with worse resting thickness. Collectively, our results in Chapter 3 add to the

literature that US is a useful clinical tool in assessing ankle joint health and influence of biomechanics on cartilage features.

The final aim of this dissertation was to assess the efficacy of a 2-week gait training program incorporating an auditory biofeedback device in improving biomechanics and US-based measures of articular cartilage health. Our main conclusion was that 8 sessions of gait training with the AudFB could reduce lateral plantar pressure immediately following the intervention and up to 1 week afterward. These findings are in line with previous results using the AudFB in a single, real-time session. However, these biomechanical improvements were not associated with better FAAM ADL or Sport scores. This finding is similar to previous rehabilitation studies targeting a single impairment and we attribute this to the lack of an actual impairment-based rehabilitation program. Additionally, we did not see any changes in cartilage characteristics after the 2-week gait intervention. It is possible years of abnormal loading on the joint cannot be corrected after only 8 sessions. However, it may still be of importance for clinicians to monitor ankle joint health during treatment.

5.2 LIMITATIONS

A potential limitation to this study was our small sample size of young adults who were physically active which may not fully represent the CAI population. Also, our sample may not have adopted abnormal biomechanics following their ankle sprain, thus not needing gait training. This limitation provides further support for implementing an impairment-based rehabilitation paradigm for the treatment of ankle sprains and CAI.

Another limitation is the novice experience of the assessor capturing US images. Using US only requires a basic understanding of how to operate the device and

knowledge of human anatomy. Although the assessor has 4 years of experience as an athletic trainer and in-depth training on human anatomy, their experience using US was limited to 2 years of peer-to-peer training and pilot testing. However, clinicians who may be considering using US in their daily practice may have a similar training background as the assessor in this dissertation.

5.3 FUTURE DIRECTIONS

The knowledge gained through this dissertation will help guide clinician practice in treating movement impairments in patients with CAI, yet there is much more to understand. Our recommendation for future research studies is to implement gait training using AudFB into an impairment-based rehabilitation program and compare outcomes to a program without AudFB gait training, further identifying the benefits of an external focus of attention on patient and clinical outcomes.

Researchers and clinicians should continue to explore the relationships between talar articular cartilage characteristics via US and impairments in those with and without CAI. In order to continue improving US and talar cartilage understanding, attention should be given to participants' body composition, as these demographics may influence the US-based characteristics.

5.4 CONCLUSIONS

This dissertation advanced the understandings on motor learning in movement rehabilitation and the associations between abnormal biomechanics and ankle joint health. First, we showed the capabilities of an AudFB device on improving clinical and laboratory outcomes in common rehabilitation tasks. Incorporating external biofeedback during movement training after a musculoskeletal injury can be beneficial to patients and

easily adopted by clinicians. Next, we were the first to identify the abnormal lateral plantar pressure profile associated with increased deformation following 30-minute walking in individuals with CAI. This finding will continue to advance the understanding of the abilities and uses of diagnostic US in a clinical setting to monitor joint health after a ligamentous ankle injury. Finally, 8 sessions of gait training with an AudFB device effectively improve biomechanics up to 1 week after the intervention. Although we did not see concomitant changes in ankle cartilage features after this intervention, we still need to monitor joint health following an ankle sprain throughout the rehabilitation process.

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APPENDIX 1: REVIEW OF THE LITERATURE

A1. Introduction

Ankle injuries continue to be the most common musculoskeletal injury among the general population,[1,2] recreationally active adults,[3] and competitive high school, collegiate, and professional athletes.[4-11] The incidence rate for acute sprains have been reported between 2 – 7/1000 person-years.[3] Over a 15-year observational period of 15 sports in the National Collegiate Athletics Association, the incident rate of ankle sprains ranged from 0.75 to 0.89/1000 athlete exposures (AEs), whereas incidence rates of anterior cruciate ligament injuries (0.11 to 0.17/1000 AEs) and concussions (0.15 to 0.41/1000 AEs) were much lower in the same reporting period. An estimated 2 million ankle sprains occur each year in the United States[3] and are associated with nearly $2 billion in annual health care costs.[12,13] Generally perceived by patients as an insignificant injury with minor consequences and a swift recovery, the lack of proper attention to treatment sparks a cycle of disability in 40% to upwards of 70% of individuals.[1,14,15] In the 12 to 18 months following an index sprain, patients develop impairments associated with balance, muscle weakness, reductions in range of motion, and alterations in their ankle function.[15-17] The persistence of these impairments, feelings of instability, episodes of giving way, and recurring sprains are collectively known as chronic ankle instability (CAI).

Compared to healthy adults with no ankle sprain history, individuals with CAI often report worse health-related quality of life[18] and higher levels of physical inactivity[19-21] which are likely influenced by the host of functional and mechanical impairments hindering their ability to perform activities of daily life or exercise.

Individuals with CAI are not meeting the recommendations for physical activity levels[20,21] as supported by the American Heart Association[22] and the Department of Health and Human Services.[23] Furthermore, in as early as 10 years after their initial injury, 78% of individuals with CAI develop ankle posttraumatic osteoarthritis (PTOA),[24] which causes further pain,[25] physical activity limitations,[26], and reductions in quality of life.[25] In the Unites States, PTOA account for nearly 80% of all OA cases and the remaining 20% are diagnosed as idiopathic.[27] The annual health care burden associated with OA is reported to be $3.06 billion.[27] Specifically, at the ankle, 90% of OA is posttraumatic arising from a single or recurring ankle injury.[28] In an attempt to mitigate the adverse effects on overall physical activity and ankle joint health, it is imperative to establish interventions targeting individuals with a history of ankle sprains and CAI.

Despite the research efforts and technological advancements over the last several decades, there is still a need for effective intervention techniques addressing the sequalae of ankle sprains. The impairment-based rehabilitation paradigm for CAI recommends an assess-treat-reassess model to combat the cycle of disability in individuals with CAI.[29] While there is evidence to support an impairment-based rehabilitation model to treat CAI,[30] there is little evidence regarding the ability of interventions targeting one impairment having a cross-over effect for other impairments.[31-37] More concerning is the lack of rehabilitative strategies targeting abnormal ankle motion during gait and functional tasks, especially considering both the National Athletic Trainers' Association[38] and the International Ankle Consortium[39] position statements suggest gait training should be a part of the rehabilitative process. To date, the only interventions generating changes in gait parameters are those specifically targeting gait.[40-43]

This review of the literature focuses on the current physical limitations associated with CAI, the progression of CAI to OA, current technological advancements in assessing and monitoring biomechanics, ankle cartilage health, and patient-reported outcomes, and the current state of the impairment-based rehabilitation model.

A1.2. Impairments of Chronic Ankle Instability

A1.2.1 The Impairment Model

The impairment paradigm of chronic ankle instability has evolved in the last several decades.[44-48] In 1965, Freeman et al.[44,49] published a duo of manuscripts explaining ankle sprains may cause either mechanical or functional instabilities. Mechanical instabilities arose from the ligamentous laxity and were the result of damaged mechanoreceptors around the ankle. The functional instabilities after an ankle sprain were the complaints of giving way and perceived instability. Decades of research was then synthesized by Hertel[48] in 2008 eluding patients with a history of ankle sprains present with a combination of mechanical and functional insufficiencies thus giving rise to chronic ankle instability. A few years later, Hiller et al.[46] progressed the CAI model to expand on the dichotomous impairments by adding a third component: recurring sprains. This model proposed individuals with CAI may present with one or a combination of any two or all three impairments, hinting this pathology is more heterogeneous than first considered. The continued advancement of research technologies and understanding of joint injuries, led to Hertel and Corbett presenting an updated model to CAI in 2019.[47] While some constructs were similar to that originally proposed by Freeman[44] in 1965 Hertel[48] in 2008, the newest model presents impairments not originally considered to be

influential to the outcome after an ankle sprain. New concerns have been given to personal and environmental factors, the unique neurosignature of patients, and the increased understanding of the sensorimotor input and possibility of neural plasticity. The current model of CAI outlines the multifactorial influence of pathomechanical, sensory-perceptual, and motor-behavioral impairments contributing to the clinical- laboratory- and patient-reported insufficiencies in this pathological population.[47] Although CAI remains largely a heterogenous condition as not all patients will experience or present with every impairment listed in the model. Rather, the model was developed based on scientific research examining differences among those with and without CAI. Nonetheless, there are several parameters that are more consistently found among those with CAI and are often the targets of prevention and intervention programs.

Sensory-perceptual impairments consist of self-reported dysfunction, perceived instability, reduced health-related quality of life, and somatosensory deficits. Subjective dysfunction and instability are captured through patient-reported outcome measures like the Foot and Ankle Ability Measure (FAAM)[50,51] and Identification of Functional Ankle Instability (IdFAI)[52] questionnaires, respectively. Somatosensory deficits include a reduced ability to sense active and joint position, impaired visual inputs and increased visual reliance, and altered plantar cutaneous sensation.

The pathomechanical construct includes factors of pathological laxity,[53,54] arthrokinematic and osteokinematic restrictions, and secondary tissue injury and adaptations.[55] Specifically, patients with CAI typically present with a reduced dorsiflexion range of motion,[56-58] likely due to arthrokinematic restrictions of an anteriorly translated talus[59] or anterior displacement of the distal fibula relative to the

tibia.[60] However, reduced laxity could also be attributed to soft tissue restrictions of the triceps surae or myofascial constraints.

The most consistently reported impairments fall into the motor-behavioral construct of the CAI model and include poor postural control,[61-70] muscle weakness,[71-76] and altered neuromechanics during gait[77-88] and functional tasks.[89-94] These factors are typically the primary focus of rehabilitation protocols in recent years because they can be quantified and monitored to assess improvements and progress over time.[33,95-98]

A1.2.2 Biomechanical Alterations

According to a systematic review and meta-analysis by Hiller et al. in 2011,[99] biomechanical outcomes were the largest collective impairment to be studied in CAI patients. The breakdown of tasks in which biomechanical impairments were studied ranged from walking, running, and jump landing kinematics, kinetics, and EMG activity. A prospective cohort study by Doherty et al.[16] followed patients for a year after sustaining an acute, index lateral ankle sprain. Two weeks after sustaining the ankle sprain, patients who could not perform a single-limb drop landing or drop vertical jump were more likely to develop CAI. In the same cohort, biomechanical alterations at the ankle, knee, and hip during a dynamic balance task were present at 6 months and were highly predictive of outcome at 12 months. This study gives rise to concerns of biomechanical discrepancies beginning early in the recovery process will have a negative impact on long-term recovery.

A handful of case reports have captured accidental ankle sprain events during laboratory testing of biomechanical and neuromuscular features and have provided a more in-depth understand of the mechanism behind this injury.[100-103] Collectively, these

reports have shown excessive ankle inversion and internal rotation along with a sudden increase in center of pressure lateral excursion are contributing the mechanism of sprain. What is more concerning, however, is the altered biomechanical pattern adopted by individuals with CAI. In a research setting, many individuals with CAI are at least 3 months removed from an acute sprain episode yet they present with an altered gait.[104]

Abnormal biomechanical patterns in this patient population regularly present during walking and jogging as increased plantarflexion[78,84,105] and inversion,[78-80,91,106-109] increased lateral plantar pressure, [77,82,87,110-112] and a laterally deviated COP.[82,87,113] These patterns are also seen during jump-landing tasks[114-116] which is logical considering the positive association between degrees of ankle inversion and task complexity.[88,94] These aberrant patterns place the ankle in a compromising position similar to the initial injury[102,107,117] and may contribute to episodes of 'giving way'[118,119] experienced by many individuals with CAI. Due to the acute nature of the mechanism of injury, it is challenging to prevent first time sprains, therefore the focus of many health care professionals is to break the cycle of dysfunction that is initiated after an acute sprain episode (secondary prevention). Addressing ankle inversion and biomechanical faults during simple tasks like walking may influence the impairment during more functional tasks like stepping down and drop vertical jump tasks. Since ankle motion is limited and relatively small, it may be easier for clinicians and patients to address and correct during cyclic walking than it would be to correct during a jump-landing tasks that requires attention to proximal joints and other task-related variables.

A1.3 Post Traumatic Osteoarthritis at the Ankle

Following an inversion ankle sprain, there are two theorized mechanisms of degenerative changes leading to posttraumatic OA (PTOA): 1) an osteochondral lesion occurring concomitantly with ankle sprain, 2) altered joint loading adopted after an ankle sprain increases talar cartilage contact strain. Although osteochondral lesions may be more prominent than expected and intensify the degeneration of the articular cartilage, they do not appear to be related to persistent complaints of patients.[120] Overall health of talar articular cartilage is dependent on the applied loading patterns it endures.[121,122] Additionally, aberrant biomechanics and abnormal contact stress can arise with or without an osteochondral lesion indicating it may be more important to address the modifiable biomechanical impairment in order to mitigate the onset of PTOA. While it is likely a combination of all physical and functional impairments have an influence on ankle PTOA progression in individuals with CAI, the primary proposed mechanism of development is mechanically driven.[123-126] Altered joint loading may arise from the positional faults of the talus and distal fibula in patients with CAI. An anteriorly translated and internally rotated talus contributes to a restricted dorsiflexion range of motion, coupled with increased joint laxity and a more inverted and plantarflexed foot position during gait, the contact stress placed on the talar articular cartilage is inevitably changing. The described biomechanical pattern reduces cartilage stress on the lateral talus, while increasing peak stress on the medial talar shoulder.[127,128] This unequal distribution of contact stress[128] promotes degeneration of the medial talar cartilage[124,126,129,130] and likely leads to an increased cartilage contact strain initiating early talar cartilage degenerative changes. Recently, a novel MRI technique identified

unstable ankles placed in a plantarflexed and supinated position created an asymmetrical mediolateral distribution of contact stress.[128] Thus, the authors concluded during weight-bearing, an unstable ankle will cause peak impact forces on the medial talar dome and escalate the risk of osteochondral degeneration.[128] This finding is in line with other reports identifying the anteromedial talar done as the most common site of ankle PTOA development.[24]

Early markers of degenerative changes in cartilage include overall compositional changes and occurs through mechanobiological factors.[121] Changes in structural integrity reduce the resiliency of articular cartilage to absorb forces during loading.[131,132] a reduced ability to absorb forces results in increased deformation.[131,132] There is a need to intervene early to improve abnormal joint loading to mitigate further damage of the talar cartilage and prevent or slow the progression of PTOA. Considering the regenerative capacity of articular cartilage is poor, reducing the abnormal or excessive stress may be the only way to prevent or slow progression. However, there is a possibility that damage to the cartilage during an ankle sprain may also ignite the pathogenesis of PTOA. Osteochondral defects are injuries to the articular cartilage and underlying subchondral bone which may be more common than perceived since this injury is not usually diagnosed at time of injury and may go undetected.

A1.4 Instrumentation

A1.4.1 Plantar Pressure

The Pedar-X system is a wireless device worn by participants to collect biomechanical data during activity. In-shoe insoles are comprised of 99 pressure sensors

which are connected to a transmitter worn by the participants around their waist. The device communicates with the Novel Database Pro via Bluetooth connection. Within the database, various parameters of pressure, force, contact area and time are calculated. For our research purposes, the insoles are segmented into 9 regions to allow for localized calculations and analysis of pressure parameters. The primary variables of interest in our research include contact area, contact time, peak pressure, maximum force, pressure-time integral, and force-time integral.

Additional information extracted from the Pedar software allow us to calculate the COP gait line during stance phase. In this software, COP is the location of pressure from the soles of the feet if that pressure were condensed into a single point. Our measurement is derived from extracting the specific COP location as the distance (mm) from the medial border of the insole. From there, we used a custom MATLAB code and followed instructions from Koldenhoven et al.[133] We condensed the COP data points into 10 distinct time points from 0-100% of the stance phase, the first 10% of COP data points are averaged to obtain the COP value at 5% of stance, the COP data points in next 11-20% are averaged to reflect the COP location at 15% of stance. Collectively, the 10 discreet points form the calculated average COP gait line.

A1.4.2 Ultrasonography

Talar articular cartilage health is important in the progression and prognosis of osteoarthritis. Early identification and intervention is key in long-term success.

After an ankle sprain, clinicians are likely to order radiographs if warranted by the Ottawa Ankle Rules to rule out a possible concomitant fracture. While this is helpful in determining no secondary joint injury has occurred, radiographs cannot provide insight

into the state of the articular cartilage or osteochondral existence after an ankle sprain. Radiographs can be used to evaluate the joint space and identify any narrowing which may provide helpful insight in an OA population it is no indication of early joint health after an ankle sprain thus no inference can be made on the health or integrity of the cartilage. Despite radiographs being accessible and rather affordable, they are not suitable to detect any underlying osteochondral or cartilage conditions which may lead to long-term joint problems.

A suitable method to determine the resiliency of human cartilage is by assessing deformational behavior. Magnetic resonance (MR) images serve as the standard for assessing cartilage deformation and has been previously used to quantify talar cartilage deformation after loading.[132] The downside to these expensive techniques is the inaccessibility of most clinicians and patients. Recently, a novel ultrasound method assessing cartilage deformation has been established at the knee[134] but has yet to be applied at the ankle. Ultrasonography is an inexpensive alternative imaging technique that is more accessible to clinicians and patients.

Talar articular cartilage is category of hyaline cartilage, made to transfer and distribute compressive forces. Injury or loss of articular cartilage is features of the pathophysiological process in development of OA. There lacks any substantial therapeutic capable of slowing the progression of OA which may be due to the insufficient ways of quantifying, assessing articular cartilage health. Recent advancements have been made in using MRI to better visualize the state of cartilage, a majority of this work focuses on femoral cartilage.

A1.5 Impairment-Based Rehabilitation Model

The impairment-based model focuses on four primary domains (balance, strength, ROM, and functional activities), suggesting clinicians focus on any deficiencies found during their evaluation. In theory, assessing patients for deficiencies, targeting those deficiencies during an intervention, and re-assessing to track improvements should alleviate dysfunction associated with the original pathology. Several studies have tested this theory by focusing on rehabilitation to a specific dysfunction associated with CAI. For example, after 4 weeks of balance training, patients with CAI improved their postural control and patient-reported outcomes.[33,36,135] Likewise, interventions targeting muscle weakness[96,97,136,137] were able to improve measures of strength and talar joint mobilizations resulted in improved ankle dorsiflexion range of motion[57,138] This theory is further supported by studies utilizing a multimodal approach targeting multiple impairments during a single intervention.[139] After a 4-week multimodal rehabilitation program consisting of balancing, strengthening, and talar joint mobilizations, individuals with CAI significantly improved postural control, strength, ROM, and PRO's immediately and 2-weeks after the intervention.[30]

For instance, individuals with CAI completed a six-week intervention focused on strength and proprioceptive exercises which had no effect on postural control or muscle fatigue.[32] Similarly, the most utilized balance training protocol by McKeon et al.[33] and a destabilization protocol[34] had no effect on gait biomechanics,[35] even though both of these protocols were able to improve postural control.[33,36,37] To date, the only interventions generating changes in gait parameters are those specifically targeting gait.[40,41,140] There is a lack of rehabilitative strategies targeting abnormal ankle motion during gait and

functional tasks, which is concerning considering both the National Athletic Trainers' Association[38] and the International Ankle Consortium[39] position statements suggest gait training should be a part of the rehabilitative process. A pair of network analysis reviews were conducted which ranked the most beneficial modes of rehabilitation for CAI patients.[31,141] An impairment-based multi modal program was the best,[31] however none of the included studies focused or attempted to address biomechanical impairments. The next best rehabilitation following an ankle sprain includes dynamic balance, however these programs do not address or alter gait abnormalities.[35]

Although current impairment-based protocols have shown moderate improvements in both clinical and patient outcomes in CAI, several studies still had moderate-to-large deficits in patient self-reported function.[30,34,37,135,142] The resultant deficits in patient function but improvements in clinical measures (balance, range of motion) suggest current impairment-based rehabilitations protocols are effective at restoring peripheral dysfunctions yet unable to influence cortical dysfunctions. Recent evidence suggests ankle sprains and recurrent injuries spark a reorganization of the central nervous system leading to neuromechanical deviations and a constrained sensorimotor system.[69,143,144] Specifically, individuals with CAI have a decreased corticomotor excitability[143,145,146], which explains deviations in activation pattern[78,147] and decreased variability[133] of the fibularis longus muscle compared to healthy controls. The inability to properly activate the fibularis longus muscle contributes to an insufficient mechanism for the prevention of inversion sprains and episodes of giving way. The constraints placed on the sensorimotor system following an ankle sprain begin a cycle of dysfunction and instability[148] which cannot be alleviated with current intervention

strategies. In order to break the cycle of disability and allow the sensorimotor system to re-organize, clinicians need to manipulate the tasks and environment during rehabilitation.[148,149] Clinicians commonly use mirrors and videos to accomplish this during movement re-education following musculoskeletal injuries.[150-153] Typically clinicians instruct patients to focus on specific joints (e.g., knees or hips) in order to correct unwanted movement patterns. This strategy may seem to be beneficial in healthy controls[154] and patients with knee pain,[151,152]; however, it was not a beneficial strategy for CAI.[155] According to the constrained action hypothesis,[156] an internal focus of attention places a constraint on the sensorimotor system, inhibits motor learning, and reduces movement variability. An internal focus of attention makes an individual consciously aware of their own movements interfering with the natural reorganization.[149] Contrastingly, an external focus of attention allows an unconstrained pathway to reorganization[157,158] as it places emphasis on a cue from the environment that is related to an individual's movement. Individuals with CAI have positively responded to single-bouts of real-time external focus of attention during walking.[40,41] We hypothesize the residual patient-reported dysfunction after traditional rehabilitation is due to the unaffected biomechanics, therefore gait specific protocols incorporating an external focus of attention should correct biomechanics and improve patient-reported function.

A1.6. Conclusions and Future Directions

Ankle sprains are more complex than the peripheral joint injury many patients and clinicians perceive them to be. Decades of research has exposed the sensorimotor adaptations occurring following ligamentous injuries. Despite several advancements in

diagnostic and treatment paradigms, outcomes following an ankle sprain are still insufficient. The aims of this dissertation are to contribute to the impairment-based rehabilitation paradigm by focusing on improving biomechanics in patients with CAI. The incorporation of an external focus of attention feedback during gait and common rehabilitation exercises is to target the sensorimotor adaptations that occur following an ankle sprain. The use of an auditory biofeedback device has shown promising improvements in real-time during a single exposure but must be studied in a gait training protocol to show efficacy over time. Future studies should understand the cortical and sensorimotor improvements of repetitive exposure to an external focus of attention during gait training to fully comprehend the adaptations occurring. A secondary aim of this dissertation is to build upon the emerging literature of diagnostic ultrasonography to identify articular cartilage health. There is a link between abnormal biomechanics exhibited by individuals with CAI and development of PTOA, but it is unknown if altering gait will also change the cartilage stress patterns.

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APPENDIX 2: ADDITONAL METHODS

A2.1 MID ATLANTIC ATHLETIC TRAINERS' ASSOCIATION RESEARCH GRANT: FUNDED

Research Problem

Lateral ankle sprains are often perceived as a simple musculoskeletal injury, yet overarching evidence suggests at least 40% of individuals will report continued disability months to years following the initial sprain and develop a condition known as chronic ankle instability (CAI).[1] An individual is considered to have CAI if they experience recurrent sprains and/or a feeling of ankle instability that lasts greater than 1 year following the primary injury. Long-term consequences associated with CAI are reduced physical activity, decreased quality of life, and increased risk of ankle osteoarthritis.[2,3] Individuals with CAI often display a multitude of functional and mechanical impairments, including but not limited to, reduced proprioception, decreased neuromuscular control, laterally displaced center of pressure (COP) during static balance, decreased dorsiflexion range of motion (ROM), decreased ankle strength, and altered biomechanics during functional activities. Specific to altered biomechanics, on average, individuals with CAI display greater inversion, altered surface electromyography (sEMG) activity of the peroneus longus,[4] a more laterally positioned COP,[5] and greater lateral peak pressure than healthy individuals during walking.[5] Given that a relationship exists between kinematics across functional tasks,[6] it is likely that the altered biomechanics displayed during walking, is also present during other functional tasks or movements (stepping, jumping, lunging etc.).

Currently, it is believed that the development of CAI is not attributed to one impairment in isolation, but rather, a combination of all previously discussed impairments. For example, if an individual with CAI walks with a laterally displaced COP, they remain close to the mechanism of injury of a lateral ankle sprain; therefore, may be at a greater risk of re-injury. Moreover, not only is the foot mal-positioned during each step, but given the associated neuromuscular control and strength deficits, the individual has a reduced ability to protect the joint from sudden perturbation, further exacerbating the risk of re-injury. Therefore, in theory, a rehabilitation program that restored all known impairments would resolve the patient's CAI and prevent the occurrence of future long-term consequences.[7] Previous studies[8-12] aimed to test the efficacy of rehabilitation programs comprised of exercises that targeted impairments associated with ROM, strength, balance and/or functional exercises (stepping, jumping, cutting) in patients with CAI. Although the rehabilitation programs demonstrated to be effective at improving dorsiflexion ROM, balance and strength in patients with CAI, many of the patients continued to report deficits in self-reported function following the intervention. One rationale as to why the previously mentioned rehabilitation programs did not fully restore patient function, is that not all impairments associated with CAI were improved. Specifically, COP location during static balance remained laterally positioned and ankle inversion and muscle activation during functional movements (walking, jogging, and jump-landing) remained unchanged.[9-12] We attribute the lack of change in balance strategy and biomechanics during functional movements not to the specific exercises, but rather the lack of feedback provided to the patient during the exercise. Including feedback that promotes a neutrally positioned ankle during functional exercises

may cause the patient to adopt a movement strategy that is not linked to recurrent ankle sprains.

Recently, our lab successfully altered walking gait, measured using an in-shoe plantar pressure insole system, in individuals with CAI using a novel laser device which provided real-time external focus of attention feedback. The objective of external feedback is to direct attention of the individuals' movement to the context of the environment[13] that is achieved by an external source.[14] Contrastingly, internal focus can be described as attention being directed to the individuals' body so that the patient is consciously aware of their movement.[13] External feedback has demonstrated to be the superior mode of feedback when altering movement strategies;[14] however, this mode of feedback has yet to be studied in individuals with CAI performing balance and functional tasks. Prior to implementing our novel laser device during balance and functional exercises in patients with CAI, we must first determine the patients' real-time response to the feedback. Therefore, the purpose of our study is to determine if real-time alterations of COP location, biomechanics, and muscle activation can be achieved during static balance and other functional exercises that include external focus of attention feedback via a novel laser device (ExFB: laser on and participant receives instructions) compared to a baseline (BASE: no laser and no instructions) and no feedback (NoFB: laser on, but participant does not receive instructions) conditions. **Specific Aim 1:** Determine the real-time ability of external focus of attention feedback using a novel laser device on relocating COP during static balance.

Hypothesis 1: Participants will have a more medially located COP during the static balance trials in which they receive ExFB when compared to trials during the BASE and NoFB conditions.

Specific Aim 2: Determine the real-time ability of external focus of attention feedback using a novel laser device on shifting plantar pressure and COP trajectory during functional activities (lateral hops, step-down, drop vertical jump, and lunges).

Hypothesis 2: Participants will decrease lateral plantar pressure and medially shift COP trajectory during functional tasks during the ExFB when compared to trials during the BASE and NoFB conditions.

Specific Aim 3: Determine the real-time ability of external focus of attention feedback using a novel laser device on muscle activity of the gluteus medius, biceps femoris, rectus femoris, lateral gastrocnemius, fibularis longus, fibularis brevis, soleus, and tibialis anterior during balance and all functional activities.

Hypothesis 3: Participants will target muscles that improve lateral ankle stability by having an increase in muscle activity of the gluteus medius, fibularis longus, and fibularis brevis muscles during all tasks in which they receive ExFB when compared to trials during the BASE and NoFB conditions. No changes will be observed in the muscle activity of the remaining muscles, representing a targeted response.

Significance of the Proposed Research

A new paradigm approach for rehabilitation of CAI outlined the importance of an impairment-based model with four main assessment domains: range of motion, strength, balance, and functional activity.[7] Presently, rehabilitative strategies for CAI are effective at improving three of the four domains, however evidence has not supported efficiency of

restoring altered functional movement activity. According to both the National Athletic Trainers' Association Position Statement on treating lateral ankle sprains[3] and the International Ankle Consortiums' consensus statement on lateral ankle sprains,[15] clinicians should address biomechanical alterations through gait re-training and functional exercises; although neither entity provides an evidence-based strategy to achieve this goal. When following current best-practices on treating lateral ankle sprains, athletic trainers are failing to correct biomechanical alterations during rehabilitation. In turn, patients are returning to activity or sport with altered biomechanics that may be predisposing them to recurrent sprains. Therefore, it is critical to establish a method that is effective at restoring neuromuscular control and proper biomechanics during the rehabilitative process in order to return athletes to activity/sport fully functional and reduce subsequent injury. The evidence surrounding external focus of attention for reconditioning motor learning strategies is well established.[14] While our lab has displayed the ability of individuals with CAI to positively respond to external focus of attention during walking, we are unable to infer if the same positive response will occur during functional tasks which are commonly used in intervention programs. Prior to investigating the long-term effects of external feedback being implementing into an impairment-based model, we need to determine if this novel tool can elicit beneficial biomechanical and neuromuscular alterations in real-time. Positive results of the proposed and future studies can have an immediate impact on the athletic training profession as this novel laser device that follows best practice of motor learning is affordable for clinicians in all settings and is readily available to be implementing into established rehabilitation models.

Procedure

Research Design

We propose a controlled laboratory study to observe changes in our dependent variables: plantar pressure (contact area, contact time, peak pressure, and pressure time integral) in nine regions of the foot (medial and lateral heel, medial and lateral midfoot, medial, central, and lateral forefoot, great toe, and lesser toes), COP trajectory, static balance (COP location), and surface electromyography (EMG) muscle activity (gluteus medius, biceps femoris, rectus femoris, lateral gastrocnemius, soleus, fibularis longus, fibularis brevis, and tibialis anterior). Our independent variable is condition: Baseline (BASE), no feedback (NoFB) and external feedback (ExFB).

Sample Size and Participants

A total of 25 participants will be enrolled in this study. Based on previous data from our lab, significant results that met minimal clinical differences were achieved with a sample size of 20. To account for an estimated 20% drop out rate, we will enroll 25 participants. Participants will be eligible to participate if they meet guidelines set by the International Ankle Consortium to identify individuals with CAI.[2] Participants must have history of ≥2 lateral ankle sprains with their initial sprain being >1 year prior to the start of the study, self-report ankle disability by scoring ≤90% on the Foot and Ankle Ability Measure Activities of Daily Living (FAAM-ADL) and ≤80% Sport (FAAM-S) subscales and ≥11 on the Identification of Functional Ankle Instability (IdFAI).

Instrumentation

Static balance will be assessed using an AMTI force-plate (AMTI, Watertown, MA) at a sampling rate of 50 Hz. EMG data will be recorded using an 8-lead wireless

system (Trigno Wireless; Delsys Inc, Natick, MA) collected at a sampling rate of 1000 Hz. EMG electrodes will be placed parallel to muscle fibers of muscle bellies located by palpation, the skin will be shaved and abraded to limit noise impendence. Plantar pressure measures will be collected at a sampling rate of 100 Hz using the Pedar-X plantar pressure system and data will be analyzed in the Novel Database Pro (Novel Inc., St. Paul, MN). The Pedar-X system consists of two pressure insoles connected to a wireless transmitter that is inserted into a belt which the participants will securely wear around their waist. ExFB will be provided by using a custom-made laser pointer that is comprised of a class IIIA cross-line diode (Calpac Lasers, Steamboat Springs, CO, USA) and 3 volt battery (2 AAA batteries). The laser will be fastened to the foot by using a strap (Motion Guidance, Castle Rock, CO, USA).

Overview of the Methods

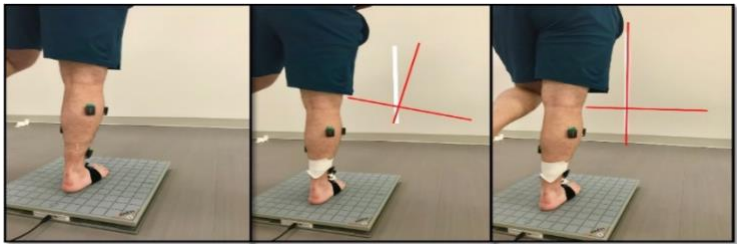
Participants will complete the informed consent process prior to data collection. Next, participants will have EMG electrodes placed over corresponding muscles of the involved limb in accordance to previously reported methods.[5] Once EMG electrode placement procedures are completed, participants will complete the following tasks: static balance, lateral hops, lunges, step-down, and jump-landing. The static balance task will always be performed first due to the task being performed barefoot and not requiring the use of the in-shoe plantar pressure insole system; however, all other functional tasks (lateral hopping, lunging, step-down, and jump-landing) will be performed in a random order. All recorded tasks will be preceded by the number of practice trials[10,12] warranted in order to eliminate a learning effect. Participants will complete each task in the following condition order (BASE, NoFB, and ExFB). During the BASE condition,

participants will not have the laser device fixed to their foot and will receive no additional feedback other than the standard instructions of how to complete the task. Next, the laser will be fixed to the participant's neutral foot in a manner in which the cross-hair beam is projected onto a wall and the vertical cross-hair is positioned perpendicular to the floor, while the horizontal cross-hair is positioned parallel to the floor. A piece of athletic tape will be placed over the vertical beam to provide the participant with a point of reference. Given the low divergence of the laser, the cross-hair being rotated out of this position, signifies the foot moving out of a neutral position. For the NoFB condition, participants will have the laser beam visible; however, participants will be asked to ignore the laser and once again complete the task using the standard instructions. The NoFB condition is included to ensure the presence of the laser itself does not influence the dependent variables. Following the BASE and NoFB trials, the laser device will remain fixed to the participant's foot and the participant will receive feedback pertaining to the position of the laser in addition to the standard instructions of how to complete the task.

Static Balance

To assess static balance, participants will stand barefoot on the force-plate, non-test limb will be in 30º hip flexion and 45º knee flexion and hands will be placed on their hips.[8,10,12] The strap that fixes the laser to the foot will be worn across all conditions to control for the sensory information provided from the

Figure 1: An example of a participant completing the BASE (left), NoFB (middle) and ExFB (right) conditions during static balance. The rotated position of the laser during the NoFB condition represents an individual inverting their ankle and shifting their COP



strap. Following three practice trials, COP location and corresponding muscle activity will be recorded during three 10s trials for each condition (BASE, NoFB, and ExFB), a failed trial will be repeated.[8,10,12] A trial is considered failed if: 1) participant moves their foot out of the test position 2) hands come off hips 3) opposite limb touches the floor. During the BASE condition, participants will be instructed to "stand as still as possible while maintaining the test position." Upon completing 3 successful trials, participants will complete the NoFB condition trials in which they will be able to see the cross-hair laser beam projected on the wall in front of them; however, they will be instructed to "ignore the laser beam and stand as still as possible while maintaining the test position." Next, participants will complete the ExFB trials and will be instructed to "stand as still as possible while maintaining the test position and to not let the cross-hair laser beam rotate or change positions away from the piece of tape on the wall." Figure 1 provides an illustration of the static balance testing procedures.

Functional Tasks

For the remaining tasks (lateral hops, lunges, step-down and jump landing) participants will be fitted with a standard neutral athletic shoe (Asics Gel-contend 4, Irvine, CA, USA) and with the in-shoe plantar pressure insoles. The plantar pressure in-soles and belt will be secured to not interfere with EMG electrodes, laser, or inhibit participants' lower extremity range of motion. During each trial across all tasks and conditions, plantar pressure measures and muscle activity will be synchronized and recorded. Following a minimum of 3 practice trials, participants will complete ten trials for each condition across all tasks. Furthermore, the same condition order as the static balance task will be used; however, the order of the functional tasks will be randomized

via random number generator. During the BASE condition, participants will not have the laser device attached to their shoe and will complete the task as indicated by standard instructions. Similar to the static balance trials, during the NoFB conditions, the participants will have the laser fixed to their shoe and will receive standard instructions of how to complete the task, but will be asked to ignore the laser beam projected on the wall. Finally, during the ExFB condition during each corresponding task, participants will receive the same standard instructions of how to complete the task, but in addition, will be instructed to maintain the vertical laser beam line overtop the reference tape on the wall throughout the exercise. Since each of the functional tasks is comprised of an aerial and stance phase, participants will be instructed the laser should go up and down; however, try not to let the laser rotate or move left or right. The specific standard instructions for each task will be as follows and are based off of previous studies:[6,8,10,12]

Lateral Hops

Participants will be instructed to stand on their involved limb and hop laterally 18 inches, maintain their balance, and hop back to the starting position. Participants will complete this task continuously until they perform ten hops. Due to the hopping task moving medial-lateral as opposed to posterior-anterior, like the other tasks, two pieces of tape separated by 18 inches will be used as a reference point during the ExFB condition (Figure 2).

Lunges

Lunges will be performed on a firm surface with hands on their hips. Participants will be instructed to lunge their involved limb forward into a 90º/90º position until the

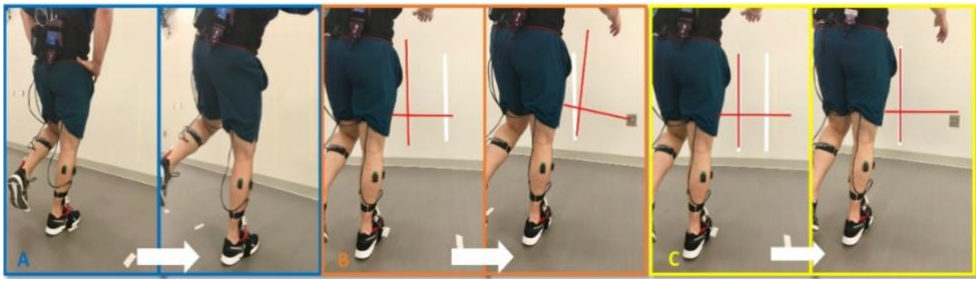
uninvolved knee touches the ground. Once the participant is in proper test position, they will be asked to immediately return to the standing position to facilitate a fluid motion.[8]

Step-Down

Participants will start from a 30-cm tall box and be instructed to step-down onto the ground with the involved limb. Upon landing on the ground, the participant will be instructed to carry their momentum forward by continuing to walk forward for an additional few steps.[6]

Jump-Landing

Figure 2: An example of a participant completing the BASE (A), NoFB (B) and ExFB (C) conditions during the lateral hopping task. The rotated position of the laser during the NoFB condition represents an individual inverting their ankle and shifting their COP laterally while landing from their lateral hop. During the ExFB condition, the participant is able to maintain a neutral foot and ankle as indicated by the non-rotated laser. Similar instructions to not let the laser rotate will be provided for the other functional tasks.



Participants will stand on a 30-cm tall box, jump forward half the distance of their height with both limbs, land on both limbs followed by another jump straight-up.[6]

Data Management and Statistical Analysis:

Center of pressure,[12] muscle activation,[5] and plantar pressure measures[5] will be processed and reduced using previously established techniques. A within-factor repeated-measures ANOVA will be conducted (SPSS v25, SPSS Inc., Chicago, IL) to compare means for each dependent variable across the three conditions (BASE, NoFB and ExFB). Cohen's *d* effect sizes (ES) and associated 95% confidence intervals (CIs) will be calculated in Microsoft Excel 2016 (Microsoft Corporation, Redmond, WA) to determine

the magnitude of difference between each condition. Alpha levels will be set *a priori* at $p<0.05$. Results will be interpreted as significant if $p\leq0.05$ and ES are moderate to large with associated 95% CIs that do not cross 0.

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A2.2 NATIONAL ATHLETIC TRAINERS' ASSOCIATION RESEARCH AND EDUCATION FOUNDATION DOCTORAL RESEARCH GRANT: FUNDED

Purpose and Rationale

Nearly 2 million lateral ankle sprains occur annually in the United States[1], with 40% of individuals developing chronic ankle instability (CAI).[2] CAI is a clinical diagnosis characterized by residual symptoms of acute injury, feelings of ankle instability, and subsequent ankle sprains.[3] Additionally, individuals with CAI tend to be less physically active,[4] have a reduced health-related quality of life,[5,6] and increased likelihood of developing posttraumatic osteoarthritis (PTOA) at the ankle compared to individuals with no ankle sprain history.[7] The most recent model of CAI development outlines the multifactorial influence of structural, biomechanical, and sensorimotor impairments contributing to the clinical- and patient-reported insufficiencies in this pathological population.[8] Disruption of the lateral ligamentous support during an ankle sprain initiates a reorganization of the sensorimotor system. Sensorimotor alterations continue to develop as peripheral impairments over the months and years after the acute inflammation subsides. The most commonly reported impairments include poor postural control,[9-18] muscle weakness,[19-24] range of motion deficits,[25-27] and altered biomechanics during gait[28-39] and functional tasks.[40-44] The insufficient structural integrity and sensorimotor dysfunction lingering after an ankle sprain influence biomechanical alterations during movement. Biomechanical alterations in this patient population commonly present as increased ankle inversion[29-31,45,46] increased lateral plantar pressure,[28,38,47-49] and a laterally deviated center of pressure (COP) trajectory.[33,38,50] Greater lateral plantar pressure and lateral COP trajectory places the individual closer to the mechanism of injury[28,29,51] and creates a disproportionate pattern of contact stress on the talar

cartilage.[52,53] While it is likely all physical and functional impairments have an influence on ankle PTOA progression in individuals with CAI, the proposed mechanism of development is mechanically driven.[54-57] Specifically, the unequal distribution of contact stress[53] promotes early degeneration of the medial talar cartilage[54-57] coinciding with the most common site of ankle PTOA development.[58] The current hypothesis for this singularity is considered to be the result of the compromised lateral ligamentous support and maladaptive biomechanical pattern exhibited by individuals with CAI.[52,57] Therefore, restoring proper ankle biomechanics is imperative to maintain long-term joint health in patients with CAI.

Determining status and advancement of OA can be assessed by monitoring cartilage thickness[59,60] through the gold standard of magnetic resonance imaging (MRI). However, obtaining an MRI can be challenging for most patients as the procedures are lengthy and expensive, making repeated assessments to monitor progress unattainable for most. Ultrasound imaging (USI) is becoming more prevalent in sports medicine settings as an inexpensive and versatile tool. Fortunately, emerging evidence is supporting the use of diagnostic USI as a surrogate to measure cartilage thickness and cross-sectional area[61,62] and is sensitive enough measure deformational changes in cartilage before and after activity.[63,64] Although most evidence is based on findings in femoral cartilage, there is evidence to support assessment of talar cartilage deformation with MRI.[65] More recently, talar cartilage volume measured with MRI has been associated with ultrasound-based cross-sectional area, providing evidence USI of the talar cartilage can be used as surrogate of MRI.[62] Monitoring talar cartilage deformation after loading and in response

to gait retraining is crucial to determine the clinical use of US to gauge ankle joint health and progression of PTOA in physically active patients.

The impairment-based rehabilitation paradigm for CAI recommends an assess-treat-reassess model to combat the cycle of disability in individuals with CAI.[66] The impairment-based model focuses on four primary domains (balance, strength, ROM, and functional activities), suggesting clinicians focus on any deficiencies found during their evaluation. In theory, assessing patients for deficiencies, targeting those deficiencies during an intervention, and re-assessing to monitor improvements should alleviate dysfunction associated with the original pathology. Several studies have tested this theory by focusing rehabilitation to a specific dysfunction associated with CAI. For example, after 4 weeks of balance training, patients with CAI improved their postural control.[67,68] Likewise, interventions targeting muscle weakness were able to increase strength,[69-71] while 2-weeks of talar joint mobilizations augmented ankle dorsiflexion range of motion.[26,72,73] Additionally, when treatments (i.e. balance training, strength exercises, joint mobilizations, etc) are given concurrently, improvements in those peripheral impairments are simultaneously observed.[74-76] Taken together, there is evidence to support an impairment-based rehabilitation model to treat CAI. However, there is little evidence regarding the ability of these interventions improving altered gait parameters at the ankle. For instance, the most commonly used balance training protocol[67] and a neuromuscular training program[77] had no effect on ankle kinematics after 4-weeks of training.[77,78] To date, the only interventions generating changes in gait parameters are those specifically targeting gait.[79-81] Considering there is an association between the amount of ankle inversion during simple tasks like walking and more demanding tasks

like step-down and jump-landing,[82] abnormal ankle biomechanics may be conserved across tasks. This is supported by evidence revealing as walking speed increases, the amount of ankle inversion also increases in individuals with CAI.[39] Perhaps targeting ankle biomechanics during early phases of recovery, while patients are only able to ambulate, may produce beneficial changes to more demanding tasks they are unable to perform yet. There is a lack of rehabilitative strategies targeting abnormal ankle motion during gait, which is of concern considering both the National Athletic Trainers' Association[83] and the International Ankle Consortium[84] position statements suggest incorporating gait training into the rehabilitative process. Current rehabilitation programs are moderately effective at restoring peripheral ankle function[67,70] and do not improve gait;[78] thereby failing to offload lateral plantar pressure, reposition the patient's COP away from the injury mechanism, and restore normal cartilage loading patterns.

Clinicians typically perform real-time gait analysis relying on visual inspection to determine unwanted movements; however real-time visual inspection of ankle motion during walking is challenging to perform due to the fast and small motions that are occurring. Clinicians commonly use mirrors and videos to accomplish gait analysis and movement re-education following musculoskeletal injuries.[85-88] Instructions to patients include focusing on specific joints (e.g., knees or hips) in order to correct unwanted movement patterns. This strategy is known as internal focus of attention feedback and seems to be beneficial in healthy controls[89] and patients with knee pain,[86,87]; however, it was not a beneficial strategy for CAI patients.[90] Perhaps current strategies are only able to generate peripheral changes and not sensorimotor system changes, thus ineffectively unconstraining the system to allow for a newly learned gait pattern. According to the

constrained action hypothesis,[91] an internal focus of attention places a constraint on the sensorimotor system, inhibits motor learning, and reduces movement variability. An internal focus of attention makes an individual consciously aware of their own movements, interfering with the natural reorganization.[92] Contrastingly, an external focus of attention allows an unconstrained pathway to reorganization[93,94] as it places emphasis on a cue from the environment that is related to an individual's movement. Individuals with CAI have positively responded to single bouts of real-time external focus of attention during walking.[79,81] Our novel auditory biofeedback instrument allows for an objective, audible detection of gait abnormalities in real-time. Our preliminary data using the novel auditory biofeedback instrument determined the devices ability to cause real-time biomechanical changes during a single session of treadmill walking in patients with CAI,[79] during balancing, and more functional movements such as step-down and lateral hopping tasks (Appendix B). Auditory biofeedback can readily enhance standard rehabilitation for patients with CAI. Prior to elucidating recommendations for use of our novel auditory instrument to clinicians, we must first determine its ability to improve gait, stabilize joint contact stress patterns, and improve patient perceived function.

The overall objectives of this project are to determine the effects of a 2-week gait retraining program using auditory biofeedback (AudFB) on (i) biomechanics during functional tasks (walking, step-down, forward lunge and lateral hops) (ii) talar cartilage deformation patterns and (iii) patient-reported outcome measures (PROs). Efficacy of AudFB over no feedback (NoFB) during gait retraining will be determined via a randomized, single-blinded study of participants with CAI. All participants will complete 2-weeks (8-sessions) of gait retraining. Both groups will complete 8 time-matched

treadmill walking sessions; however, the NoFB group will receive no biofeedback, while the AudFB group will receive auditory biofeedback during each session. We will evaluate biomechanics, ankle cartilage, and PROs during three testing sessions; prior to the intervention (baseline), 24-48 hours after the intervention (immediate-post), and 7 days after the intervention (1-week post). The intervention sessions will begin within 48-72 hours after the baseline testing session.

Specific Aim 1: Identify the effects of a two-week gait retraining program using auditory feedback on biomechanics during functional tasks. We hypothesize participants within the AudFB group will demonstrate reduced lateral plantar pressure and a medially shifted COP trajectory during all functional tasks at both the immediate-post and 1-week post time points compared to their baseline measures. We hypothesize there to be no changes in biomechanics in the NoFB group between baseline and post gait retraining.

Specific Aim 2: Identify the effects of a two-week gait retraining program using auditory feedback on talar cartilage deformation assessed with ultrasonography. We hypothesize that participants within the AudFB group will show less cartilage deformation at the immediate-post and 1-week post. We hypothesize there to be no changes in talar cartilage deformation in the NoFB group between baseline and post gait retraining.

Specific Aim 3: I**dentify the effects of a two-week gait retraining program using auditory feedback on patient-reported outcomes.** We hypothesize that participants in the AudFB group will improve PROs at both the immediate-post and 1-week post time

points. We hypothesize there to be no changes in PROs in the NoFB group between baseline and post gait retraining.

Anticipated Outcomes

Specific Aim 1

We hypothesize the participants in the AudFB group will significantly reduce plantar pressure in the lateral foot column with concurrent increases in medial plantar pressure during walking, step-down, forward lunge, and lateral hops. The reduction of lateral plantar pressure will be coupled with a medial shift in COP trajectory for all tasks. We hypothesize these biomechanical improvements will be present immediately following gait retraining and remain present in the subsequent week of no intervention. Subsequently, we anticipate seeing no changes in any plantar pressure or COP measurement during any tasks from baseline to immediately-post or 1-week after the intervention in our NoFB group. This finding will support the changes seen in our AudFB group was due to the intervention and not the additional physical activity provided during gait retaining.

Findings from this study will clarify recommendations to clinicians on implementation of auditory biofeedback during movement re-education for patients with CAI. Since patients are able to ambulate before they are able to perform more difficult task, it is logical to target abnormal ankle mechanics in the early stages of rehabilitation before progressing to more advanced stages. Improvements of ankle biomechanics should reduce the occurrence of giving way and recurrent injuries once patients have returned to activities of daily living or sport. Our results will contribute to the development of future intervention studies by creating a foundation of evidence individuals with CAI are

capable of learning and retaining new gait strategies with the use of an external auditory biofeedback.

Specific Aim 2

We hypothesize our AudFB group to have a more uniform deformation pattern after 2-weeks of gait retraining compared to their baseline measures and to those in the NoFB group. The feedback provided during gait retraining will allow participants to offload the medial talar cartilage and redistribute contact stresses evenly across the joint. We anticipate seeing no changes in talar cartilage deformation in our NoFB group at any time point. This finding will support the changes seen in our AudFB group was due to the intervention and not a result of measurement error or any ensuing benefits from additional physical activity.

The findings from this study will support the ability of AudFB during gait to influence the longevity of talar cartilage health by equalizing abnormal deformation patterns during loading conditions. Improving deformation patterns should increase cartilage resiliency thus slowing down early degeneration and PTOA progression. Our novel AudFB tool may impact short-term goals of patients with CAI, but also may influence long-term joint heath and patients' quality of life. Ultrasonography is becoming more a prevalent tool in sports medicine practice as it is relatively inexpensive and user-friendly. The emerging body of literature is supporting the use of US imaging as a surrogate to magnetic resonance imaging (MRI). Although still considered the gold standard assessment tool, MRI images are expensive, time-consuming, and not practical for repeated use. This current investigation will add to the growing body of literature using ultrasonography as a clinical measure to assess cartilage health while advancing the

current knowledge by showing the ability of USI to monitor changes in cartilage over time with repeated measures.

Specific Aim 3

We hypothesize the AudFB group will significantly improve their self-reported function after 2-weeks of gait retraining compared to their baseline levels of function. Conversely, we do not anticipate seeing any changes in self-reported function in our NoFB group across time. This finding will support the improvements reported by the AudFB group is a result of the intervention and not the additional physical activity.

Our results will bring attention to the need of incorporating gait retraining into the treatment of patients with CAI. Overwhelming evidence supports the efficacy of targeted impairment-based interventions in improving PROs, however little evidence exists regarding the benefits of isolated gait retraining and patient-outcomes. The potential improvements in PROs after gait retraining with AudFB adds to the evidence an external focus of attention produces sensorimotor adaptations. The current knowledge supports external feedback eliciting a sensorimotor adaptation, the results from our study will add support to this by showing AudFB can improve PROs.

Experimental Design and Methods

Experimental Design

The proposed study will demonstrate scientific rigor with a single-blind, randomized controlled study design. The principal investigator (PI; doctoral candidate) will perform all testing sessions (baseline, immediate-post, and 1-week post), complete all data analysis, and will be blinded to interventions. A second investigator (faculty advisor) will oversee all intervention sessions (AudFB and NoFB) and will be blinded to

the testing sessions. Randomization will occur via sealed, opaque envelopes with separate allocation schedules for males and females to ensure equal distribution between groups. A member of the dissertation committee will control randomization, record codes, and will not be a part of the data collection, interventions, or analysis process.

Power Analysis

An *a priori* power analysis was conducted to determine the sample size needed to find statistical significance at $\alpha \leq 0.05$, with power (1-β) set at 0.8 and an effect size of 0.6 (moderate effect).[95] The power analysis concluded a total sample size of 29 would be needed to observe between and within-group differences. We will enroll 40 participants to account for attrition and the possibility of using age or body-mass index as a covariate.

Participants

Forty adults (18 – 40 years of age) with CAI will be enrolled and recruited from a university and surrounding community. Individuals will qualify as having CAI if they meet the following recommended criteria determined by the International Ankle Consortium[96]: 1) History of at least 1 significant ankle sprain 12 months prior to study enrollment 2) most recent ankle sprain occurred greater than 3 months prior 3) history of "giving way" established by scoring ≥11 on the Identification of Functional Ankle Instability (IdFAI) 4) self-reported ankle function determined by scoring ≤90% and ≤80% on the Foot and Ankle Ability Measure (FAAM) Activities of Daily living (-ADL) and Sport subscales, respectively. Individuals will be excluded from participating if they do not meet the aforementioned criteria or they report any of the following: 1) history of lower extremity surgery 2) history of lower extremity fracture which required realignment 3) any acute lower extremity musculoskeletal injury within the previous 6

weeks of enrollment 4) any other known pathologies that would cause an alteration in plantar pressure during gait. In the event an eligible participant reports a history of bilateral ankle sprains, their worst perceived unstable ankle will be chosen as the involved limb.

Methods

Once eligibility has been established, participants will report to the Biodynamics Research Laboratory for informed consent, testing, and intervention sessions. On their first visit, participants will complete a baseline testing session (Figure 1). Participants will report back within 48-72 hours for their first intervention session. During this time, participants will be randomly assigned to either the AudFB or NoFB groups. The intervention will consist of 8 sessions of gait retraining over a 2-week period with each session lasting 30 minutes. During the first intervention session, ultrasound images and PROs will be collected prior to beginning the gait training protocol to establish minimal detectable change (MDC) scores (Figure 1 a,b,d). After the 8 intervention sessions have been completed, participants will be asked back to the laboratory within 24-48 hours for a post-intervention testing session (immediate post), which will follow the same protocol as baseline (Figure 1). Seven days after the conclusion of the final intervention session, participants will report back for a final testing session (1-week post), which will follow the same procedure as baseline and immediate-post sessions (Figure 1). During the time between the immediate-post and 1-week post-testing, participants will be instructed to continue their regular activity.

Figure 1. Procedures for Testing Sessions

Testing Sessions (Baseline, Immediate-post, 1-week post)

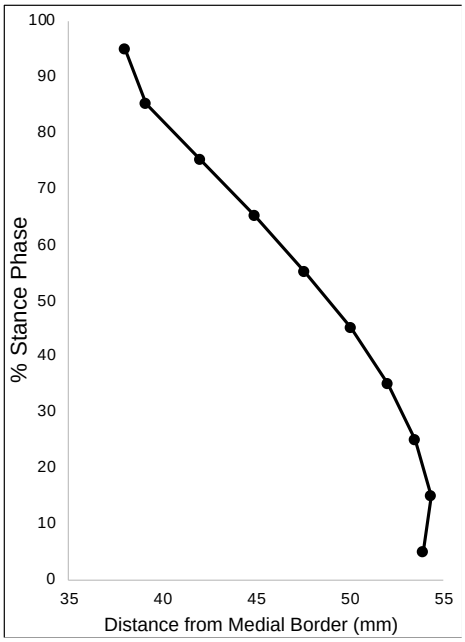
Biomechanical Assessment

Participants will be fitted with neutral athletic shoes (model M680V3, New Balance Inc., Boston, MA) and the Pedar-X in-shoe pressure insoles (Novel Electronics, Inc., St. Paul, MN). Next, they will be instructed to walk on a treadmill at a comfortable, self-selected pace for a total of 30 minutes (Figure 1c). Every 5 minutes of walking, a 30-second recording of plantar pressure will be taken. Plantar pressure of the involved limb will be sampled at 200 Hz. Ten repetitions of a step-down, forward lunge, and lateral hop task in a randomized order (Figure 1e). The step-down task will follow previously reported methods.[86,87] Participants will stand on a 30 cm box and be asked to step-down with their involved limb and continue forward momentum with a few more steps on level ground. Forward lunges will be performed with participants starting in a neutral stance and hands on their hips. They will lunge forward with their involved limb until the uninvolved knee reaches 90° flexion then push off with their involved limb to return to the start position. The lateral hop will be performed with individuals starting in a neutral stance, with a piece of 1.5-inch white athletic tape on the floor just lateral to their foot. With hands on their hips they will be instructed to hop laterally over the tape and immediately back to the starting position while gazing straight ahead and not at the ground.

All plantar pressure data will be processed in Novel Database Pro (Novel Electronics, Inc., St. Paul, MN). The average of the middle 10 steps during each successful trial of walking, step down, forward lunge, and lateral hops will be used for analysis. The specific variables of interest will be contact area, contact time, peak

pressure, max force, pressure-time integral, force-time integral, and instant to peak pressure. The foot will be divided into 10 regions: total foot, medial heel, lateral heel, medial midfoot, lateral midfoot, medial forefoot, central forefoot, lateral forefoot, lesser toes, and great toe. Each plantar pressure variable will be calculated for each region. The same middle 10 steps will also be used to calculate the COP trajectory during walking, step-down, forward lunge, and lateral hops using a custom MATLAB (version R2019b, MathWorks, Natick, MA) code using previously reported methods.[92,97] Briefly, COP trajectory will be calculated by taking the distance (mm) of the COP location from the medial border of the foot and averaged in 10% increments producing 10 data points representing 100% of the stance phase of gait (Figure 2). For example, 1-10% COP data points will be averaged and represent the first 5% of stance, likewise 11-20% COP data points will represent 15% of stance and so forth.

Figure 2. Example of COP Trajectory

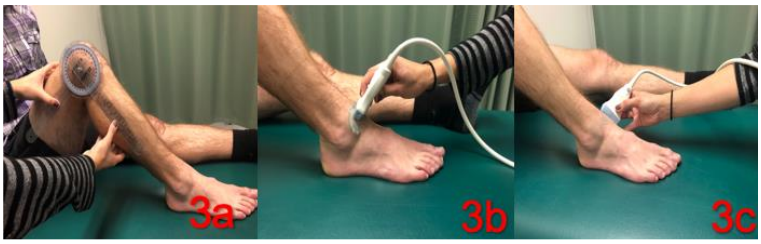


Ultrasonographic Assessment

Once participants arrive at the Biodynamics Research Lab, they will be seated for 30 minutes to reduce the effects of cartilage deformation from walking prior to arriving for testing (Figure 1a).[64,98] After the unloading period has lapsed, participants will be positioned on the treatment table with their back against the wall, their involved hip and knee flexed to 90°, and the sole of their foot flat on the table (Figure 3a).[62] A LOGIQe ultrasound system (General Electric, Fairfield, CT, USA) and a 12-MHz linear probe will

be used to collect talar cartilage images in two views in a randomized order (Figure 1b). The probe will be positioned transversely between the medial and lateral malleoli (Figure 3b) and longitudinally over the medial tibiotalar joint (Figure 3c) while being adjusted until the talar cartilage appears to be maximally reflected. Three images will be captured in each position before (Figure 1b) and immediately after (Figure 1d) the 30 minutes of treadmill walking (Figure 1c) to measure deformation.

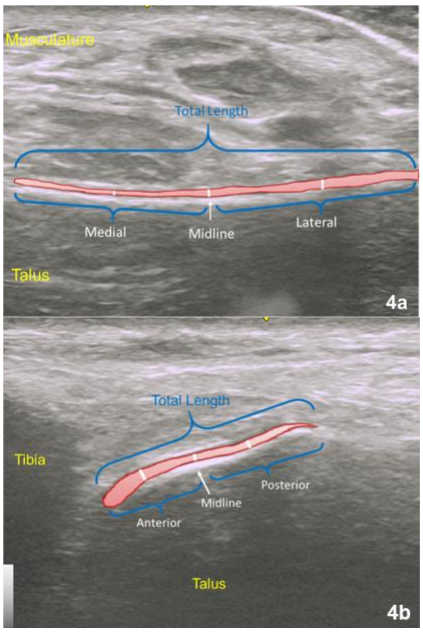
Figure 3. Ultrasound Testing Procedure. A) Patient position, B) Transverse ultrasound placement, C) Longitudinal ultrasound placement



In order to blind the PI during image processing, each image will be exported from the ultrasound unit and re-coded using a custom MATLAB code removing identifiers. Cartilage deformation will be measured in a random order using ImageJ (National Institute for Health, Bethesda, MD). Talar cartilage thickness (mm) will be measured as the distance between the synovial and osteochondral interfaces at three locations in each view (Figure 4a,b). The midline will represent the center of the entire length of cartilage. In the transverse view (Figure 3b and Figure 4a), the medial and lateral thickness will be measured at the center of the distance between the midline and visible edge of the cartilage, respectively. The cross-sectional area (mm^2) of the medial and lateral segments will be calculated from the midline to the visible edge of the cartilage, respectively (Figure 4a). In the longitudinal view (Figure 3c and Figure 4b), the anterior and posterior thickness will be measured at the center of the distance between the midline and visible edge of the cartilage, respectively. Similarly, the anterior and

posterior cross-sectional areas will be calculated from the midline to the visible edge of the cartilage (Figure 4b). Cartilage deformation will be calculated as a percent to determine the change in thickness and cross-sectional area, individually, before and after 30 minutes of treadmill walking (Figure 1b, d). The PI has demonstrated good intra-rater and inter-session reliability in measuring and analysis talar cartilage measurements (Appendix B).

Figure 4. Ultrasound Measurements. A) Transverse image, B) Longitudinal image

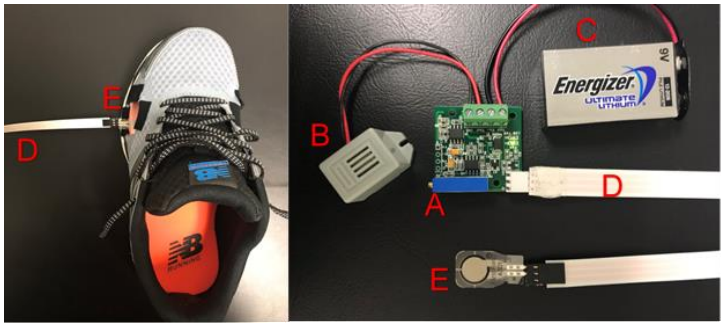


$$\text{Deformation} = \left(\frac{\text{MEAN}_{PRE} - \text{MEAN}_{POST}}{\text{MEAN}_{PRE.}} \right) * 100$$

Patient Reported Outcome Measures

Questionnaires will be completed by each participant at baseline, intervention day 1, immediately-post, and 1-week post gait retraining (Figure 1a). The FAAM ADL and Sport subscales will be completed only for the involved limb. Participants will self-report their responses based on instructions given on the questionnaires. A member of the research team will be available to clarify any instructions for the participants. Minimal detectable changes (MDC) will be calculated between scores obtained on the FAAM ADL and Sport from baseline and intervention day 1. The MDC will be used to further determine significant improvements in PROs after the intervention.

Figure 5. Placement of load sensor in shoe and auditory instrument consisting of a potentiometer (A), buzzer (B), 9V battery (C), extension cable (D), and load sensor (E).



Intervention

The proposed intervention was designed from previous studies using gait re-training,[82,99] auditory feedback instructions, [99] and best practices from motor learning research.[64,98] Each group (AudFB, NoFB) will perform 8 intervention sessions in 2 weeks (4 sessions/week) consisting of 30 minutes of walking. The NoFB group will spend the same amount of time walking (minutes) as the AudFB group to account for any possible effects of the additional physical activity and steps taken per day; however, they will not receive any instruction on how to walk or be introduced to the auditory feedback. The auditory feedback will be given through a thin (14 x 25.4 x 0.203 mm) FlexiForce Load Sensor (Tekscan, Inc. South Boston, MA) placed on the sole of the shoe under the head of the 5th metatarsal for each participant (Figure 5). The pressure sensor is connected to a FlexiForce Quickstart Board (31.75 x 31.75 mm) and a potentiometer (Tekscan, Inc. South Boston, MA) with an attached buzzer, powered with a 9-volt battery (Figure 5). The auditory instrument will be calibrated for each participant prior to each intervention session. Once the load sensor is placed in the shoe, participants will be asked to shift all of their weight onto the sensor, leaning in an anterolateral direction (Figure 6). The potentiometer will be adjusted to the first point where noise can be heard when full weight is placed on the load sensor (Figure 6b). After calibration, participants will step onto a treadmill (Precor, Inc. Woodinville, WA) with a safety cord attached to their shirt. They will be instructed to increase the treadmill to the same speed used during

Figure 6. Participant wearing the auditory instrument in the starting position (A) and the position for calibration (B).

baseline testing, which will be used during all intervention sessions. The AudFB group will be instructed to follow the cue to "walk in a manner where you do not hear a noise, but that is still as natural and comfortable as possible." It is recommended regular exposure to an external focus enriches the motor learning and performance effects,[97]; therefore, participants will be exposed to the auditory feedback and instructed to follow our cue during the entire gait retraining session (30 minutes).

Statistical Analysis

Separate 2 x 3 (group by time) mixed methods analysis of variances will be applied to each dependent variable (plantar pressure measures, COP trajectory, talar cartilage thickness and cross-sectional area deformation, and FAAM-ADL and Sport). The between-subject factor is group (AudFB, NoFB) and the repeated measure, within-subject factor, is time (baseline, immediately-post, 1-week post). In the event age or body mass index is statistically different among the groups, we will run analysis of covariance. The assumption of independence will be met through the research design, as each participant will be tested individually, and their results will have no effect on other participants. The assumption of normality will be tested through visual inspection of histograms, Q-Q plots, box plots, and Levene's test of normality. Homogeneity of variance will be tested through a Shapiro-Wilks test. Statistical significance will be set a prior as $p<0.05$, and according to recent recommendations for statistical testing in sports medicine studies,[100] we will not control for multiple comparisons. However, significance will be determined with $p \leq 0.05$ and Hedges *g* effect sizes of moderate to large scales with 95% confidence intervals that do not cross 0. Additionally, MDC will be reported for deformation and PROs to further determine clinical significance. All statistical analyses will be conducted

in SPSS v26 (SPSS, Inc., Chicago, IL) and Excel (Microsoft Office 2019, Microsoft, Redmond, WA).

Alternative Approaches

It is necessary to determine the effect of an independent gait retraining intervention prior to inclusion of a full impairment-based rehabilitation program. While gait alterations are a common finding in individuals with CAI compared to healthy counterparts, we understand not every patient with CAI will present with aberrant gait. However, there are no clinically valid tools to assess which patients may need gait retraining. Similar to previous work targeting specific impairments, not every patient with CAI presents with balance deficits, muscle weakness, or range of motion restrictions, yet evidence supports the use of these interventions for the majority of this patient population. Therefore, prior to supporting the use of our novel AudFB biofeedback for the purposes of gait retraining, this research study is critical to understand the potential benefits of this intervention in isolation.

Institutional Resources and Environment

All assessments and interventions will be completed within facilities housed in the College of Health and Human Services, specifically within the Biodynamics Research Laboratory of the Department of Kinesiology.

Biodynamics Research Laboratory

The Biodynamics Research Laboratory (BRL) is housed in Belk Gymnasium. It is part of a recent, $20 million renovation that resulted in state-of-the-art research spaces and equipment. This laboratory space includes one Biodex System III Pro isokinetic dynamometer and associated attachments for strength assessment; a Digitimer DS7AH,

Magstim Rapid Transcranial magnetic stimulator, and 40 channel NuAmps electroencephalograpy system for neurophysiological assessments; two Biopac MP150 data acquisition units with 16 channels for electromyography assessment; a 10 camera Vicon Vantage V5 high speed motion capture system; 2 Bertec force platforms and 1 AMTI force platform for biomechanical and balance assessments; one GE logic diagnostic ultrasound device; one Optogait system for gait analysis; one Pedar pressure insole system for additional gait analysis and an 8 channel Delsys Trigno wireless electromyography system. Additional equipment includes one treadmill and one stationary bicycle for aerobic exercise as well as rehabilitation equipment including foam balance pads and elastic resistance bands. The laboratory has supporting numerous computer workstations loaded with software word processing, and statistical analyses (SPSS 23.0), data processing (MATLAB 16.0, AcqKnowledge 4.2, Vicon Nexus 2.3, Visual 3D 5, CURRY 7, Balance Clinic, EMG works, and the full Microsoft Office Professional suite) as well as internet web browsers. Complete technological support is available through the College of Health and Human Services Academic Technologies staff.

Graduate and undergraduate student involvement in research is highly encouraged at UNC Charlotte. On average, the Biodynamics Research Laboratory (BRL) has 10 undergraduate students per year volunteer as research assistants and an additional 3-5 master's degree students and 3 PhD students completing research projects under the guidance of our faculty.

Personnel

Senior and experienced personnel will be available to the principal investigator during the entire research process. Both Dr. Donovan (faculty advisor) and Dr. Thomas (committee member) are experienced in the area of interest, knowledgeable with the equipment and technology being used, and will be available during the entire duration of the study. Both Drs. Donovan and Thomas have offices in the Belk Gymnasium where the BRL is located.

Additional Materials

Relationship Of Biomechanics Across Functional Tasks

Members of our lab have established a relationship between ankle inversion during less functional and more functional tasks. Specifically, there were strong correlations between ankle inversion at initial contact ($r = 0.73$, $R^2 = 52.9\%$, $p < 0.001$) and the aerial phase ($r = 0.68$, $R^2 = 45.7\%$, $p < 0.001$) during walking and a step-down task.[82] The significance of this correlation indicates the potential to intervene during less functional tasks where altering ankle mechanics might be more manageable and may lead to less ankle inversion during functional tasks later in the rehabilitation process. Inversion ankle sprains rarely occur during walking; therefore, the ability to reduce ankle inversion during sport-like tasks may reduce the risk for lateral ankle sprains.

External Focus Of Attention Using An Auditory Device Alters Measures Of Plantar Pressure

Our lab conducted a preliminary study to determine the real-time effects of our novel auditory instrument (AudFB) during walking on plantar pressure in individuals with CAI. Results of this study (Figure 1) support our auditory biofeedback instruments immediate ability to reduce peak pressure in the lateral midfoot ($p<0.01$, ES= -2.19) and

lateral forefoot ($p<0.01$, ES= -1.97) while increasing peak pressure at the great toe ($p<0.01$, ES= 1.44).[79]

A second preliminary study using the auditory instrument was conducted to determine its effect on postural control and functional performance in CAI participants. During a baseline single limb static balance, our preliminary data showed individuals with CAI have more COP data points in the lateral quadrants of the foot. When auditory biofeedback was introduced during balance, COP data points transitioned from the lateral to medial quadrants (Figure 2). Our participants completed two more functional tasks: a step-down and forward-lunge. The AudFB condition during a step-down task significantly reduced max force in the lateral midfoot (ES = -0.84) and forefoot (ES = -1.11) compared to a baseline trial ($p<0.001$). Likewise, the AudFB condition during the forward lunge significantly reduced max force in lateral midfoot (ES = -0.66) and forefoot (ES = -0.86) compared to a baseline trial ($p<0.001$). The combined results of our preliminary data indicate our novel auditory biofeedback instrument is capable of producing real-time effects on plantar pressure measures in a CAI population; however, the long-term implementation and retention effects on plantar pressure parameters have yet to be explored.

Reliability Measuring Talar Cartilage Via Ultrasonography

Preliminary data was collected to establish intra-rater and inter-day reliability within subjects. A single member of the research team collected three ultrasound images of the talar cartilage in a group of volunteers on two days separated by 1 week. The same researcher then measured cartilage thickness using ImageJ. Images were re-coded to remove identifiers to eliminate measurement bias. Intraclass correlation coefficients

(ICC) were calculated for intra-rater consistency between images within individuals. Results indicate good reliability ($ICC_{2,1}$= 0.727, 95% CI: .207, .934). Inter-day reliability was also established in the same cohort of volunteers, where three more ultrasound images were captured on the same limb. The average thickness during each session was used to establish consistency between days for the same rater. ICC's were calculated for consistency and results indicate good reliability (ICC = 0.895, 95% CI: 0.158, 0.984). Our preliminary studies and pilot data have established that individuals with CAI 1) have walking biomechanics predictive of biomechanics during other function tasks 2) are capable of adopting new biomechanical strategies during walking and other functional tasks in real-time response to the auditory biofeedback 3) can have their cartilage reliably assessed using ultrasonography. As such using the following methods, we will determine the ability of our novel auditory biofeedback tool to 1) alter biomechanics during walking, step-down, and lateral hopping 2) change talar cartilage deformation patterns 3) improve patient-reported outcomes.

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A2.3 Consent Form

UNC CHARLOTTE
Department of Kinesiology
9201 University City Boulevard, Charlotte, NC 28223-0001
t/ 704-687-8611 f/ 704-687-0930 www.kinesiology.uncc.edu

Consent to Participate in a Research Study

Title of the Project: Effects of gait retraining with auditory feedback on functional biomechanics and ankle joint health in individuals with chronic ankle instability
Principal Investigator: Luke Donovan, PhD, ATC, UNC Charlotte
Co-investigator: Danielle Torp, MS, ATC, UNC Charlotte
Study Sponsor: Faculty Research Grant

You are invited to participate in a research study. Participation in this research study is voluntary. The information provided is to help you decide whether or not to participate. If you have any questions, please ask.

Important Information You Need to Know

- The purpose of this study is to determine is patients with CAI respond differently to a gait retraining program with auditory feedback or no feedback.
- We are looking for individuals between the age of 18 and 40 who have a condition known as chronic ankle instability (CAI).
- You will complete 3 testing session with each session lasting between 1 – 2 hours and 8 intervention sessions lasting approximately 45 minutes. You will complete one testing session prior to the intervention and two testing sessions after you finish the intervention.
- The total time commitment for this study is 12.5 hours over a 5-week period, average 2-4 hours per week. Once you have completed all 11 sessions you will have completed the study and be compensated with a $75 Amazon gift card.
- Each testing session will include ultrasound images of your ankles, walking, balancing, lunging, hopping, and a step-down task. The intervention session will consist of 30 minutes of walking. You will be randomly assigned to one of two intervention groups. You will either receive auditory feedback while walking, or no feedback.
- Please read this form and ask any questions you may have before you decide whether to participate in this research study.

Why are we doing this study?

The information gathered from this research study will assist in developing new rehabilitation techniques for treating people with chronic ankle instability

Why are you being asked to be in this research study.

You are invited to participate in this study if you have a condition known as chronic ankle instability "CAI" and are between the age of 18 and 40. In order to be considered to have CAI you must have had more than 1 lateral ankle sprain with the 1st ankle sprain occurring greater than 1 year prior to today's date. In addition, your ankle must feel like you can easily roll it again and/or feels like it gives way during physical activity. Furthermore, you must report a decrease in ankle function, which was determined based on your answers from an online questionnaire. Finally, all volunteers must participate in moderate to vigorous intensity physical activity for at least 30 minutes 3 days per week. Physical activity intensity was defined by another questionnaire.

You will not be able to participate in this study if you do not meet all of the above criteria. In addition, you will not be able to participate in this study if any of the following are true: 1) had an ankle sprain within the past 6 weeks 2) had another injury (sprain or strain) to your legs or feet within the past 6 weeks 3) had any type of orthopedic surgery to your ankle or feet 4) have any other condition that will make you unable to complete the functional tasks.

You are invited to participate in this study because you have met the above eligibility criteria based on your answers from an online questionnaire regarding your overall health history, ankle healthy history, and perceived ankle function.

What will happen if I partake in this study?

If you volunteer to participate in this study, you will be first asked to answer questions about your overall health history. This information will be used to make sure you do not have any past injuries or illnesses that increase your risk of being harmed by participating in this study. This questionnaire should take approximately 5 minutes to complete. Next, we will have you fill out questionnaires related to your ankle joint health.

TESTING SESSIONS

You will complete the following testing session three times: baseline, 24-72 hours after you finish the intervention, and 7 days after you finish the intervention. These testing sessions will last approximately 2 hours.

Preparation: After the questionnaires are completed, we will take 6 ultrasound images of your ankle joint for both ankles. An aqueous gel will be applied to your ankle and a transducer will be placed in two positions on your ankle. Next, we will prepare your skin for placement of surface electromyography (sEMG) electrodes. We will use an abrasive gel and alcohol pad to clean your area at the site of electrode placement. After all the electrodes are secured, we will ask you to perform three 5 second muscle contractions for several muscles of your leg. Next, we will fit you for a standard pair of athletic shoes and in-soles. These insoles contain sensors that are able to measure how much pressure goes through your feet while you move. The insoles will be connected to a transmitter that will be placed in a belt and wrapped around your waist. Then, you will walk on a treadmill for 30 minutes while every 5 minutes we collect muscle activity and plantar pressure. Next,

you will perform a serious of 4 tasks (balance, step-down, lunge, and lateral hop). All tasks will be recorded using a video camera and will be positioned in a manner which will not record your face. We will randomly decide which order you complete the tasks. The first task you will complete is a single-limb balance task.

Balance Task: Before starting this task, we will measure the length and width of your foot with a measuring tape which will create a grid to stand on while we measure your balance. You will be barefoot on a force plate and asked to perform 3 trials of standing as still as possible for 10 seconds. During this time, we will be recording pressure from the force plate and muscle activation from the sEMG electrodes. After 3 successful trials, we will repeat the procedures with your eyes closed.

Lateral hopping, Step-down, and Lunging Tasks: In a random order, you will perform three other functional tasks. You will perform a lateral hop by starting on your involved limb, jumping side-to-side continuously until you have performed 10 hops. The lunge will be performed by standing on a hard surface with your hands on your hips. You will lunge your involved limb forward until the uninvolved knee touches the ground. As soon as you reach proper position, you will be asked to immediately return to the starting position. You will perform 10 continuous lunges. The step-down task will be completed by standing on a box, stepping down with the involved limb and continuing to take a few additional steps. You will perform 10 step down trials. Once you have completed all 5 tasks you will have completed the testing session.

INTERVENTION SESSIONS

All intervention sessions will be conducted in the same manner. You will complete 8 sessions during a 2-week period (4x per week). The first intervention session will be scheduled within 24-72 hours after your baseline testing session. During this time, you will be randomly placed into one of two groups: you will receive auditory feedback while walking (AudFB) or you will receive no instruction while walking (NoFB). Each group will follow the same walking time and procedures, minus the feedback. Each intervention session will take approximately 40 minutes.

Intervention: We will again fit you with standard athletic shoes and the plantar pressure insoles. You will be instructed to walk on a treadmill at your self-selected pace for 30 minutes. If you are in the NoFB group you will not receive any instruction other than to walk at your normal pace.

Auditory Feedback: We will place a small sensor inside of the athletic shoes and the auditory unit will be placed inside the plantar pressure belt. The force sensitive resistor sensor connected to a trimming potentiometer, buzzer, and battery. The system has an on/off switch and transmits no energy into the body. The system is designed that when a certain level of force is applied to the sensor, the buzzer will elicit a noise. First, we will calibrate the sensor so it is sensitive to your movements. Then, you will be instructed to walk in a manner where you cannot hear a noise, yet you are still walking as naturally and comfortably as possible. You will continue to walk in this way during the duration of the intervention sessions.

FOLLOW UP TESTING SESSION
You will report back between 24 and 72 hours to complete the immediate-post testing session. Further, you will be scheduled to report back 7 days after your final intervention session for your final 1-week post testing session. Both of these testing sessions will follow the same procedures as the baseline testing sessions. Once you have completed the final testing session (1-week post), you will have completed the study and be given a $75 Amazon gift card.

What benefits might I experience?
There may a direct benefit for those participants enrolled in the auditory feedback group. It is unknown if those in the no feedback group will experience any benefits.

What risks might I experience?
The project may involve risks that are not currently known. Potential known risks include the following. There is a risk of people outside of this study finding out you completed this study; however, this risk is rare (<1% of this occurring). This risk will be minimized by not having any identifiable information on the questionnaires and storing all questionnaires in a locked filing cabinet inside a locked room. Furthermore, the consent forms will be stored in a separate locked filing cabinet from the questionnaires. There is a minor risk of discomfort for remaining in a seated position for a duration of time while ultrasound images are captured. The ultrasound itself will not cause pain or harm and does not have radiation exposure. Another minor risk is experiencing mild soreness from performing balance and jumping tasks. We estimate about 1-10% of participants will experience mild soreness and believe the cause of any soreness is a result of performing tasks in a new manner that activates muscles that are not usually used for those tasks. In addition to mild muscle soreness, there is a minor risk of developing skin rash or irritation from the skin cleaning process for the sEMG sensors (<10%). Another risk is falling and sustaining an injury during the functional tasks. This risk is serious, but rare, with <1% chance of this occurring. This risk is minimized by allowing you to complete the task at your normal speed and intensity.

How will my information be protected?
Any identifiable information collected as part of this study will remain confidential to the extent possible and will only be disclosed with your permission or as required by law.

We will maintain confidentiality by not including any identifiable information on our questionnaires, but instead will assign you a participant ID number. All questionnaires will be stored in a locked cabinet inside a locked room. Furthermore, all consent forms will be stored inside a different locked cabinet inside a locked room. In addition, plantar data recorded during walking will be stored on a password-protected computer and will not list any identifiable information. Video recording during the study will not include your face.

How will my information be used after the study is over?
After this study is complete, study data may be used as part of publishing our results. The data we share will NOT include information that could identify you.

Will I receive an incentive for taking part in this study?
You will receive a $75 Amazon gift card at the completion of participation. If you choose not to complete the study, you will not receive any portion of the gift card.

What other choices do I have if I don't take part in this study?
Other treatment alternatives for your chronic ankle instability would be seeking care from a physician, physical therapist, or athletic trainer.

What are my rights if I take part in this study?
You are a volunteer. The decision to participate in this study is completely up to you. If you decide to be in the study, you may stop at any time. You will not be treated any differently if you decide not to participate in the study or if you stop once you have started; however, you will not be reimbursed with the $50 Amazon gift card.

Who can answer my questions about this study and my rights as a participant?
UNC Charlotte wants to make sure that you are treated in a fair and respectful manner. Contact the Office of Research Compliance at 704-687-1871 or uncc-irb@uncc.edu if you have questions about how you are treated as a study participant. If you have any questions about the actual project or study, please contact Dr. Luke Donovan (704-687-8611, ldonova2@uncc.edu).

Consent to Participate
I have read the information in this consent form. I have had the chance to ask questions about this study, and those questions have been answered to my satisfaction. I am at least 18 years of age, and I agree to participate in this research project. I understand that I will receive a copy of this form after it has been signed by me and the principal investigator of this research study.

_____
Participant Name (PRINT) DATE

_____
Participant Signature

_____
Investigator Signature DATE

Please Check the Box

☐ I give permission to store my name, age, email, and phone number in a separate secure location away from my data, as I want to be contacted about future study opportunities.

☐ I **do not** give permission to store my name, age, email, and phone number in a separate secure location away from my data, as I **do not** want to be contacted about future study opportunities.

A2.4 Patient Reported Outcome Measures

Foot and Ankle Ability Measure (FAAM)
Activities of Daily Living Subscale

Please Answer **every question** with **one response** that most closely describes your condition within the past week.
If the activity in question is limited by something other than your foot or ankle mark "Not Applicable" (N/A).

	No Difficulty	Slight Difficulty	Moderate Difficulty	Extreme Difficulty	Unable to do	N/A
Standing	☐	☐	☐	☐	☐	☐
Walking on even Ground	☐	☐	☐	☐	☐	☐
Walking on even ground without shoes	☐	☐	☐	☐	☐	☐
Walking up hills	☐	☐	☐	☐	☐	☐
Walking down hills	☐	☐	☐	☐	☐	☐
Going up stairs	☐	☐	☐	☐	☐	☐
Going down stairs	☐	☐	☐	☐	☐	☐
Walking on uneven ground	☐	☐	☐	☐	☐	☐
Stepping up and down curbs	☐	☐	☐	☐	☐	☐
Squatting	☐	☐	☐	☐	☐	☐
Coming up on your toes	☐	☐	☐	☐	☐	☐
Walking initially	☐	☐	☐	☐	☐	☐
Walking 5 minutes or less	☐	☐	☐	☐	☐	☐
Walking approximately 10 minutes	☐	☐	☐	☐	☐	☐
Walking 15 minutes or greater	☐	☐	☐	☐	☐	☐

Foot and Ankle Ability Measure (FAAM)
Activities of Daily Living Subscale
Page 2

Because of your foot and ankle how much difficulty do you have with:

	No Difficulty at all	Slight Difficulty	Moderate Difficulty	Extreme Difficulty	Unable to do	N/A
Home responsibilities	☐	☐	☐	☐	☐	☐
Activities of daily living	☐	☐	☐	☐	☐	☐
Personal care	☐	☐	☐	☐	☐	☐
Light to moderate work (standing, walking)	☐	☐	☐	☐	☐	☐
Heavy work (push/pulling, climbing, carrying)	☐	☐	☐	☐	☐	☐
Recreational activities	☐	☐	☐	☐	☐	☐

How would you rate your current level of function during you usual activities of daily living from 0 to 100 with 100 being your level of function prior to your foot or ankle problem and 0 being the inability to perform any of your usual daily activities.

__ __ __ . 0 %

Martin, R; Irrgang, J; Burdett, R; Conti, S; VanSwearingen, J: Evidence of Validity for the Foot and Ankle Ability Measure. Foot and Ankle International. Vol.26, No.11: 968-983, 2005.

Foot and Ankle Ability Measure (FAAM)
Sports Subscale

Because of your foot and ankle how much difficulty do you have with:

	No Difficulty at all	Slight Difficulty	Moderate Difficulty	Extreme Difficulty	Unable to do	N/A
Running	☐	☐	☐	☐	☐	☐
Jumping	☐	☐	☐	☐	☐	☐
Landing	☐	☐	☐	☐	☐	☐
Starting and stopping quickly	☐	☐	☐	☐	☐	☐
Cutting/lateral Movements	☐	☐	☐	☐	☐	☐
Ability to perform Activity with your Normal technique	☐	☐	☐	☐	☐	☐
Ability to participate In your desired sport As long as you like	☐	☐	☐	☐	☐	☐

How would you rate your current level of function during your sports related activities from 0 to 100 with 100 being your level of function prior to your foot or ankle problem and 0 being the inability to perform any of your usual daily activities?

___ . 0%

Overall, how would you rate your current level of function?

☐ Normal ☐ Nearly Normal ☐ Abnormal ☐ Severely Abnormal

IDENTIFICATION OF FUNCTIONAL ANKLE INSTABILITY (IdFAI)

Instructions: This form will be used to categorize your ankle stability status. A separate form should be used for the right and left ankles. Please fill out the form completely and if you have any questions, please ask the administrator. Thank you for your participation.

Please carefully read the following statement:

"Giving way" is described as a temporary uncontrollable sensation of instability or rolling over of one's ankle.

I am completing this form for my **RIGHT/LEFT** ankle (circle one).

1.) Approximately how many times have you sprained your ankle? _____

2.) When was the last time you sprained your ankle?

❑Never ❑ > 2 years ❑ 1-2 years ❑ 6-12 months ❑ 1-6 months ❑< 1 month

3.) If you have seen an athletic trainer, physician, or healthcare provider how did he/she categorize your most serious ankle sprain?

❑Have **not** seen someone ❑Mild (Grade I) ❑Moderate (Grade II) ❑Severe (Grade III)

4.) If you have ever used crutches, or other device, due to an ankle sprain how long did you use it?

❑Never used a device ❑1-3 days ❑4-7 days ❑1-2 weeks ❑2-3 weeks ❑>3 weeks

5.) When was the last time you had ***"giving way"*** in your ankle?

❑Never ❑> 2 years ❑1-2 years ❑6-12 months ❑ 1-6 months ❑< 1 month

6.) How often does the ***"giving way"*** sensation occur in your ankle?

❑Never ❑Once a year ❑Once a month ❑Once a week ❑Once a day

7.) Typically when you start to roll over (or 'twist') on your ankle can you stop it?

❑Never rolled over ❑Immediately ❑Sometimes ❑Unable to stop it

8.) Following a typical incident of your ankle rolling over, how soon does it return to 'normal'?

❑Never rolled over ❑Immediately ❑ < 1 day ❑1-2 days ❑> 2 days

9.) During "Activities of daily life" how often does your ankle feel ***UNSTABLE***?

❑Never ❑Once a year ❑Once a month ❑Once a week ❑Once a day

10.) During "Sport/or recreational activities" how often does your ankle feel ***UNSTABLE***?

❑Never ❑Once a year ❑Once a month ❑Once a week ❑Once a day

A2.5 Data Collection Form

UNC Charlotte
Biodynamics Research Laboratory

BASELINE TESTING

Participant ID:_____ Date:_____

Demographics

Age: _____ Height (cm): _____ Weight (kg): _____

Sex: _____ Dominant Limb: _____ Test Limb: _____

Right Ankle History
1. How many times have your sprained your right ankle? _____
2. How many years/months ago was your first right ankle sprain? _____
3. How many years/months ago was your most recent right ankle sprain? _____

Left Ankle History
1. How many times have your sprained your left ankle? _____
2. How many years/months ago was your first left ankle sprain? _____
3. How many years/months ago was your most recent left ankle sprain? ___

Questionnaires

FAAM-ADL	
FAAM-Sport	
IdFAI	
IPAQ	
Health History Form	

Pre-Ultrasound Offload Start time: Depth:

Walking Speed: Shoe Size: Insole:

Baseline ☐ **5'** ☐ **10'** ☐ **15'** ☐ **20'** ☐ **25'** ☐ **30'** ☐

Functional Task 1:_____

☐☐☐☐☐☐☐☐☐☐

Functional Task 2:_____

☐☐☐☐☐☐☐☐☐☐

Static Balance Width: Length: Foot Width: Foot Length: _____

Eyes Open: ☐☐☐☐☐☐☐☐☐☐

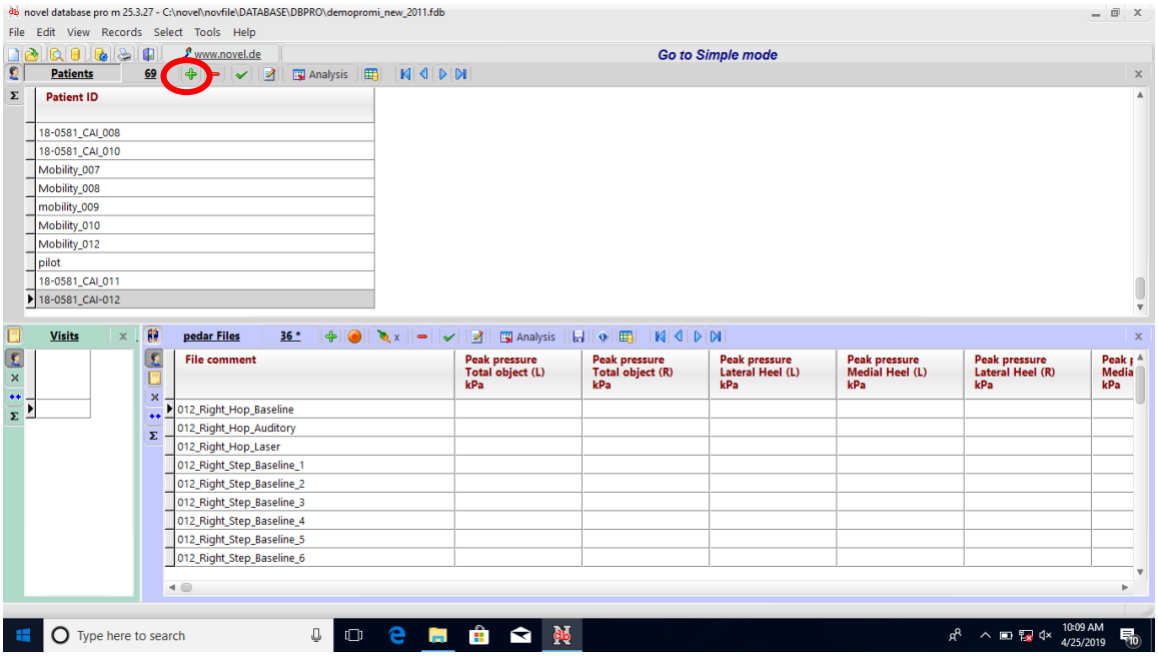
Eyes Closed: ☐☐☐☐☐☐☐☐☐☐

Weight Bearing Lunge Test

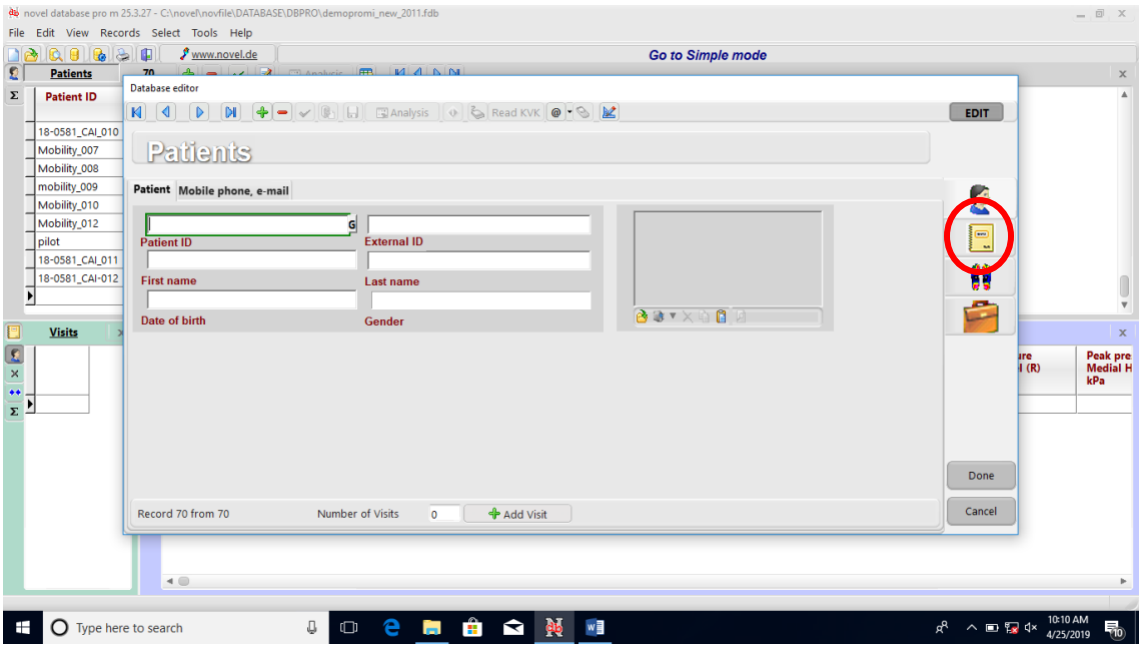
Hindfoot photo: Yes ☐ No ☐

Novel Database Pro Pedar-X Procedure Manual

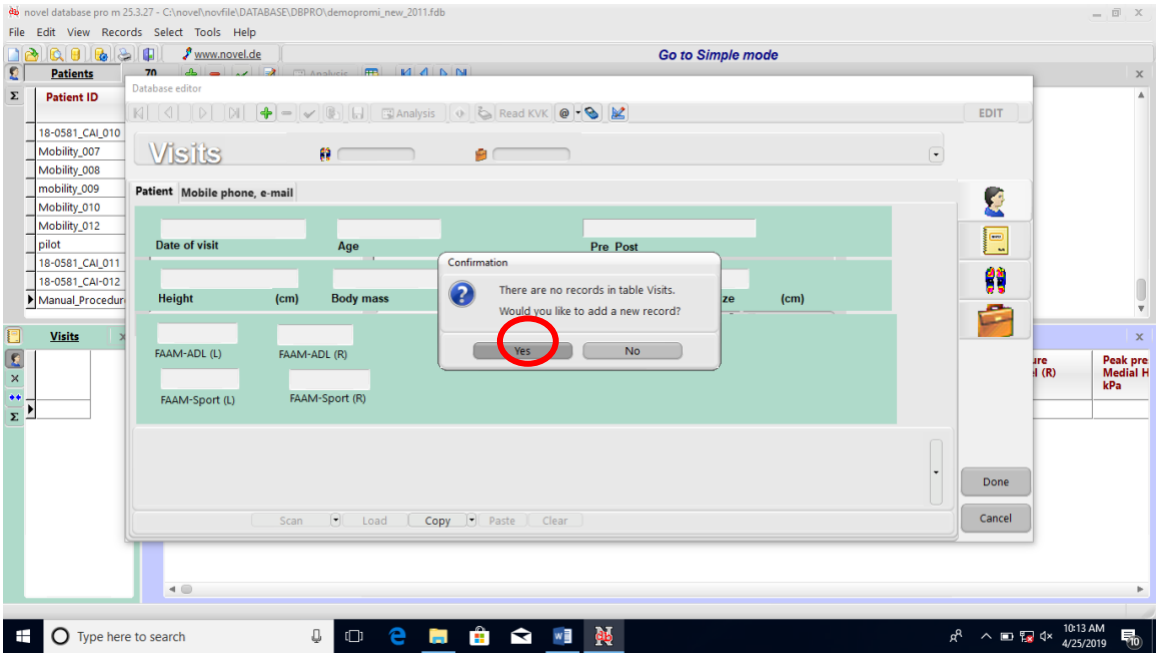
1. In patient window, click green +



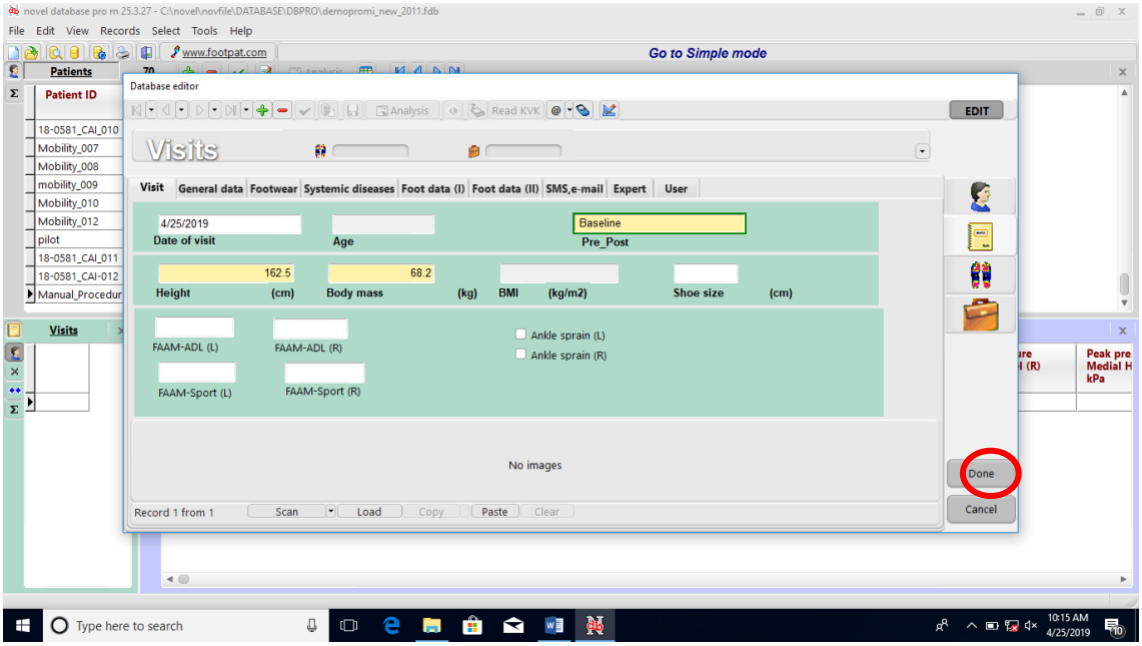
2. Enter in Patient ID then select Visit Information from right side icons.



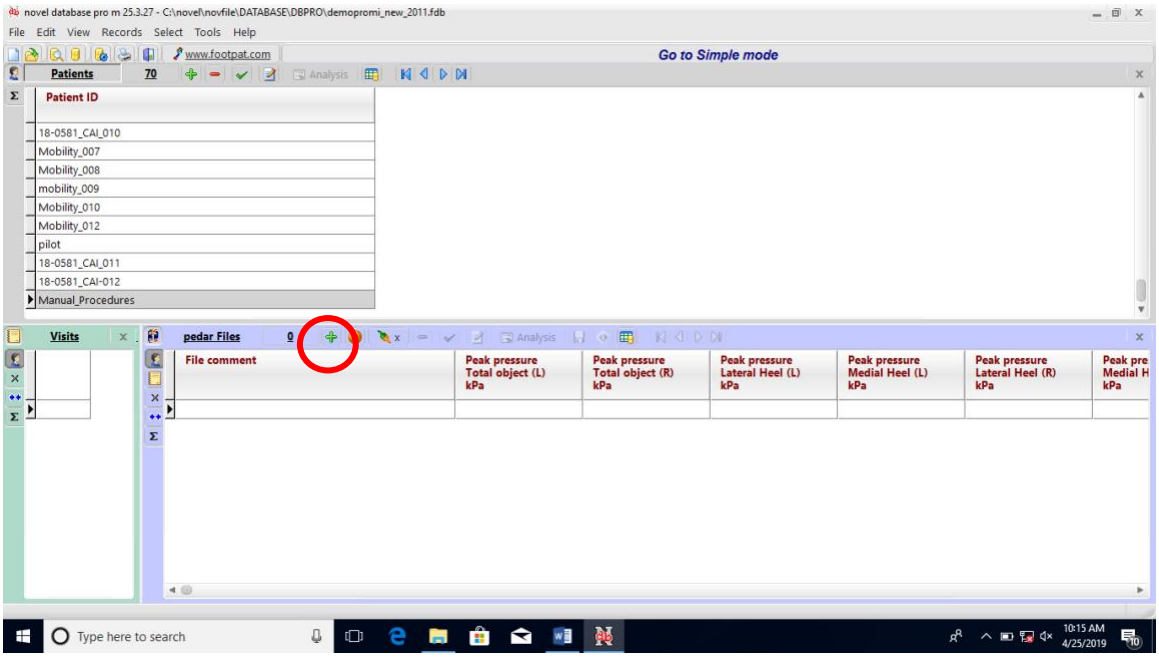
3. Click yes to add a new record.



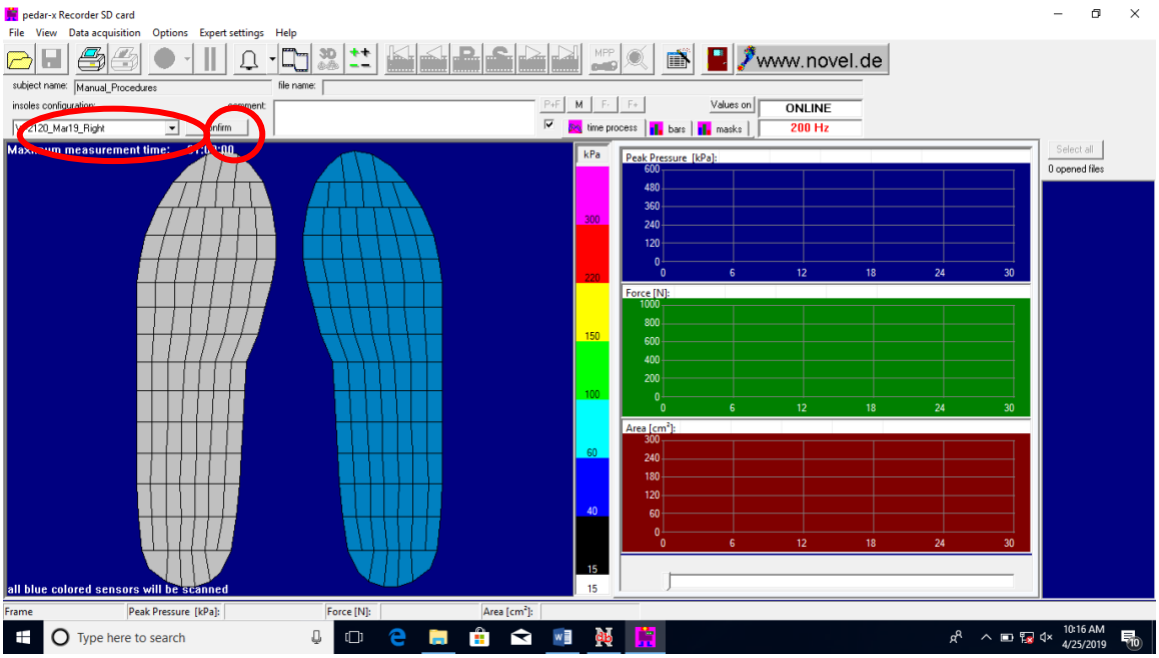
4. Enter in visit information. Then click done.



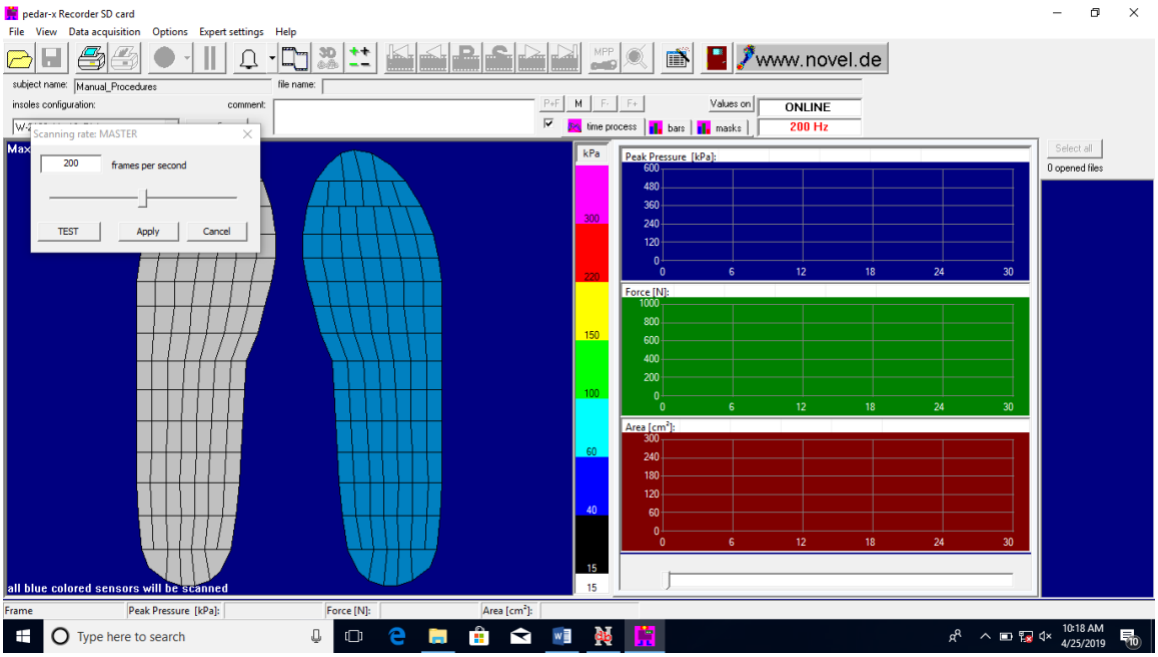
5. Once patient is created, click the red record button in the Pedar section.



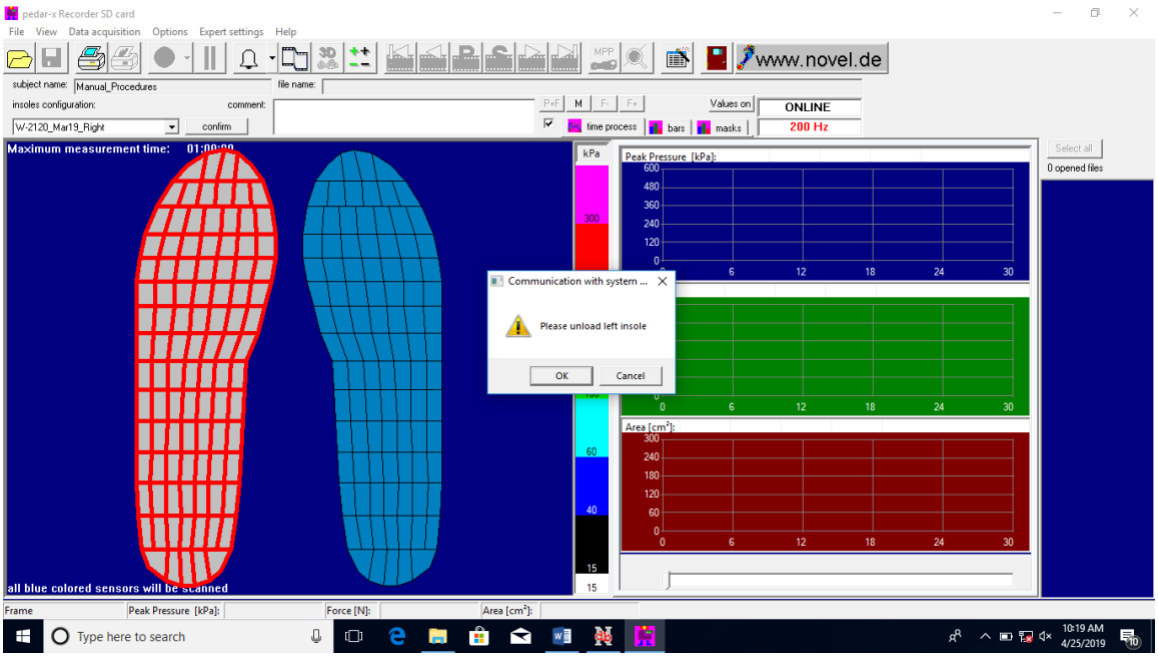
6. Once in the Pedar-X online screen, select the insoles being used. Then hit Confirm to check the Bluetooth connection to the transmitter.



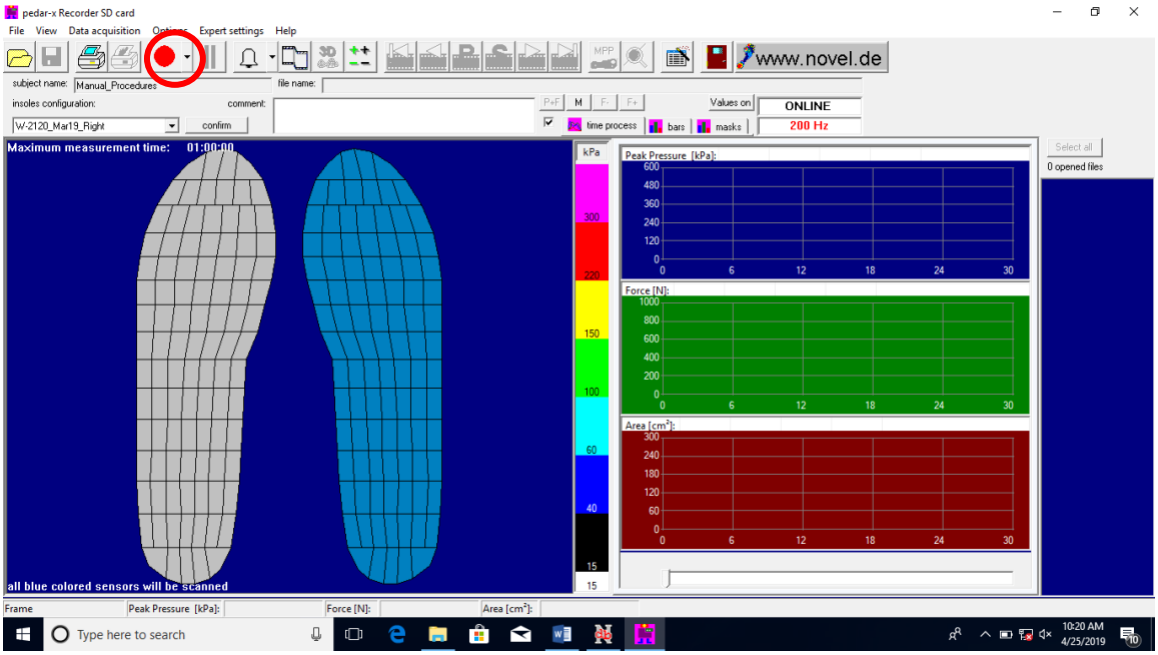
7. If collecting from 1 insole, change frequency to 200Hz; If collecting bilateral data, set frequency to 100Hz.



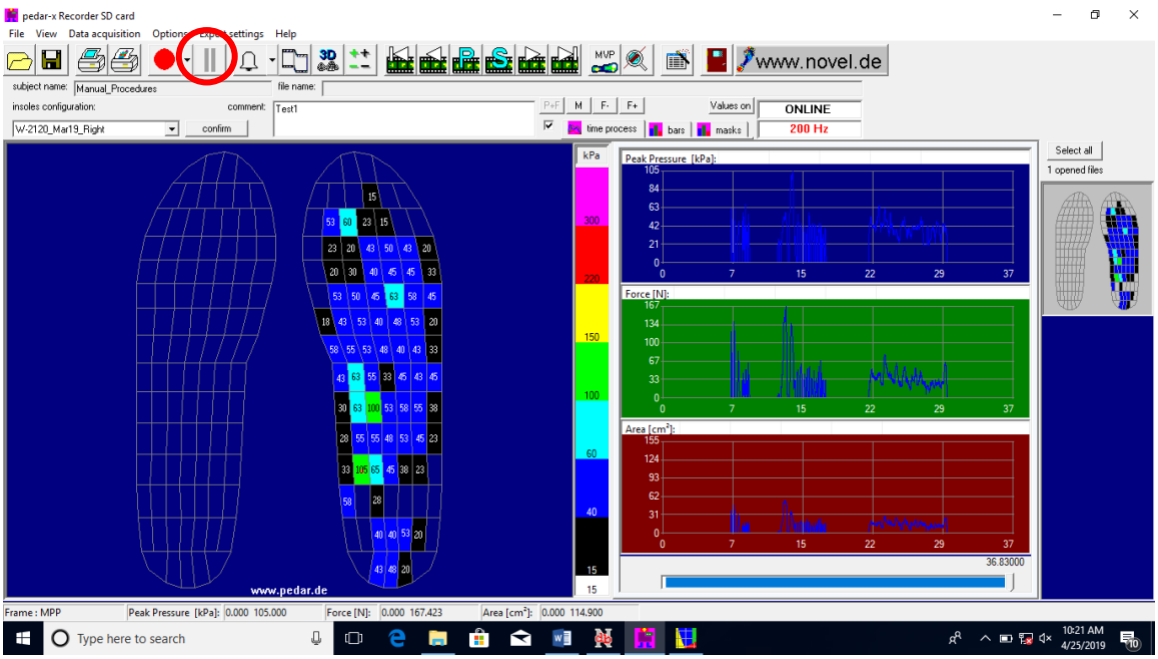
8. Begin calibration settings by following the prompts for patients to offload each insole.



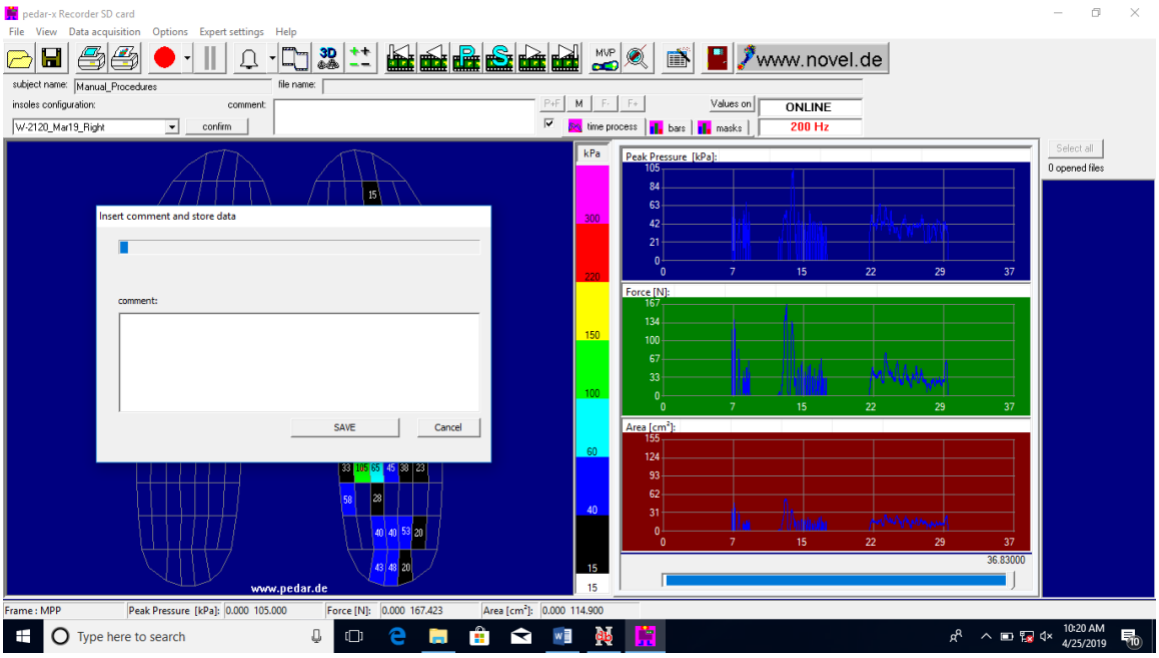
9. Click the record button to begin recording.



10. Press the pause button to end recording.

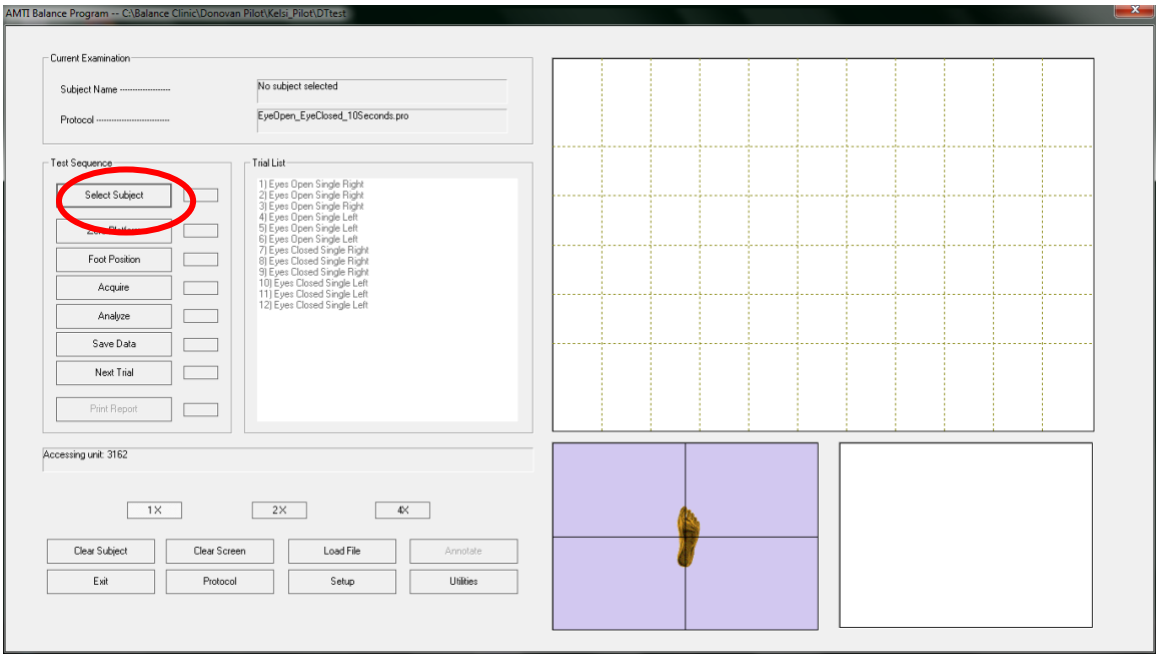


11. Enter the comment file for your trial.

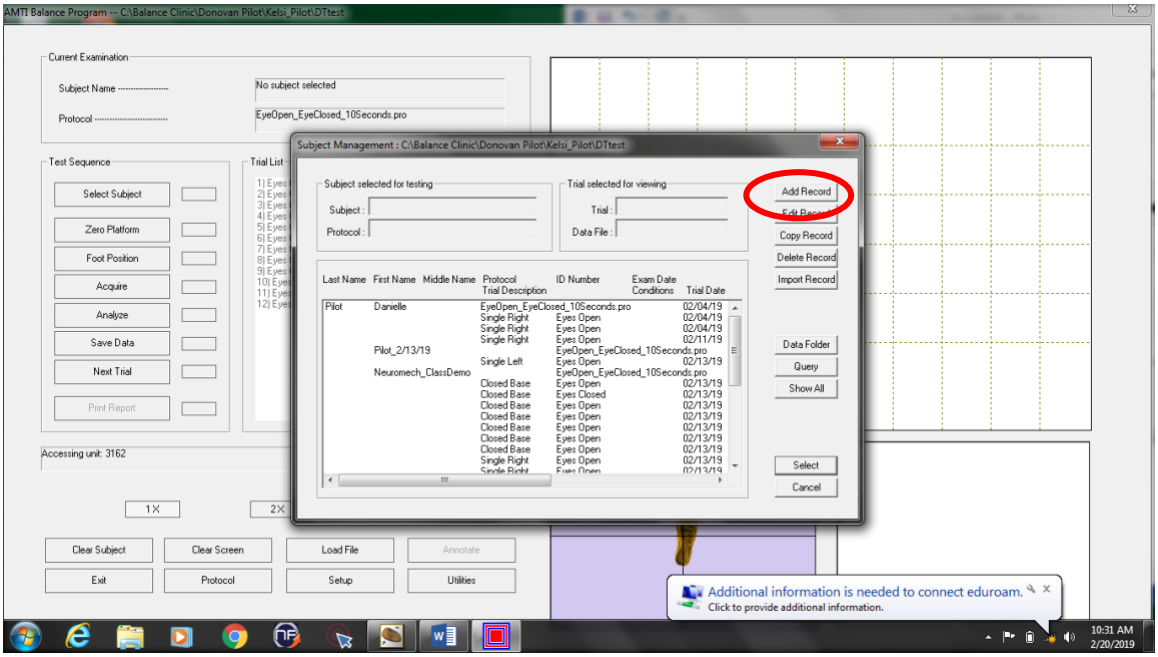


Balance Clinic Manual

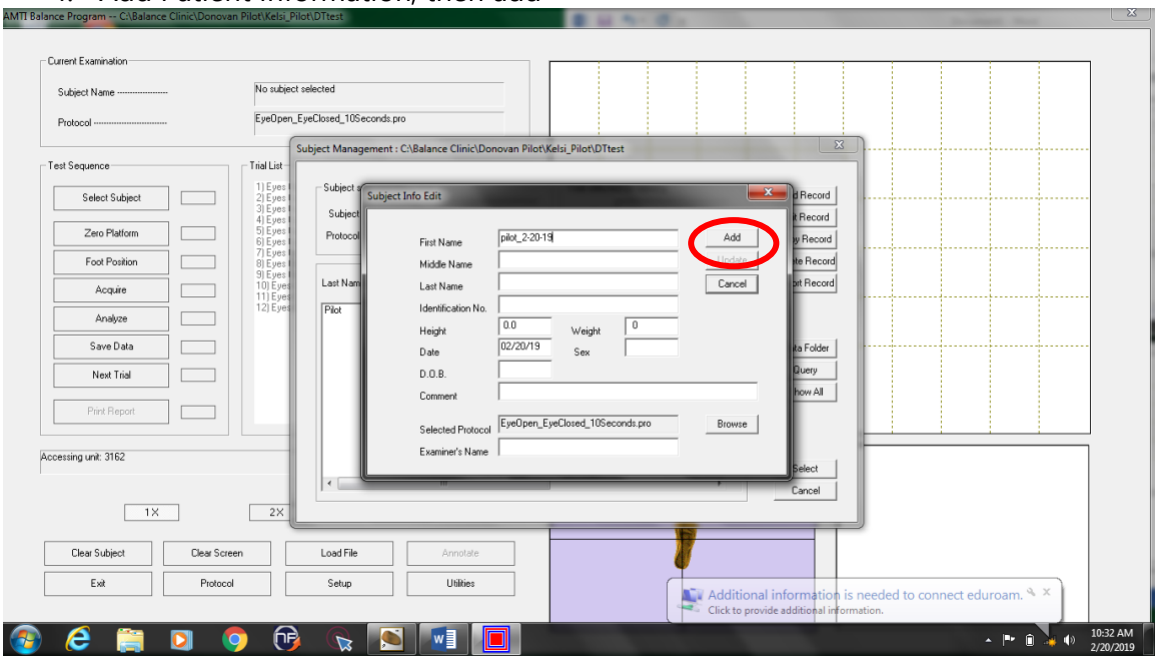
1. Open Balance Clinic
2. Click Select Subject



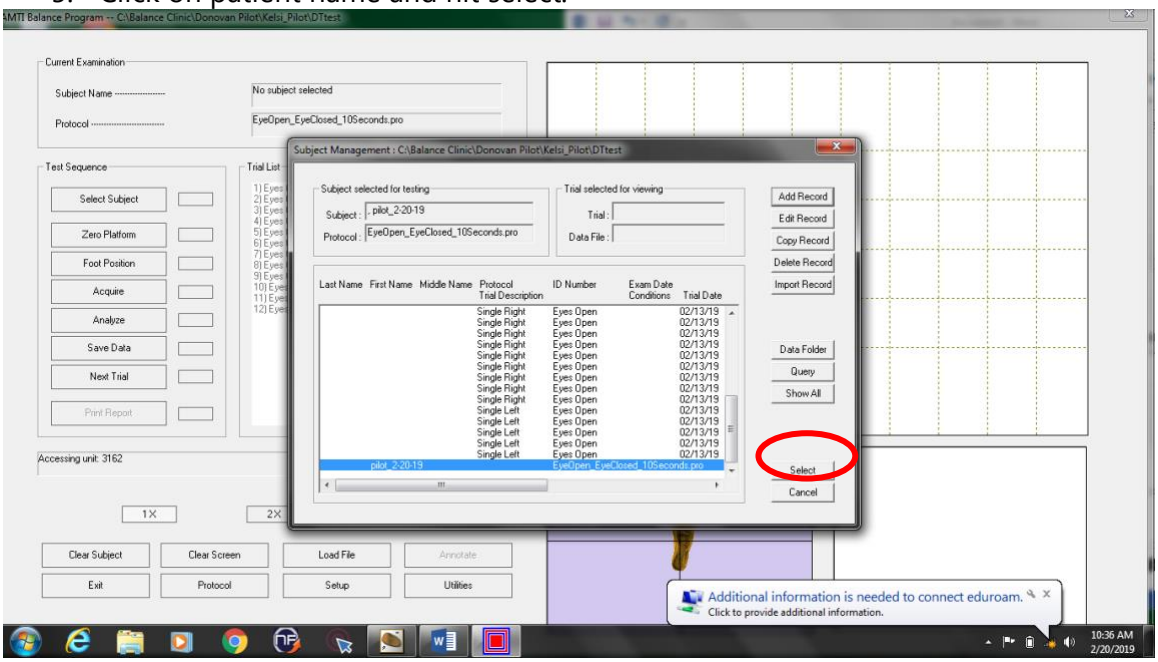
3. Select Add Record



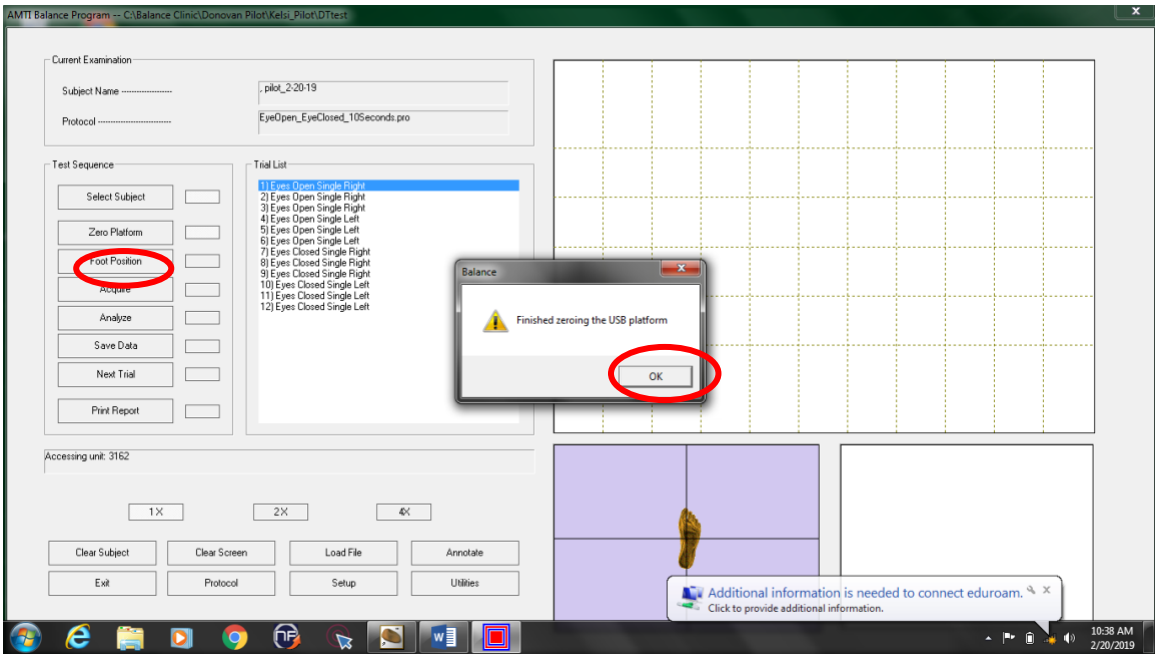
4. Add Patient Information, then add



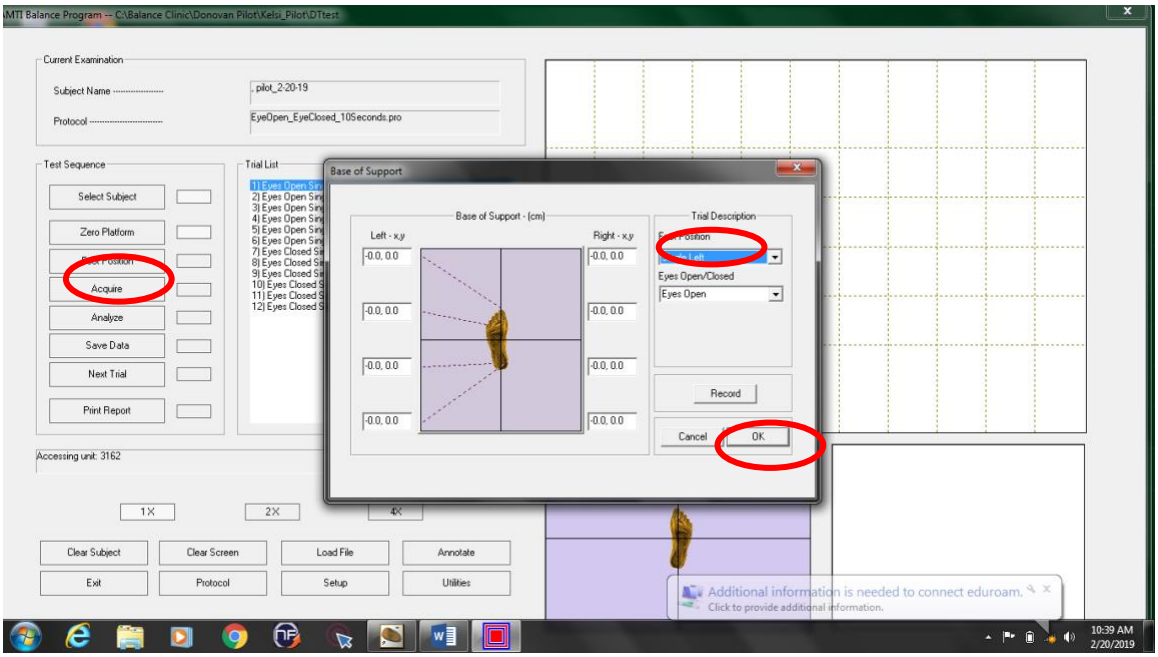
5. Click on patient name and hit select.



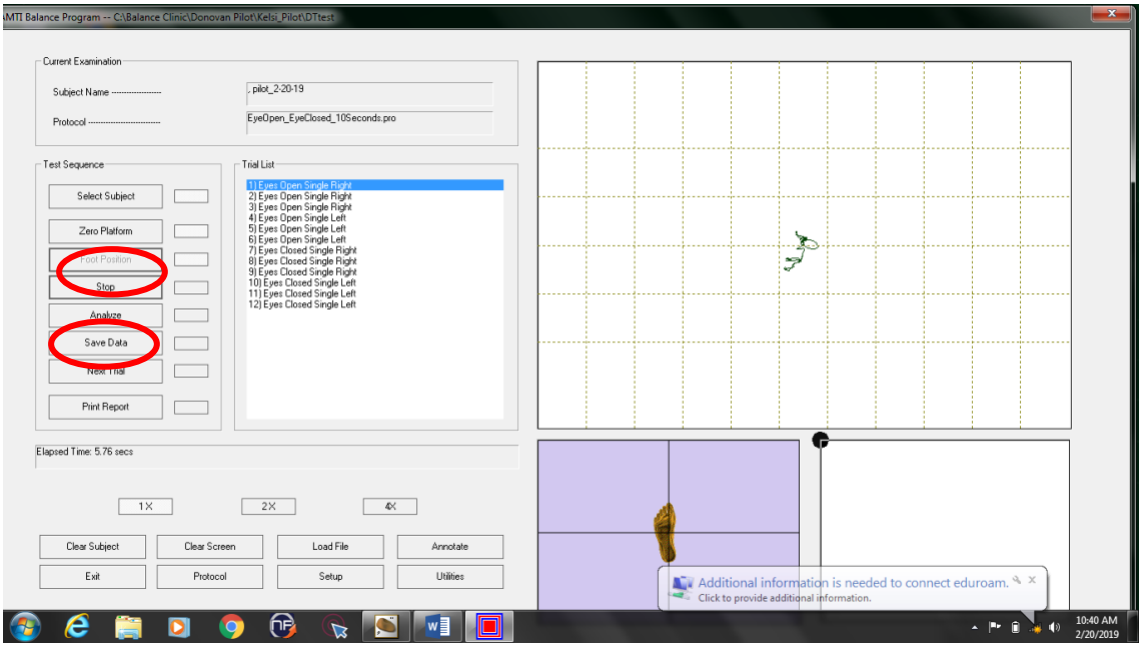
6. Zero the platform. Click OK.



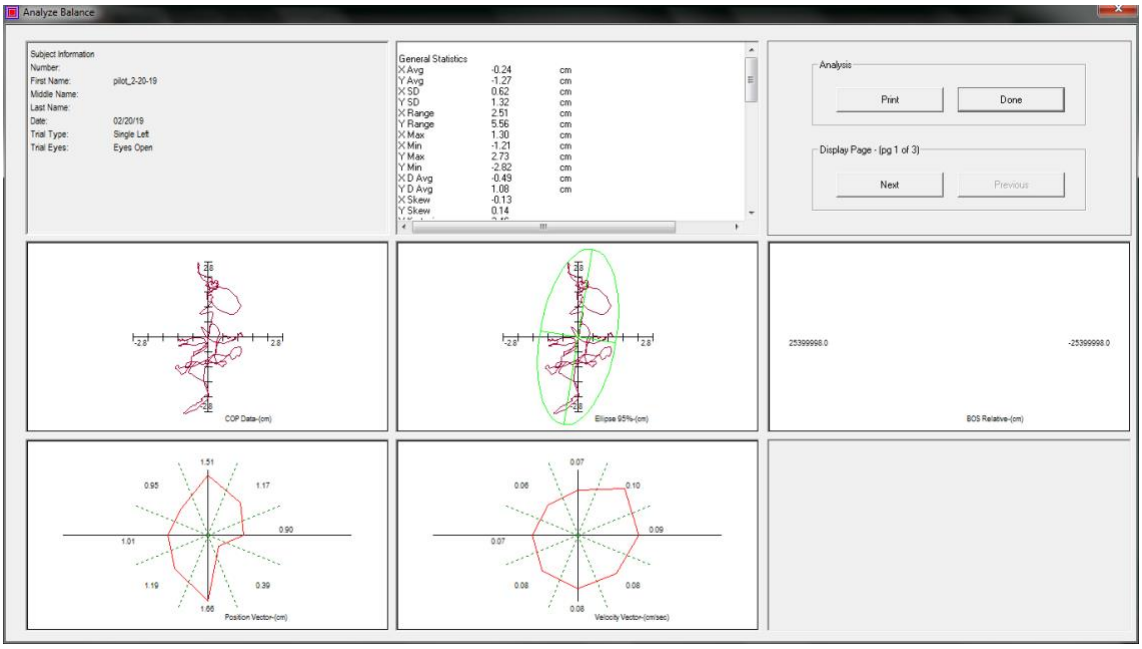
7. Select foot position. Click OK.



8. Begin recording by clicking Acquire. Save trial once finished.

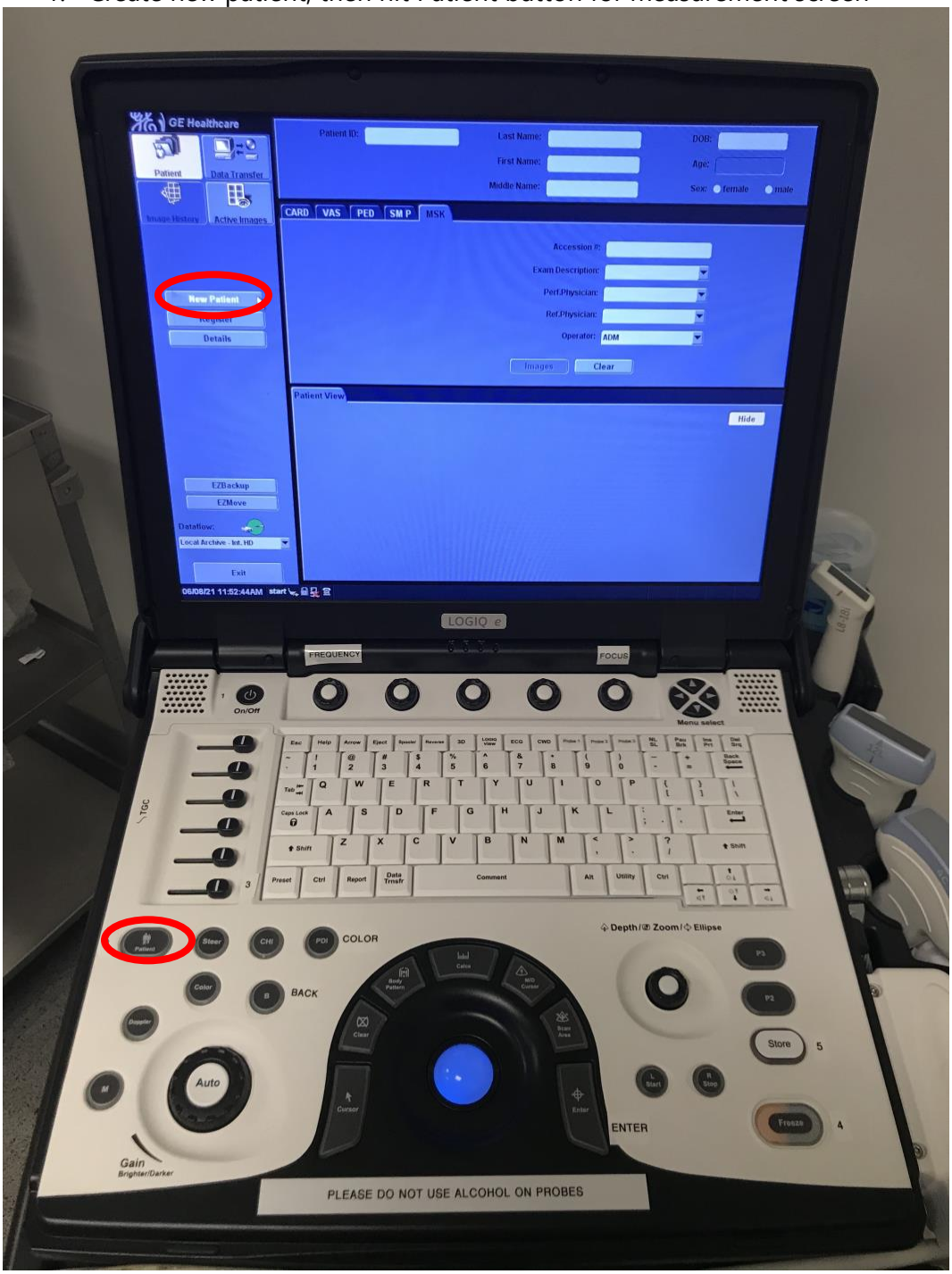


9. Click Analyze to view trial data.



Capturing Ultrasound Images using LOGIQe Unit

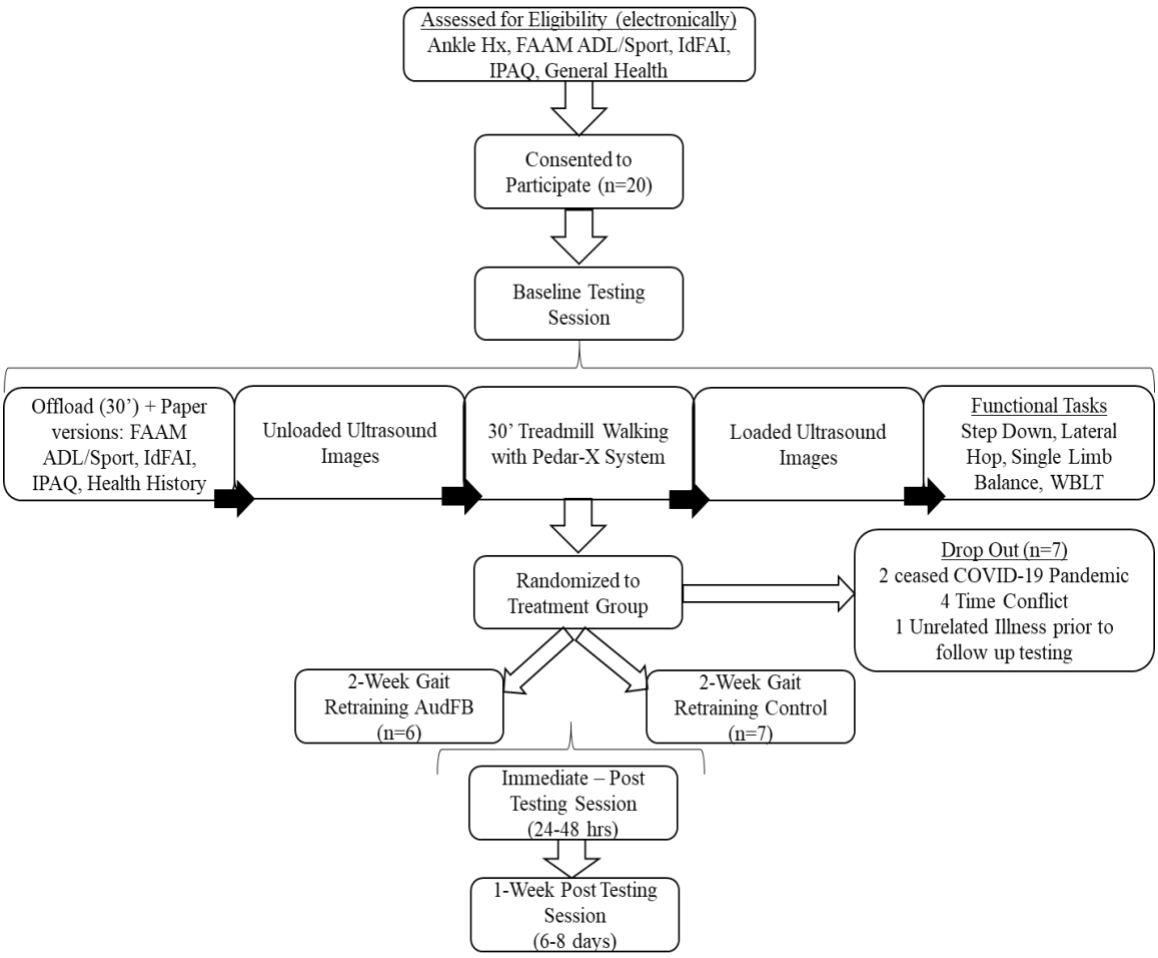
1. Create new patient, then hit Patient button for measurement screen



2. Adjust Depth

3. To store an image, first select FREEZE, then STORE

Consort flow chart of procedures



APPENDIX 3: ADDITIONAL RESULTS

A3.1 SUPPLEMENTARY TABLES FROM CHAPTER 2

Table A3.1 Mean and Standard Deviations of Center of Pressure Area and Velocity and Time to Boundary (TTB) in the Mediolateral (ML) and Anteroposterior (AP) Directions Mean Minima (Min) and Standard Deviation of the Minima (SD Min) During Static Balance in the Baseline, Visual and Auditory Biofeedback Conditions.

	Eyes Open				Effect Size (95% Confidence Interval)		Eyes Closed				Effect Size (95% Confidence Interval)	
	Baseline (n=19)	Visual (n=19)	Auditory (n=19)	P Value	Baseline – Visual	Baseline – Auditory	Baseline (n=18)	Visual (n=19)	Auditory (n=18)	P Value	Baseline – Visual	Baseline - Auditory
Area	9.7 (3.8)	11.7 (4.6)	**12.7 (3.4)**	0.012	-0.48 (-1.11,0.18)	**-0.80 (-1.46,-0.14)**	21.1 (5.7)	19.9 (5.3)	23.1 (6.8)	0.067	0.21 (-0.44,0.87)	-0.31 (-0.97,0.3
Velocity	4.9 (0.9)	5.4 (1.2)	**5.9 (1.1)**	0.002	-0.44 (-1.07,0.22)	**-0.94 (-1.61,-0.27)**	8.3 (1.7)	9.3 (5.1)	8.8 (1.9)	0.562	-0.26 (-0.92,0.40)	-0.26 (-0.92,0.4
TTBML min	0.36 (0.09)	0.34 (0.07)	0.31 (0.06)	0.048	0.24 (-0.40,0.88)	0.64 (-0.01,1.29)	0.21 (0.05)	0.22 (0.05)	0.22 (0.05)	0.634	-0.20 (-0.84,0.45)	-0.20 (-0.82,04
TTBAP min	1.12 (0.29)	**0.90 (0.25)**	**0.76 (0.22)**	0.001	**0.80 (0.13,1.46)**	**1.37 (0.66,2.08)**	0.64 (0.16)	0.67 (0.20)	**0.51 (0.16)**	0.021	-0.16 (-0.82,0.49)	**0.79 (0.12,1.47**
TTBML SD min	2.89 (0.06)	2.87 (0.05)	2.88 (0.04)	0.215	0.35 (-0.29,1.00)	0.19 (-0.45,0.82)	2.89 (0.04)	2.89 (0.05)	2.88 (0.04)	0.726	0.00 (-0.65,0.65)	0.24 (-0.41,0.9
TTBAP SD min	2.88 (0.05)	2.86 (0.05)	2.88 (0.04)	0.348	0.39 (-0.25,1.03)	0.00 (-0.64,0.64)	2.90 (0.04)	2.89 (0.06)	**2.86 (0.07)**	0.086	0.19 (-0.46,0.85)	**0.69 (0.01,1.3**

Bolded numbers indicate a statistically significant difference from baseline with moderate to large effect sizes and 95% confidence intervals that do not cross 0; P values from repeated measures analysis of variance; A negative effect size represents an increase in the biofeedback condition from baseline; A positive effect size represents a decrease in the biofeedback condition from baseline.

Table A3.2. Peak Pressure (kPa) and Pressure Time Integral (kPa*s) (Mean (Standard Deviation)) in Each Region of the Foot During Baseline, Visual and Auditory Biofeedback Conditions During the Step Down, Lateral Hop, and Forward Lunge Tasks.

	Peak Pressure				Effect Size (95% Confidence Interval)		Pressure time integral				Effect Size (95% Confidence Interval)	
	Baseline	Visual	Auditory	P value	Baseline-Visual	Baseline-auditory	Baseline	Visual	Auditory	P value	Baseline-Visual	Baseline-aud
TO	279.3 (61.8)	297.6 (72.0)	324.1 (97.0)	0.004	-0.27 (-0.91,0.37)	-0.54 (-1.19,0.11)	133.1 (26.0)	137.5 (27.1)	137.9 (39.4)	0.805	-0.16 (-0.80,0.48)	-0.14 (-0.78,
MH	119.2 (42.2)	150.0 (93.6)	**175.4 (103.8)**	0.022	-0.42 (-1.06,0.23)	**-0.69 (-1.35,-0.04)**	17.4 (9.1)	24.9 (16.0)	**29.6 (17.4)**	0.001	-0.56 (-1.21,0.09)	**-0.85 (-1.52,**
LH	106.7 (34.7)	135.3 (89.1)	**156.1 (94.1)**	0.038	-0.41 (-1.06,0.23)	**-0.68 (-1.34,-0.03)**	16.5 (8.1)	22.9 (15.0)	**26.7 (17.1)**	0.003	-0.52 (-1.16,0.13)	**-0.75 (-1.41,**
MM	134.1 (30.2)	132.1 (33.4)	134.0 (36.8)	0.905	0.06 (-0.57,0.70)	0.00 (-0.63,0.64)	43.9 (22.4)	45.2 (20.8)	47.3 (23.4)	0.326	-0.06 (-0.69,0.58)	-0.15 (-0.78,
LM	135.9 (31.7)	134.3 (34.8)	125.8 (37.2)	0.086	0.05 (-0.59,0.68)	0.29 (-0.35,0.93)	48.8 (20.7)	52.5 (23.6)	45.1 (25.3)	0.023	-0.16 (-0.80,0.47)	0.16 (-0.48,
MF	208.7 (40.0)	202.6 (43.7)	210.9 (51.9)	0.440	0.14 (-0.49,0.78)	-0.05 (-0.68,0.59)	100.1 (21.8)	97.7 (24.4)	93.6 (25.0)	0.415	0.10 (-0.53,0.74)	0.27 (-0.37,
CF	207.8 (35.4)	201.2 (43.1)	199.7 (35.6)	0.239	0.17 (-0.47,0.80)	0.22 (-0.41,0.86)	100.5 (21.6)	99.8 (26.8)	88.9 (21.5)	0.012	0.03 (-0.61,0.66)	0.53 (-0.12,
LF	191.4 (38.1)	185.4 (45.1)	168.2 (38.2)	<0.001	0.14 (-0.50,0.78)	0.60 (-0.05,1.25)	89.4 (18.8)	90.4 (27.0)	**74.2 (23.8)**	<0.001	-0.04 (-0.68,0.60)	0.70 (0.04,
GT	258.1 (73.9)	252.1 (77.2)	269.1 (119.2)	0.519	0.08 (-0.56,0.71)	-0.11 (-0.75,0.53)	114.3 (30.8)	112.4 (33.4)	110.6 (52.2)	0.934	0.06 (-0.58,0.69)	0.08 (-0.55,
LT	174.6 (48.1)	169.6 (48.2)	162.2 (51.0)	0.085	0.10 (-0.53,0.74)	0.25 (-0.39,0.88)	83.4 (20.6)	82.9 (25.7)	71.7 (24.2)	0.011	0.02 (-0.62,0.65)	0.51 (-0.14,
TO	312.8 (81.0)	310.3 (65.2)	325.7 (72.9)	0.355	0.03 (-0.60,0.67)	-0.16 (-0.80,0.47)	124.0 (36.7)	**164.1 (52.9)**	149.1 (47.8)	0.001	**-0.86 (-1.53,-0.20)**	-0.58 (-1.23,
MH	116.2 (47.2)	**152.7 (50.0)**	126.2 (48.5)	0.001	**-0.73 (-1.39,-0.08)**	-0.20 (-0.84,0.43)	31.7 (17.6)	**61.3 (34.6)**	41.3 (30.9)	<0.001	**-1.06 (-1.73,-0.38)**	-0.37 (-1.02,
LH	106.2 (41.8)	**139.7 (47.5)**	114.8 (47.2)	0.001	**-0.73 (-1.39,-0.08)**	-0.19 (-0.83,0.45)	31.8 (18.4)	**61.4 (36.3)**	40.8 (32.1)	0.001	**-1.01 (-1.68,-0.33)**	-0.33 (-0.98,
MM	146.5 (32.9)	158.7 (27.6)	157.3 (30.7)	0.006	-0.30 (-1.03,0.25)	-0.33 (-0.97,0.31)	51.1 (19.8)	**73.9 (30.6)**	63.6 (28.0)	<0.001	**-0.87 (-1.53,-0.20)**	-0.50 (-1.15,
LM	159.4 (34.3)	165.5 (28.8)	156.5 (40.3)	0.083	-0.19 (-0.82,0.45)	0.08 (-0.56,0.71)	60.7 (27.0)	**88.0 (40.6)**	70.0 (40.5)	0.001	**-0.78 (-1.44,-0.12)**	-0.26 (-0.90,
MF	245.9 (74.1)	236.8 (51.6)	261.6 (65.9)	0.045	0.14 (-0.50,0.78)	-0.22 (-0.86,0.42)	90.8 (31.1)	109.6 (36.9)	106.8 (30.4)	<0.001	-0.54 (-1.19,0.11)	-0.51 (-1.16,
CF	239.2 (65.3)	226.2 (47.2)	244.4 (62.8)	0.102	0.22 (-0.41,0.86)	-0.08 (-0.72,0.56)	91.5 (31.1)	110.3 (38.3)	105.3 (34.7)	0.001	-0.53 (-1.18,0.12)	-0.41 (-1.05,
LF	214.1 (54.8)	203.6 (43.4)	210.7 (60.3)	0.274	0.21 (-0.43,0.84)	0.06 (-0.58,0.69)	83.4 (28.5)	102.2 (38.8)	94.1 (38.9)	0.011	-0.54 (-1.19,0.11)	-0.31 (-0.95,
GT	292.9 (70.5)	297.4 (66.0)	305.4 (74.2)	0.475	-0.06 (-0.70,0.57)	-0.17 (-0.81,0.47)	102.2 (25.5)	**128.8 (34.4)**	118.9 (31.5)	0.005	**-0.86 (-1.53,-0.20)**	-0.57 (-1.22,
LT	194.6 (61.5)	184.0 (40.8)	191.3 (47.2)	0.237	0.20 (-0.44,0.84)	0.06 (-0.58,0.70)	73.7 (21.6)	86.5 (21.4)	81.4 (22.3)	0.006	-0.58 (-1.23, 0.07)	-0.34 (-0.98,
TO	223.6 (47.6)	218.3 (49.6)	232.7 (52.4)	0.033	0.11 (-0.53,0.74)	-0.18 (-0.82,0.46)	203.6 (54.3)	214.5 (66.4)	193.9 (51.6)	0.011	-0.18 (-0.81,0.46)	0.18 (-0.46,
MH	202.3 (41.1)	199.6 (52.6)	217.1 (56.9)	0.008	0.06 (-0.58,0.69)	-0.29 (-0.93,0.35)	127.3 (30.1)	135.8 (41.7)	137.9 (44.2)	0.241	-0.23 (-0.87,0.41)	-0.27 (-0.91,
LH	193.1 (35.0)	188.3 (42.7)	201.4 (45.4)	0.029	0.12 (-0.52,0.76)	-0.20 (-0.84,0.44)	119.5 (29.0)	125.9 (37.5)	125.1 (37.1)	0.545	-0.19 (-0.82,0.45)	-0.17 (-0.80,
MM	85.5 (18.6)	84.9 (19.9)	89.3 (19.4)	0.024	0.08 (-0.56,0.71)	-0.15 (-0.78,0.49)	86.2 (22.8)	89.9 (31.4)	85.2 (25.6)	0.359	-0.13 (-0.77,0.50)	0.04 (-0.60,
LM	105.1 (22.2)	103.1 (23.3)	96.9 (18.3)	0.005	0.09 (-0.55,0.73)	0.40 (-0.24,1.04)	102.5 (26.0)	104.8 (34.1)	86.4 (22.5)	<0.001	-0.08 (-0.71,0.56)	0.64 (-0.01,
MF	113.8 (29.1)	114.8 (22.0)	120.6 (25.0)	0.237	-0.04 (-0.67,0.60)	-0.25 (-0.88,0.39)	95.3 (32.6)	100.8 (32.3)	88.1 (26.4)	0.061	-0.16 (-0.80,0.47)	0.24 (-0.40,
CF	101.6 (24.4)	104.6 (18.8)	103.1 (20.0)	0.602	-0.14 (-0.77,0.50)	-0.07 (-0.70,0.57)	95.8 (31.0)	101.3 (29.3)	81.7 (22.8)	<0.001	-0.18 (-0.82,0.46)	0.51 (-0.14,
LF	99.1 (28.0)	100.9 (27.8)	85.4 (22.7)	<0.001	-0.07 (-0.70,0.57)	0.52 (-0.12,1.17)	94.9 (33.3)	98.6 (35.1)	**71.3 (25.6)**	<0.001	-0.11 (-0.74,0.53)	**0.78 (0.12,1**
GT	160.8 (55.6)	157.4 (52.5)	148.8 (55.0)	0.266	0.06 (-0.57,0.70)	0.21 (-0.42,0.85)	129.7 (53.0)	134.7 (63.3)	112.8 (53.0)	0.006	-0.08 (-0.72,0.55)	0.31 (-0.33,
LT	99.5 (23.5)	98.7 (21.7)	92.4 (24.5)	0.071	0.03 (-0.60,0.67)	0.29 (-0.35,0.93)	92.0 (26.9)	95.0 (28.9)	**74.7 (24.4)**	<0.001	-0.11 (-0.74,0.53)	**0.66 (0.01,1**

TO= Total; MH= Medial Heel; LH=Lateral Heel; MM= Medial Midfoot; LM= Lateral Midfoot; MF= Medial Forefoot; CF=Central Forefoot; LF= Lateral Forefoot; GT=Great Toe; LT= Lesser Toes; Bold numbers indicates statistically significant differences between baseline with moderate to large effect sizes with 95% confidence intervals that do not cross 0; P values from repeated measures analysis of variance; A negative effect size represents an increase in the biofeedback condition from baseline; A positive effect size represents a decrease in the biofeedback condition from baseline.

Table A3.3. Contact Area (cm^2) and Contact Time (cm*s) (Mean (Standard Deviation)) in Each Region of the Foot During Baseline, Visual and Auditory Biofeedback Conditions During the Step Down, Lateral Hop, and Forward Lunge Tasks.

	Contact Area				Effect Size (95% Confidence Interval)		Contact Time				Effect Size (95% Confidence Interval)	
	Baseline	Visual	Auditory	P value	Baseline-Visual	Baseline-auditory	Baseline	Visual	Auditory	P value	Baseline-Visual	Baseline-aud
TO	157.0 (20.0)	154.1 (22.2)	152.7 (25.7)	0.170	0.13 (-0.50,0.77)	0.18 (-0.45,0.82)	711.1 (78.5)	753.4 (85.0)	698.5 (91.5)	0.004	-0.51 (-1.15,0.14)	0.15 (-0.49,(
MH	19.5 (4.3)	18.8 (5.1)	19.4 (5.7)	0.535	0.15 (-0.49,0.78)	0.03 (-0.60,0.67)	328.7 (120.1)	406.6 (157.2)	391.2 (176.5)	0.017	-0.54 (-1.19,0.10)	-0.40 (-1.05,
LH	16.9 (3.8)	15.9 (5.2)	16.5 (5.6)	0.460	0.21 (-0.43,0.85)	0.07 (-0.56,0.71)	355.3 (134.3)	416.8 (167.5)	403.0 (192.2)	0.083	-0.40 (-1.04,0.25)	-0.28 (-0.92,
MM	24.5 (4.0)	23.8 (5.1)	22.8 (6.4)	0.136	0.14 (-0.49,0.78)	0.31 (-0.33,0.95)	646.7 (124.3)	683.8 (123.4)	625.3 (152.9)	0.029	-0.29 (-0.93,0.35)	0.15 (-0.49,(
LM	26.0 (3.2)	25.9 (3.3)	24.9 (4.4)	0.036	0.05 (-0.58,0.69)	0.30 (-0.34,0.94)	663.5 (94.2)	706.9 (85.8)	633.2 (126.6)	0.001	-0.47 (-1.12,0.17)	0.27 (-0.37,(
MF	12.9 (1.5)	12.8 (1.5)	12.9 (1.5)	0.165	0.04 (-0.59,0.68)	0.01 (-0.62,0.65)	710.3 (78.6)	738.3 (93.0)	674.8 (103.8)	0.013	-0.32 (-0.96,0.32)	0.38 (-0.26,
CF	14.5 (1.6)	14.5 (1.6)	14.5 (1.7)	0.331	0.00 (-0.64,0.64)	0.01 (-0.63,0.65)	710.6 (78.6)	741.1 (92.5)	680.6 (102.1)	0.012	-0.35 (-0.99,0.29)	0.32 (-0.32,(
LF	14.0 (1.7)	14.0 (1.7)	13.9 (1.6)	0.044	0.02 (-0.62,0.66)	0.08 (-0.56,0.72)	710.8 (78.7)	741.8 (92.1)	683.0 (102.5)	0.039	-0.35 (-0.99,0.29)	0.30 (-0.34,(
GT	10.3 (1.1)	10.2 (1.1)	10.2 (1.2)	0.482	0.09 (-0.55,0.72)	0.11 (-0.53,0.75)	710.9 (78.4)	738.8 (97.6)	677.7 (104.6)	0.019	-0.31 (-0.95,0.33)	0.35 (-0.29,(
LT	18.1 (2.1)	18.0 (2.3)	17.5 (2.2)	0.091	0.08 (-0.56,0.71)	0.27 (-0.37,0.91)	711.1 (78.5)	737.1 (95.6)	674.4 (104.4)	0.020	-0.29 (-0.93,0.35)	0.39 (-0.25,
TO	156.7 (22.8)	161.2 (19.7)	157.5 (19.8)	0.012	-0.21 (-0.85,0.43)	-0.04 (-0.67,0.60)	613.6 (236.2)	**886.7 (314.7)**	734.4 (306.9)	<0.001	**-0.96 (-1.63,-0.29)**	-0.43 (-1.08,
MH	19.0 (5.1)	20.9 (3.6)	19.4 (4.6)	0.007	-0.42 (-1.06,0.22)	-0.08 (-0.72,0.55)	525.0 (238.9)	**808.1 (325.1)**	640.5 (315.1)	<0.001	**-0.97 (-1.64,-0.30)**	-0.40 (-1.05,
LH	16.9 (4.8)	18.8 (3.1)	17.0 (4.3)	0.007	-0.44 (-1.09,0.20)	-0.02 (-0.65,0.62)	521.8 (238.9)	**798.9 (327.2)**	631.0 (320.8)	<0.001	**-0.95 (-1.62,-0.28)**	-0.38 (-1.02,
MM	24.3 (4.2)	25.1 (3.5)	24.8 (3.6)	0.048	-0.21 (-0.85,0.42)	-0.13 (-0.76,0.51)	598.7 (247.0)	**874.6 (323.6)**	725.2 (313.5)	<0.001	**-0.94 (-1.61,-0.27)**	-0.44 (-1.08,
LM	26.0 (3.3)	26.1 (3.5)	25.9 (3.2)	0.114	-0.05 (-0.69,0.58)	0.02 (-0.61,0.66)	586.2 (237.7)	**859.8 (319.3)**	699.8 (311.5)	<0.001	**-0.95 (-1.62,-0.28)**	-0.40 (-1.04,
MF	12.9 (1.5)	12.9 (1.5)	12.9 (1.5)	0.363	0.00 (-0.64,0.64)	-0.01 (-0.64,0.63)	613.6 (236.2)	**886.2 (314.8)**	734.4 (306.9)	<0.001	**-0.96 (-1.63,-0.29)**	-0.43 (-1.08,
CF	14.5 (1.6)	14.5 (1.6)	14.5 (1.6)	0.378	0.00 (-0.64,0.64)	0.00 (-0.64,0.64)	613.6 (236.2)	**886.7 (314.7)**	734.3 (306.9)	<0.001	**-0.96 (-1.63,-0.29)**	-0.43 (-1.07,
LF	14.0 (1.7)	14.0 (1.7)	14.0 (1.7)	0.330	0.00 (-0.64,0.64)	0.01 (-0.63,0.64)	612.8 (236.3)	**885.6 (314.9)**	732.3 (306.5)	<0.001	**-0.96 (-1.63,-0.29)**	-0.43 (-1.07,
GT	10.6 (1.3)	10.5 (1.2)	10.6 (1.2)	0.147	0.09 (-0.55,0.72)	-0.04 (-0.67,0.60)	613.6 (236.2)	**886.2 (314.8)**	734.4 (306.9)	<0.001	**-0.96 (-1.63,-0.29)**	-0.43 (-1.08,
LT	18.4 (2.4)	18.2 (2.4)	18.2 (2.2)	0.321	0.05 (-0.59,0.68)	0.06 (-0.58,0.69)	613.6 (236.1)	**886.7 (314.7)**	733.9 (306.8)	<0.001	**-0.96 (-1.63,-0.29)**	-0.43 (-1.07,
TO	149.7 (22.0)	149.3 (22.1)	147.2 (22.6)	0.069	0.02 (-0.62,0.65)	0.11 (-0.53,0.75)	1569.6 (296.3)	1670.8 (429.5)	1446.5 (277.6)	<0.001	-0.27 (-0.91,0.37)	0.42 (-0.22,
MH	21.8 (2.7)	21.8 (2.6)	21.7 (2.8)	0.017	-0.01 (-0.65,0.63)	0.01 (-0.62,0.65)	1564.9 (295.3)	1664.5 (425.0)	1443.8 (279.1)	<0.001	-0.27 (-0.91,0.37)	0.41 (-0.23,
LH	20.2 (2.5)	20.2 (2.4)	20.1 (2.5)	0.554	-0.02 (-0.66,0.61)	0.01 (-0.62,0.65)	1562.1 (295.0)	1662.7 (426.1)	1442.3 (279.6)	<0.001	-0.27 (-0.91,0.37)	0.41 (-0.23,
MM	16.4 (8.1)	16.1 (8.6)	16.9 (8.3)	0.017	0.04 (-0.60,0.68)	-0.06 (-0.70,0.57)	1514.1 (276.6)	1609.2 (406.4)	1383.0 (262.4)	<0.001	-0.27 (-0.91,0.37)	0.48 (-0.17,
LM	24.8 (3.7)	24.6 (4.6)	23.9 (5.2)	0.162	0.02 (-0.61,0.66)	0.19 (-0.45,0.82)	1525.1 (279.4)	1616.4 (404.9)	1391.5 (259.2)	<0.001	-0.26 (-0.90,0.38)	0.49 (-0.16,
MF	12.2 (1.9)	12.3 (1.7)	12.4 (1.7)	0.166	-0.01 (-0.65,0.62)	-0.12 (-0.75,0.52)	1242.6 (249.3)	1323.8 (366.8)	1107.0 (215.5)	<0.001	-0.25 (-0.89,0.38)	0.57 (-0.08,
CF	14.4 (1.7)	14.5 (1.7)	14.4 (1.7)	0.704	-0.03 (-0.66,0.61)	0.00 (-0.64,0.64)	1315.5 (294.2)	1381.9 (404.7)	1160.3 (245.2)	<0.001	-0.18 (-0.82,0.45)	0.56 (-0.09,
LF	13.9 (1.7)	13.9 (1.6)	13.6 (1.7)	0.026	-0.01 (-0.65,0.62)	0.20 (-0.44,0.83)	1390.6 (289.5)	1443.3 (400.1)	1218.6 (261.3)	<0.001	-0.15 (-0.78,0.49)	0.61 (-0.04,
GT	9.9 (1.3)	10.0 (1.2)	9.8 (1.2)	0.312	-0.04 (-0.67,0.60)	0.11 (-0.53,0.74)	1432.0 (335.5)	1497.5 (457.4)	1281.4 (311.4)	<0.001	-0.16 (-0.80,0.48)	0.46 (-0.19,
LT	16.0 (2.6)	15.8 (2.8)	14.1 (3.4)	0.021	0.07 (-0.57,0.70)	0.60 (-0.05,1.25)	1415.0 (324.1)	1480.9 (440.4)	1255.4 (297.1)	<0.001	-0.17 (-0.80,0.47)	0.50 (-0.14,

TO= Total; MH= Medial Heel; LH=Lateral Heel; MM= Medial Midfoot; LM= Lateral Midfoot; MF= Medial Forefoot; CF=Central Forefoot; LF= Lateral Forefoot; GT=Great Toe; LT= Lesser Toes; Bolded numbers indicate a statistically significant difference from baseline with moderate to large effect sizes and 95% confidence intervals that do not cross 0; P values from repeated measures analysis of variance; A negative effect size represents an increase in the biofeedback condition from baseline; A positive effect size represents a decrease in the biofeedback condition from baseline.

Table A3.4. Maximum Force (N) and Force Time Integral (N*s) (Mean (Standard Deviation)) in Each Region of the Foot During Baseline, Visual and Auditory Biofeedback Conditions During the Step Down, Lateral Hop, and Forward Lunge Tasks.

	Maximum Force				Effect Size (95% Confidence Interval)		Force time integral				Effect Size (95% Confidence Interval)	
	Baseline	Visual	Auditory	P value	Baseline-Visual	Baseline-auditory	Baseline	Visual	Auditory	P value	Baseline-Visual	Baseline-aud
TO	192.0 (30.8)	176.4 (30.4)	**168.4 (26.0)**	<0.001	0.50 (-0.15,1.14)	**0.81 (0.15,1.47)**	68.2 (7.6)	69.7 (6.7)	64.2 (6.6)	0.004	-0.20 (-0.84,0.43)	0.55 (-0.10,
MH	25.1 (9.7)	29.3 (20.0)	34.4 (20.7)	0.048	-0.26 (-0.90,0.37)	-0.57 (-1.21,0.08)	2.7 (1.5)	4.1 (3.2)	**5.1 (3.0)**	<0.001	-0.53 (-1.18,0.12)	**-0.98 (-1.65,**
LH	17.5 (6.9)	21.7 (17.6)	25.2 (16.6)	0.079	-0.30 (-0.94,0.34)	-0.59 (-1.24,0.06)	2.1 (1.4)	3.2 (3.0)	**4.0 (3.3)**	0.004	-0.46 (-1.10,0.18)	**-0.76 (-1.42,**
MM	24.3 (9.1)	20.9 (8.4)	19.5 (9.0)	0.003	0.38 (-0.26,1.02)	0.51 (-0.14,1.16)	3.3 (1.5)	3.6 (1.8)	3.7 (2.0)	0.346	-0.16 (-0.79,0.48)	-0.20 (-0.84,
LM	31.2 (7.1)	27.4 (6.5)	**24.2 (7.8)**	<0.001	0.54 (-0.11,1.19)	**0.91 (0.25,1.58)**	6.7 (2.1)	7.1 (3.1)	6.3 (3.9)	0.358	-0.16 (-0.80,0.47)	0.11 (-0.53,(
MF	26.1 (4.6)	24.9 (5.2)	26.4 (7. 7)	0.378	0.24 (-0.40,0.88	-0.05 (-0.68,0.59)	11.1 (2.4)	10.8 (2.6)	10.8 (3.6	0.836	0.15 (-0.49,0.79)	0.11 (-0.53,(
CF	29.3 (5.0)	27.7 (4.9)	26.5 (4.2)	0.001	0.31 (-0.33,0.95)	0.58 (-0.07,1.23)	13.4 (2.4)	13.1 (2.4)	**11.5 (2.2)**	0.003	0.13 (-0.51,0.77)	**0.82 (0.16,1**
LF	23.9 (4.7)	22.1 (4.6)	**18.7 (4.4)**	<0.001	0.37 (-0.28,1.01)	**1.12 (0.44,1.81)**	9.9 (1.8)	9.7 (2.0)	**7.5 (2.1)**	<0.001	0.08 (-0.56,0.71)	**1.19 (0.50,1**
GT	22.3 (6.2)	21.4 (6.2)	21.6 (8.4)	0.759	0.14 (-0.50,0.77)	0.08 (-0.55,0.72)	10.0 (3.2)	9.6 (3.4)	8.7 (3.8)	0.300	0.09 (-0.54,0.73)	0.34 (-0.30,(
LT	19.4 (6.1)	18.2 (5.6)	16.4 (5.9)	0.005	0.21 (-0.43,0.85)	0.50 (-0.14,1.15)	9.0 (2.9)	8.5 (3.1)	**6.6 (2.9)**	<0.001	0.17 (-0.47,0.80)	**0.82 (0.16,1**
TO	207.1 (22.0)	211.1 (21.0	207.6 (21.3)	0.343	-0.18 (-0.82,0.46)	-0.02 (-0.66,0.61)	76.1 (24.4)	**103.4 (32.2)**	87.1 (31.1)	<0.001	**-0.94 (-1.61,-0.27)**	-0.39 (-1.03,
MH	23.6 (11.7)	**32.8 (10.8)**	25.9 (10.3)	0.002	**-0.81 (-1.47,-0.15)**	-0.20 (-0.84,0.44)	5.0 (3.3)	**10.4 (5.3)**	6.6 (5.2)	<0.001	**-1.19 (-1.88,-0.50)**	-0.37 (-1.01,
LH	19.1 (10.3)	**26.8 (10.8)**	21.3 (11.2)	0.001	**-0.72 (-1.37,-0.06)**	-0.20 (-0.84,0.44)	4.8 (3.4)	**10.1 (6.7)**	6.5 (5.9)	0.001	**-0.97 (-1.64,-0.30)**	-0.33 (-0.97,
MM	24.6 (7.6)	28.5 (7.3)	27.0 (7.6)	<0.001	-0.52 (-1.17,0.13)	-0.31 (-0.95,0.33)	5.3 (2.7)	**8.0 (4.2)**	6.5 (3.7)	<0.001	**-0.75 (-1.41,-0.09)**	-0.38 (-1.02,
LM	32.9 (6.7)	35.0 (6.0)	31.5 (7.7)	0.002	-0.31 (-0.95,0.33)	0.19 (-0.45,0.83)	11.2 (5.8)	**16.1 (7.7)**	12.1 (7.2)	0.001	**-0.69 (-1.35,-0.04)**	-0.13 (-0.76,
MF	30.3 (6.6)	29.9 (6.4)	32.5 (6.7)	0.012	-0.06 (-0.58,0.70)	-0.33 (-0.97,0.31)	10.2 (3.1)	12.4 (3.7)	12.2 (3.2)	<0.001	-0.63 (-1.28,0.02)	-0.64 (-1.19,
CF	34.0 (6.4)	32.7 (6.5)	34.5 (6.7)	0.148	0.20 (-0.44,0.84)	-0.08 (-0.72,0.55)	12.5 (3.9)	14.7 (4.5)	14.1 (4.2)	0.001	-0.51 (-1.16,0.14)	-0.39 (-1.03,
LF	27.7 (6.4)	26.3 (6.2)	26.0 (7.5)	0.067	0.22 (-0.42,0.86)	0.25 (-0.39,0.88)	10.0 (3.6)	11.8 (4.3)	10.6 (4.7)	0.042	-0.44 (-1.06,0.20)	-0.13 (-0.77,
GT	26.2 (6.2)	26.0 (7.0)	29.6 (7.9)	0.520	0.02 (-0.62,0.66)	-0.11 (-0.74,0.53)	9.0 (2.5)	11.1 (3.9)	10.4 (4.1)	0.023	-0.63 (-1.28,0.03)	-0.41 (-1.05,
LT	23.0 (6.5)	21.5 (6.0)	21.3 (5.9)	0.045	0.23 (-0.41,0.86)	0.26 (-0.38,0.90)	7.9 (2.5)	8.8 (3.1)	7.9 (3.0)	0.143	-0.30 (-0.94, 0.34)	-0.01 (-0.65,
TO	91.3 (7.8)	89.4 (8.8)	90.9 (10.0)	0.127	0.22 (-0.42,0.86)	0.04 (-0.60,0.67)	115.7 (7.8)	118.5 (23.1)	**104.2 (15.7)**	<0.001	-0.13 (-0.77,0.51)	**0.67 (0.02,1**
MH	36.9 (6.8)	35.1 (7.7)	38.3 (8.3)	<0.001	0.25 (-0.39,0.88)	-0.18 (-0.82,0.46)	23.6 (6.8)	24.3 (8.7)	25.7 (9.2)	0.282	-0.09 (-0.72,0.55)	-0.24 (-0.88,
LH	32.0 (4.4)	30.9 (4.4)	31.5 (4.1)	0.279	0.26 (-0.38,0.90)	0.11 (-0.52,0.75)	18.5 (4.4)	19.2 (6.7)	19.0) (5.8)	0.269	-0.10 (-0.73,0.54)	-0.08 (-0.71,
MM	6.9 (4.3)	6.8 (4.5)	7.8 (5.0)	0.001	0.03 (-0.61,0.66)	-0.17 (-0.81,0.47)	5.6 (4.3)	5.7 (3.9)	5.8 (3.7)	0.850	-0.03 (-0.66,0.61)	-0.05 (-0.69,
LM	18.3 (4.0)	18.0 (4.6)	15.7 (4.7)	<0.001	0.07 (-0.57,0.71)	0.58 (-0.06,1.23)	15.1 (4.0)	15.0 (6.1)	**11.1 (4.6)**	<0.001	0.03 (-0.61,0.66)	**0.81 (0.15,1**
MF	13.5 (3.5)	13.6 (3.1)	14.8 (3.8)	0.060	-0.03 (-0.67,0.60)	-0.33 (-0.97,0.31)	10.1 (3.5)	10.5 (3.3)	9.8 (3.1)	0.457	-0.14 (-0.77,0.50)	0.09 (-0.55,(
CF	13.9 (3.1)	14.3 (2.5)	13.7 (2.4)	0.409	-0.13 (-0.76,0.51)	0.07 (-0.57,0.70)	12.4 (3.1)	13.1 (2.7)	**10.2 (2.3)**	<0.001	-0.23 (-0.86,0.41)	**0.69 (0.04,1**
LF	13.3 (2.8)	13.3 (2.9)	**11.0 (2.7)**	<0.001	0.01 (-0.63,0.65)	**0.81 (0.15,1.48)**	11.5 (2.8)	11.7 (2.9)	**8.0 (2.3)**	<0.001	-0.06 (-0.70,0.57)	**1.29 (0.59,1**
GT	13.7 (4.0)	13.5 (4.0)	12.7 (4.9)	0.249	0.04 (-0.59,0.68)	0.22 (-0.42,0.86)	10.4 (4.0)	10.5 (4.1)	8.8 (3.6)	0.005	-0.03 (-0.67,0.60)	0.43 (-0.22,
LT	10.8 (2.9)	10.3 (3.0)	8.6 (4.0)	0.004	0.16 (-0.48,0.79)	0.62 (-0.03,1.27)	8.4 (2.9)	8.4 (3.1)	**5.9 (3.2)**	<0.001	0.02 (-0.62,0.65)	**0.82 (0.15,1**

TO= Total; MH= Medial Heel; LH=Lateral Heel; MM= Medial Midfoot; LM= Lateral Midfoot; MF= Medial Forefoot; CF=Central Forefoot; LF= Lateral Forefoot; GT=Great Toe; LT= Lesser Toes; Bolded numbers indicate a statistically significant difference from baseline with moderate to large effect sizes and 95% confidence intervals that do not cross 0; P values from repeated measures analysis of variance; A negative effect size represents an increase in the biofeedback condition from baseline; A positive effect size represents a decrease in the biofeedback condition from baseline.

A3.2 SUPPLEMENTARY TABLES FROM CHAPTER 3

Table A3.5 Correlation coefficients between talar cartilage characteristics and contact area during 30-minute treadmill walking

	Total	Medial Heel	Lateral Heel	Medial Midfoot	Lateral midfoot	Medial Forefoot	Central Forefoot	Lateral Forefoot	Great Toe	Lesser Toes
Resting Thickness										
Total	0.334	0.347	0.366	0.223	0.391	.445*	0.420	0.408	0.421	0.390
Medial	0.244	0.288	0.300	0.150	0.315	0.385	0.346	0.325	0.352	0.293
Lateral	0.426	0.419	0.430	0.362	.459*	.465*	.495*	.466*	.492*	.478*
Deformation after Walking										
Total	-0.271	-0.253	-0.307	-0.326	-0.310	-0.405	-0.303	-0.217	-0.185	-0.088
Medial	-0.253	-0.260	-0.281	-0.296	-0.297	-0.362	-0.282	-0.243	-0.218	-0.178
Lateral	-0.386	-0.366	-0.420	-0.409	-0.406	-.498*	-0.430	-0.325	-0.292	-0.175
Resting Echo Intensity										
Total	-0.047	-0.014	0.000	-0.041	-0.071	-0.083	-0.072	-0.038	-0.059	-0.038
Medial	-0.087	-0.036	-0.057	-0.065	-0.099	-0.104	-0.115	-0.101	-0.147	-0.132
Lateral	-0.044	-0.012	0.054	-0.059	-0.053	-0.069	-0.039	0.030	0.022	0.060
Change Echo Intensity										
Total	0.110	0.223	0.155	0.005	0.200	0.221	0.230	0.113	0.136	0.105
Medial	-0.111	0.028	-0.028	-0.170	0.006	0.056	0.023	-0.078	-0.093	-0.054
Lateral	0.398	0.320	0.278	0.307	0.347	0.268	0.374	0.305	0.366	0.327

**. Correlation is significant at the 0.01 level (2-tailed). *. Correlation is significant at the 0.05 level (2-tailed).

Table A3.6 Correlation coefficients between talar cartilage characteristics and contact time during 30-minute treadmill walking

	Total	Medial Heel	Lateral Heel	Medial Midfoot	Lateral midfoot	Medial Forefoot	Central Forefoot	Lateral Forefoot	Great Toe	Lesser Toes
Resting Thickness										
Total	0.106	-0.210	-0.213	0.043	0.017	0.000	0.002	-0.005	-0.026	0.030
Medial	0.127	-0.189	-0.214	0.054	0.023	-0.048	-0.023	-0.003	-0.051	-0.021
Lateral	0.102	-0.202	-0.174	0.050	0.038	0.075	0.052	0.015	0.026	0.105
Deformation										
Total	0.252	0.232	0.195	0.235	0.298	0.314	0.312	0.298	0.257	0.265
Medial	0.383	0.181	0.168	0.330	0.402	0.415	0.430	0.386	0.317	0.354
Lateral	0.029	0.227	0.174	0.065	0.100	0.130	0.101	0.121	0.128	0.106
Resting Echo Intensity										
Total	-0.210	0.072	0.044	-0.136	-0.118	-0.018	-0.050	-0.081	-0.068	-0.090
Medial	-0.196	0.038	0.083	-0.101	-0.102	-0.019	-0.048	-0.064	-0.061	-0.087
Lateral	-0.206	0.111	-0.016	-0.169	-0.126	-0.015	-0.046	-0.094	-0.069	-0.085
Change Echo Intensity										
Total	-0.218	-0.124	-0.047	-0.072	-0.180	-0.073	-0.106	-0.109	-0.094	-0.109
Medial	-0.261	-0.107	-0.008	-0.088	-0.209	-0.119	-0.147	-0.150	-0.155	-0.190
Lateral	-0.056	-0.098	-0.091	-0.015	-0.058	0.031	0.006	0.004	0.044	0.069

**. Correlation is significant at the 0.01 level (2-tailed). *. Correlation is significant at the 0.05 level (2-tailed).

Table A3.7 Correlation coefficients between talar cartilage characteristics and pressure-time integral during 30-minute treadmill

	Total	Medial Heel	Lateral Heel	Medial Midfoot	Lateral midfoot	Medial Forefoot	Central Forefoot	Lateral Forefoot	Great Toe	Lesser Toes
Resting Thickness										
Total	0.253	-0.027	-0.063	0.037	-0.070	0.379	0.205	-0.045	0.365	0.203
Medial	0.237	0.036	0.000	0.114	-0.027	0.341	0.120	-0.135	0.335	0.081
Lateral	0.264	-0.080	-0.112	-0.031	-0.095	.484*	0.400	0.053	.480*	0.324
Deformation										
Total	0.164	0.383	0.382	0.051	-0.047	0.326	0.044	-0.032	-0.123	0.035
Medial	0.235	0.329	0.331	0.019	-0.078	0.299	0.023	-0.077	-0.090	0.129
Lateral	0.049	0.341	0.342	0.060	0.005	0.203	-0.072	0.002	-0.161	-0.068
Resting Echo Intensity										
Total	-0.127	-0.122	-0.089	-0.166	-0.040	-0.080	0.063	0.042	-0.065	0.007
Medial	-0.248	-0.183	-0.140	-0.089	-0.005	-0.188	-0.054	-0.017	-0.224	-0.079
Lateral	0.055	-0.024	-0.007	-0.252	-0.083	-0.056	0.081	0.044	0.021	0.125
Change Echo Intensity										
Total	-0.167	-0.307	-0.351	-0.052	-0.051	-0.003	0.192	0.137	-0.015	-0.089
Medial	-0.240	-0.265	-0.279	-0.063	-0.036	0.011	0.150	0.084	-0.248	-0.276
Lateral	0.021	-0.245	-0.321	-0.013	-0.055	0.099	0.361	.460*	0.347	0.252

**. Correlation is significant at the 0.01 level (2-tailed). *. Correlation is significant at the 0.05 level (2-tailed

Table A3.8 Correlation coefficients between talar cartilage characteristics and force-time integral during 30-minute treadmill

	Total	Medial Heel	Lateral Heel	Medial Midfoot	Lateral midfoot	Medial Forefoot	Central Forefoot	Lateral Forefoot	Great Toe	Lesser Toes
Resting Thickness										
Total	0.165	-0.015	-0.101	0.055	-0.074	0.497*	0.232	0.131	0.370	0.144
Medial	0.097	0.059	-0.026	-0.032	-0.168	0.440	0.158	0.047	0.305	-0.009
Lateral	0.247	-0.073	-0.160	0.148	0.050	0.532*	0.444	0.219	0.449	0.297
Deformation										
Total	0.141	0.366	0.370	-0.322	-0.206	0.242	0.058	-0.001	-0.032	-0.021
Medial	0.284	0.350	0.374	-0.227	-0.128	0.363	0.121	0.150	-0.014	0.000
Lateral	-0.060	0.274	0.267	-0.353	-0.238	0.052	-0.235	-0.159	-0.119	-0.027
Resting Echo Intensity										
Total	-0.204	-0.082	-0.035	-0.158	-0.040	-0.360	-0.160	-0.036	-0.181	-0.081
Medial	-0.228	-0.115	-0.092	-0.121	0.052	-0.353	-0.232	-0.047	-0.282	-0.120
Lateral	-0.147	-0.026	0.048	-0.192	-0.163	-0.328	-0.072	-0.016	-0.042	-0.018
Change Echo Intensity										
Total	0.001	-0.224	-0.369	-0.002	-0.156	0.129	0.295	0.304	0.089	0.322
Medial	-0.163	-0.136	-0.265	-0.178	-0.295	-0.048	0.042	0.162	-0.204	0.125
Lateral	0.270	-0.276	-0.388	0.288	0.136	0.366	.654**	0.411	.526*	.512*

**. Correlation is significant at the 0.01 level (2-tailed). *. Correlation is significant at the 0.05 level (2-tailed)

Table A3.9 Correlation coefficients between talar cartilage characteristics and dorsiflexion range of motion

Resting Thickness	WBLT
Total	0.226
Medial	0.146
Lateral	0.324
Deformation	
Total	0.183
Medial	0.133
Lateral	0.196
Resting Echo Intensity	
Total	-0.415
Medial	-0.375
Lateral	-0.419
Change Echo Intensity	
Total	0.465
Medial	0.306
Lateral	0.539*

WBLT: Weight Bearing Lunge Test *. Correlation is significant at the 0.05 level (2-tailed)

Table A3.10 Correlation coefficients between talar cartilage characteristics and time to boundary during static balance

	Eyes Open				Eyes Closed			
	TTB ML Mean Minima	TTB ML SD Minima	TTB AP Mean Minima	TTB AP SD Minima	TTB ML Mean Minima	TTB ML SD Minima	TTB AP Mean Minima	TTB AP SD Minima
Resting Thickness								
Total	-0.441	0.436	0.009	-0.149	0.227	.445*	-0.245	-0.033
Medial	-0.442	0.395	-0.024	-0.077	0.295	.464*	-0.110	-0.086
Lateral	-0.406	.468*	0.061	-0.194	0.148	0.407	-0.379	0.031
Deformation								
Total	-0.018	-0.006	0.290	0.034	0.153	0.099	-0.059	-0.061
Medial	-0.047	0.146	0.419	-0.062	0.228	0.038	-0.333	0.064
Lateral	0.044	-0.164	0.041	0.132	0.035	0.165	0.254	-0.206
Resting Echo Intensity								
Total	0.254	-.543*	-0.003	0.171	-0.107	-.476*	-0.073	0.053
Medial	0.299	-.470*	-0.090	0.318	-0.124	-0.439	-0.017	0.046
Lateral	0.164	-.580**	0.118	-0.053	-0.071	-.473*	-0.141	0.056
Change Echo Intensity								
Total	-0.333	-0.246	0.044	0.031	0.102	0.307	0.091	0.001
Medial	-0.217	-0.358	0.034	0.273	0.175	0.268	0.194	-0.081
Lateral	-0.383	0.039	0.041	-0.376	-0.061	0.241	-0.115	0.134

TTB:Time to Boundary; ML: mediolateral; AP: anteroposterior; SD: standard deviation; Correlation significant at **0.01 or * 0.05 level

Table A3.11 Correlation coefficients between talar cartilage characteristics and COP location during static balance

	Eyes Open				Eyes Closed			
	Anteromedial	Anterolateral	Posteromedial	Posterolateral	Anteromedial	Anterolateral	Posteromedial	Posterolateral
Resting Thickness								
Total	-0.279	0.131	-0.212	0.017	-0.024	0.168	-0.251	0.092
Medial	-0.307	0.120	-0.206	0.014	-0.029	0.103	-0.196	0.104
Lateral	-0.218	0.120	-0.170	0.054	-0.018	0.233	-0.293	0.048
Deformation								
Total	-0.027	-0.028	-0.174	-0.167	0.206	-0.084	-0.057	-0.287
Medial	-0.049	-0.026	-0.226	-0.111	0.045	-0.110	-0.062	0.015
Lateral	0.011	-0.012	-0.006	-0.180	0.362	-0.043	-0.024	-.474*
Resting Echo Intensity								
Total	0.248	0.058	0.083	-0.358	0.025	-0.213	0.322	-0.220
Medial	0.270	-0.047	0.170	-0.290	-0.047	-0.204	0.342	-0.147
Lateral	0.188	0.197	-0.087	-0.390	0.121	-0.202	0.257	-0.259
Change Echo Intensity								
Total	-0.278	-0.074	0.208	.517*	-0.151	-0.071	-0.037	0.161
Medial	-0.271	-0.098	0.230	0.341	-0.166	-0.190	0.161	-0.005
Lateral	-0.174	-0.003	-0.153	.460*	-0.064	0.152	-0.344	0.259

*. Correlation is significant at the 0.05 level (2-tailed)

Table A3.12 Correlation coefficients between talar cartilage characteristics and plantar pressure during lateral hop

	Total	Medial Heel	Lateral Heel	Medial Midfoot	Lateral midfoot	Medial Forefoot	Central Forefoot	Lateral Forefoot	Great Toe	Lesser Toes
Resting Thickness										
Total	-0.001	-0.174	-0.249	0.155	-0.375	0.236	-0.211	-0.436	-0.293	-0.188
Medial	0.026	-0.209	-0.306	0.165	-0.368	0.236	-0.206	-0.403	-0.260	-0.196
Lateral	-0.060	-0.103	-0.149	0.115	-0.363	0.122	-0.230	-0.458*	-0.321	-0.181
Deformation										
Total	-0.176	-0.219	-0.196	-0.266	-0.076	0.164	0.061	0.134	-0.220	0.289
Medial	-0.361	-0.022	0.051	-0.263	-0.021	-0.107	-0.110	-0.058	-0.337	0.080
Lateral	0.104	-0.389	-0.429	-0.205	-0.134	0.341	0.246	0.314	-0.009	.463*
Resting Echo Intensity										
Total	0.076	0.229	0.327	0.044	.625**	-0.057	0.277	0.413	0.242	0.176
Medial	-0.018	0.246	0.338	0.050	.622**	-0.087	0.204	0.369	0.169	0.097
Lateral	0.196	0.180	0.274	0.031	.558*	-0.026	0.347	0.425	0.315	0.264
Change Echo Intensity										
Total	-0.115	0.143	0.069	0.102	-0.060	-0.119	-0.207	-0.131	-0.197	-0.346
Medial	-0.083	0.190	0.121	0.178	0.160	0.018	-0.141	-0.045	-0.177	-0.343
Lateral	-0.118	0.006	-0.044	-0.064	-0.394	-0.211	-0.450*	-0.217	-0.147	-0.207

**. Correlation is significant at the 0.01 level (2-tailed). *. Correlation is significant at the 0.05 level (2-tailed)

Table A3.13 Correlation coefficients between talar cartilage characteristics and plantar pressure during lateral hop

	Total	Medial Heel	Lateral Heel	Medial Midfoot	Lateral midfoot	Medial Forefoot	Central Forefoot	Lateral Forefoot	Great Toe	Lesser Toes
Resting Thickness										
Total	-0.318	-0.231	-0.132	-0.016	-.459*	0.422	-.075	-.474*	0.167	0.092
Medial	-0.364	-0.252	-0.199	-0.086	-.527*	.523*	-.006	-.463*	0.113	0.064
Lateral	-0.255	-0.172	-0.028	0.066	-0.346	0.261	-0.125	-.460*	0.047	0.109
Deformation										
Total	-0.136	-0.128	-0.086	-.477*	-0.169	0.145	0.356	0.159	-0.215	0.230
Medial	-0.033	0.071	0.190	-0.302	-0.058	0.058	0.253	0.083	-0.218	0.076
Lateral	-0.237	-0.334	-0.382	-.563**	-0.269	0.207	0.241	0.187	-0.171	0.333
Resting Echo Intensity										
Total	0.409	0.272	0.194	0.057	.551*	-0.236	0.150	.542*	-0.005	-0.168
Medial	0.354	0.301	0.220	0.095	.598**	-0.277	0.063	.525*	-0.126	-0.246
Lateral	0.439	0.200	0.135	-0.001	0.422	-0.152	0.262	.502*	0.198	-0.042
Change Echo Intensity										
Total	-0.081	0.192	0.103	-0.098	-0.010	-0.168	-0.146	0.044	-0.420	-0.030
Medial	-0.026	0.249	0.120	-0.136	0.115	-0.050	-0.045	0.192	-0.417	-0.134
Lateral	-0.137	0.017	0.031	0.005	-0.209	-0.290	-0.248	-0.215	0.096	0.152

**. Correlation is significant at the 0.01 level (2-tailed). *. Correlation is significant at the 0.05 level (2-tailed)

Table A3.14 Correlation coefficients between talar cartilage characteristics and plantar pressure during step down

	Total	Medial Heel	Lateral Heel	Medial Midfoot	Lateral midfoot	Medial Forefoot	Central Forefoot	Lateral Forefoot	Great Toe	Lesser Toes
Resting Thickness										
Total	0.121	-0.068	-0.121	0.034	-0.230	0.123	-0.381	-.465*	0.019	-0.169
Medial	0.145	-0.170	-0.224	-0.023	-0.316	0.242	-0.364	-.480*	0.112	-0.176
Lateral	0.100	0.047	-0.002	0.100	-0.120	-0.010	-0.379	-0.427	-0.071	-0.152
Deformation										
Total	-0.258	-0.182	-0.181	-0.239	-0.166	0.330	0.170	0.095	-0.216	0.303
Medial	-0.108	-0.077	-0.068	-0.194	-0.100	0.174	0.080	-0.026	-0.272	0.205
Lateral	-0.362	-0.339	-0.387	-0.232	-0.202	0.432	0.237	0.220	-0.110	0.339
Resting Echo Intensity										
Total	-0.032	0.128	0.252	0.180	.535*	-0.003	0.437	.460*	-0.019	0.320
Medial	-0.004	0.268	0.378	0.278	.546*	-0.072	0.373	0.419	-0.039	0.247
Lateral	-0.068	-0.111	0.011	0.023	.460*	0.093	.477*	.465*	0.012	0.386
Change Echo Intensity										
Total	-0.130	0.168	0.121	-0.084	0.082	-0.259	-0.189	-0.001	-0.086	-0.279
Medial	-0.129	0.104	0.078	-0.136	0.201	-0.116	-0.087	0.068	-0.039	-0.262
Lateral	-0.078	0.181	0.076	0.029	-0.131	-0.367	-0.266	-0.104	-0.120	-0.188

**. Correlation is significant at the 0.01 level (2-tailed). *. Correlation is significant at the 0.05 level (2-tailed)

Table A3.15 Correlation coefficients between talar cartilage characteristics and maximum force during step down

	Total	Medial Heel	Lateral Heel	Medial Midfoot	Lateral midfoot	Medial Forefoot	Central Forefoot	Lateral Forefoot	Great Toe	Lesser Toes
Resting Thickness										
Total	-0.405	-0.125	-0.189	-0.064	-0.340	0.128	-0.298	-0.423	0.208	0.149
Medial	-.509*	-0.233	-0.261	-0.148	-.457*	0.252	-0.281	-.488*	0.285	0.088
Lateral	-0.261	-0.030	-0.058	0.021	-0.190	-0.005	-0.291	-0.314	0.107	0.205
Deformation										
Total	-0.067	-0.051	-0.067	-0.379	-0.247	0.342	0.295	0.198	-0.229	0.411
Medial	0.077	0.026	0.098	-0.335	-0.146	0.285	0.223	0.194	-0.209	0.391
Lateral	-0.227	-0.204	-0.319	-0.340	-0.307	0.310	0.182	0.139	-0.223	0.319
Resting Echo Intensity										
Total	.486*	0.119	0.239	0.195	.467*	-0.001	0.202	0.439	-0.142	-0.159
Medial	.537*	0.211	0.339	0.230	.531*	-0.042	0.102	0.435	-0.223	-0.200
Lateral	0.358	-0.018	0.054	0.124	0.325	0.057	0.277	0.394	-0.013	-0.083
Change Echo Intensity										
Total	-0.154	0.114	0.047	-0.245	-0.015	-0.434	0.023	0.199	0.034	0.088
Medial	-0.146	0.037	0.005	-0.325	0.040	-0.268	0.060	0.315	0.009	0.005
Lateral	-0.103	0.165	-0.037	-0.022	-0.093	-.505*	-0.005	-0.059	0.057	0.176

**. Correlation is significant at the 0.01 level (2-tailed). *. Correlation is significant at the 0.05 level (2-tailed)

A3.3 SUPPLEMENTARY TABLES FROM CHAPTER 4

Table A3.16. Contact area in each region of the foot within each group across time during walking

	Control			AudFB			Time Main Effect	Group Main Effect	Group x Time Interaction
	Baseline	Immediate	1-Week Post	Baseline	Immediate	1-Week Post	P Value	P Value	P Value
Total	147.28 ± 27	141.4 ± 26.6	138.9 ± 29.7	147.6 ± 22.2	141.5 ± 15	144.6 ± 16.8	.072	.878	.460
Medial Heel	21.6 ± 3.2	21.6 ± 3.6	21.5 ± 3.6	21.1 ± 2.7	21 ± 2.6	21 ± 2.5	.659	.753	.823
Lateral Heel	19.6 ± 2.4	19.8 ± 3.1	19.6 ± 2.5	19.1 ± 2	18.9 ± 1.7	18.7 ± 1.6	.539	.566	.595
Medial Midfoot	13.7 ± 7.4	11.2 ± 6.4	10.7 ± 7	15.8 ± 6.3	14.3 ± 5.7	14.7 ± 6.5	.265	.373	.722
Lateral Midfoot	25.4 ± 4.8	25.2 ± 4.4	24.2 ± 5.9	24.7 ± 3.6	21.3 ± 7.3	23 ± 4.1	.268	.461	.334
Medial Forefoot	12.6 ± 2.2	11.8 ± 2.2	11.4 ± 2.2	11.9 ± 1.1	12.1 ± 1	12.1 ± 1.1	.052	.908	.008*
Central Forefoot	14.4 ± 2.3	14.2 ± 2.4	13.8 ± 2.6	13.9 ± 1.6	14 ± 1.6	14 ± 1.6	.113	.905	.053
Lateral Forefoot	13.7 ± 2.2	13.5 ± 2.2	13.3 ± 2.5	13.4 ± 1.7	12.9 ± 1.6	13.4 ± 1.7	.266	.833	.216
Great Toe	10 ± 2.2	9 ± 2.2	9.4 ± 2.3	10.1 ± 1.6	10.1 ± 1.1	10.2 ± 1.2	.089	.532	.063
Lesser Toes	16.3 ± 3.7	15 ± 4.4	14.9 ± 5.7	17.4 ± 3.5	16.9 ± 3.1	17.3 ± 3.3	.077	.433	.284

Table A3.17. Contact time in each region of the foot within each group across time during walking

	Control			AudFB			Time Main Effect	Group Main Effect	Group x Time Interaction
	Baseline	Immediate	1-week Post	Baseline	Immediate	1-week Post	P Value	P Value	P Value
Total	899.81 ± 130.86	883.9 ± 128.23	888.54 ± 133.36	739.81 ± 63.14	730.26 ± 53.91	736.03 ± 52.72	.416	.019*	873
Medial Heel	733.28 ± 206.69	688.31 ± 184.98	696.66 ± 179.21	607.93 ± 105.52	547.79 ± 118.19	556.99 ± 116.6	.113	.140	.843
Lateral Heel	735.98 ± 176.19	730.8 ± 199.96	720.5 ± 202.69	645.38 ± 124.32	533.67 ± 112.85	546.47 ± 116.37	.188	.087	.273
Medial Midfoot	831.98 ± 126.25	791.07 ± 127.07	765.52 ± 142.23	689.12 ± 111.27	643.71 ± 83.25	647.38 ± 81.53	.109	.038*	.757
Lateral Midfoot	878.03 ± 136.71	846 ± 131.23	838.24 ± 132.68	728.81 ± 58.83	662.17 ± 57.05	680.52 ± 47.52	.018*	.014*	.442
Medial Forefoot	797.99 ± 143.99	697.35 ± 106.7	654.53 ± 154.05	674.43 ± 98.94	612.93 ± 39.89	632.03 ± 47.84	.008*	.182	.180
Central Forefoot	825.62 ± 137.08	748.64 ± 107.2	731.52 ± 121.56	696 ± 84.86	621.24 ± 40.56	641.4 ± 42.96	.001*	.044*	.458
Lateral Forefoot	855 ± 131.39	800.88 ± 109.61	794.73 ± 117.36	706.33 ± 88.1	613.07 ± 64.02	644.71 ± 47.97	.003*	.009*	.460
Great Toe	788.33 ± 149.68	627.74 ± 161.57	628.66 ± 167.7	672.64 ± 98.58	598.71 ± 70.57	628.92 ± 40.54	.008*	.443	.212
Lesser Toes	789.96 ± 151.38	663.06 ± 86.2	665.14 ± 124.55	662.95 ± 117.47	565.81 ± 62.08	600.2 ± 50.16	.003*	.083	.485

Table A3.18. Pressure time integral in each region of the foot within each group across time during walking

	Control			AudFB			Time Main Effect	Group Main Effect	Group x Time Interaction
	Baseline	Immediate	1-week Post	Baseline	Immediate	1-week Post	P Value	P Value	P Value
Total	119.51 ± 20.31	114.34 ± 17.11	114.78 ± 21.58	112.44 ± 15.24	123.05 ± 31.96	117.45 ± 21.97	.599	.904	.077
Medial Heel	65.54 ± 23.74	71.43 ± 24.12	72.24 ± 24.08	54.08 ± 13.27	61.27 ± 22.69	56.93 ± 15.43	.096	.304	.574
Lateral Heel	64.5 ± 22.99	70.87 ± 25.38	70.96 ± 24.03	53.45 ± 11.37	56.05 ± 17.62	52.81 ± 12.93	.257	.203	.411
Medial Midfoot	54.79 ± 13.03	55.12 ± 16.21	50.96 ± 17.51	45.77 ± 9.11	44.24 ± 10.73	44.63 ± 11.05	.506	.243	.587
Lateral Midfoot	72.25 ± 13.02	72.64 ± 15.45	70.64 ± 17.71	60.57 ± 8.25	46.64 ± 13.21	48.21 ± 12.18	.009*	.018*	.015*
Medial Forefoot	75.63 ± 21.18	59.88 ± 16.59	56.41 ± 21.95	65.71 ± 6.3	71.57 ± 12.98	72.21 ± 12.86	.154	.503	.003*
Central Forefoot	78.07 ± 25.18	62.61 ± 16.02	61.26 ± 21.71	72.22 ± 5.05	63.75 ± 9.69	67.67 ± 5.83	.003*	.948	.151
Lateral Forefoot	76.11 ± 25.46	65.82 ± 12.26	65.63 ± 19.09	72.78 ± 9.39	55.15 ± 15.63	60.69 ± 11.36	.008*	.465	.511
Great Toe	63.54 ± 29.53	46.1 ± 25.28	46.04 ± 27.58	62.69 ± 13.76	69.67 ± 21.43	67.54 ± 18.49	.172	.266	.003*
Lesser Toes	58.22 ± 23.21	42.39 ± 16.38	44.59 ± 19.76	55.47 ± 12.43	50.01 ± 9.19	53.59 ± 9.56	.045*	.571	.280

Table A3.19. Force time integral in each region of the foot within each group across time during walking

	Control			AudFB			Time Main Effect	Group Main Effect	Group x Time Interaction
	Baseline	Immediate	1-week Post	Baseline	Immediate	1-week Post	P Value	P Value	P Value
Total	71.02 ± 10.95	64.41 ± 8.36	62.49 ± 8.84	64.81 ± 11.18	56.82 ± 5.7	57.61 ± 4.77	.007*	.157	.775
Medial Heel	13.01 ± 5.58	14.19 ± 5.11	14.3 ± 4.98	9.73 ± 1.71	11.48 ± 4.26	10.69 ± 2.75	.064	.201	.678
Lateral Heel	11.52 ± 5.02	12.96 ± 5.77	12.93 ± 5.19	8.54 ± 1.9	9.25 ± 3.21	8.53 ± 2.57	.155	.140	.393
Medial Midfoot	2.65 ± 1.52	1.93 ± 1.18	1.92 ± 1.22	2.99 ± 1.55	2.03 ± 1.33	2.2 ± 1.52	.030*	.740	.817
Lateral Midfoot	10.35 ± 2.72	9.86 ± 2.44	9.35 ± 3.47	9.23 ± 2.61	5.46 ± 2.92	5.65 ± 2.67	.006*	.049*	.059
Medial Forefoot	7.31 ± 1.49	5.64 ± 1.72	5.1 ± 2.11	6.22 ± 1.1	7.49 ± 1.9	7.48 ± 2.24	.532	.243	.007*
Central Forefoot	9.5 ± 2.48	7.4 ± 1.7	6.85 ± 2.41	9.58 ± 1.54	8.28 ± 1.59	8.93 ± 1.13	.002*	.298	.112
Lateral Forefoot	8.72 ± 2.06	7.24 ± 1.13	6.99 ± 1.67	8.45 ± 2.81	5.11 ± 2	5.91 ± 1.33	.004*	.174	.306
Great Toe	4.08 ± 2.23	2.61 ± 1.47	2.56 ± 1.6	4.65 ± 1.51	4.6 ± 2.17	4.67 ± 2.08	.047*	.141	.050*
Lesser Toes	3.82 ± 1.34	2.54 ± 1.23	2.46 ± 1.48	5.37 ± 2.76	3.07 ± 1.29	3.51 ± 1.27	.009*	.167	.509

Table A3.20 Eyes open balance measures within groups across time.

	Control			AudFB			Time Main Effect P Value	Group Main Effect P Value	Group x Time Interaction P Value
	Baseline	Immediate	1-week Post	Baseline	Immediate	1-week Post			
Area (cm^2)	6.8 ± 2.73	6.9 ± 2.08	6.21 ± 1.6	10.37 ± 6.22	92.36 ± 201.7	7.9 ± 3.5	.302	.246	.307
Velocity (cm*s)	4.23 ± 1.41	4.37 ± 1.47	3.84 ± 0.91	5.47 ± 2.33	4.53 ± 1.79	4.34 ± 1.33	.093	.441	.264
TTB ML Mean Minima (ms)	5.04 ± 0.08	5.03 ± 0.1	4.97 ± 0.18	4.95 ± 0.05	5.06 ± 0.1	5.05 ± 0.08	.536	.794	.170
TTB ML SD Minima (ms)	2.89 ± 0.02	2.90 ± 0.06	2.84 ± 0.05	2.86 ± 0.05	2.85 ± 0.04	2.92 ± 0.04	.930	.975	<0.001
TTB AP Mean Minima (ms)	5.03 ± 0.07	5.03 ± 0.1	5.02 ± 0.16	5.03 ± 0.08	5.09 ± 0.09	5.07 ± 0.11	.826	.290	.722
TTB AP SD Minima (ms)	2.89 ± 0.04	2.91 ± 0.05	2.88 ± 0.04	2.87 ± 0.02	2.89 ± 0.04	2.9 ± 0.03	.639	.543	.374
Anteromedial (#)	134.81 ± 126.73	101.48 ± 71.73	96.71 ± 71.88	160.83 ± 110.32	117.44 ± 75.92	126.69 ± 150.81	.151	.659	.944
Anterolateral (#)	87.52 ± 95.9	123.05 ± 69.23	119.38 ± 77.57	184.22 ± 118.29	156.75 ± 100.7	118.33 ± 110.11	.752	.315	.262
Posteromedial (#)	126.71 ± 129	105.48 ± 52.26	108.86 ± 57.96	70.39 ± 61.03	100.89 ± 86.29	121.86 ± 119.63	.769	.707	.363
Posterolateral (#)	151.38 ± 175.95	170.24 ± 90.23	175.29 ± 96.94	85.11 ± 68.28	125.42 ± 112.23	133.39 ± 93.97	.412	.363	.896

Table A3.21 Eyes closed balance measures within groups across time.

	Control			AudFB			Time Main Effect P Value	Group Main Effect P Value	Group x Time Interaction P Value
	Baseline	Immediate	1-week Post	Baseline	Immediate	1-week Post			
Area (cm^2)	27.73 ± 12.98	26.81 ± 12.87	25.81 ± 11.38	26.95 ± 13.61	24.47 ± 7.73	19.93 ± 10.15	.166	.624	.530
Velocity (cm*s)	10.09 ± 4.66	10.22 ± 2.79	9.09 ± 2.8	9.08 ± 3.06	8.72 ± 1.55	8.24 ± 2.69	.185	.504	.809
TTB ML Mean Minima (ms)	5.01 ± 0.1	5 ± 0.09	4.94 ± 0.14	4.9 ± 0.11	4.94 ± 0.09	4.99 ± 0.11	.896	.380	.130
TTB ML SD Minima (ms)	2.87 ± 0.04	2.87 ± 0.06	2.85 ± 0.04	2.9 ± 0.05	2.86 ± 0.04	2.86 ± 0.06	.279	.744	.579
TTB AP Mean Minima (ms)	5.04 ± 0.08	5 ± 0.13	5.04 ± 0.13	5.02 ± 0.07	4.99 ± 0.1	5.05 ± 0.09	.299	.933	.956
TTB AP SD Minima (ms)	2.87 ± 0.03	2.88 ± 0.04	2.88 ± 0.07	2.89 ± 0.06	2.86 ± 0.05	2.91 ± 0.07	.555	.719	.517
Anteromedial (#)	89.47 ± 84.28	88.81 ± 82.27	53.33 ± 38.27	123.77 ± 77.18	83.83 ± 20.64	121.17 ± 75.4	.620	.521	.310
Anterolateral (#)	107.54 ± 70.89	120.55 ± 98.33	106.12 ± 93.23	112.17 ± 77.98	139.14 ± 88.43	103.11 ± 102.55	.173	.889	.728
Posteromedial (#)	130.53 ± 74.76	105.17 ± 51.82	135.31 ± 60.58	168.43 ± 114.14	141.58 ± 76.66	146.06 ± 96.29	.415	.471	.698
Posterolateral (#)	172.73 ± 109.83	185.88 ± 139.65	205.52 ± 86.02	95.97 ± 39.83	135.69 ± 29.36	129.78 ± 71.77	.258	.157	.770

Table A3.22. Peak pressure in each region of the foot within each group across time during step down

	Control			AudFB			Time Main Effect	Group Main Effect	Group x Time Interaction
	Baseline	Immediate	1-week Post	Baseline	Immediate	1-week Post	P Value	P Value	P Value
Total	306.37 ± 61.06	292.87 ± 70.43	292.63 ± 69.31	280.13 ± 46.55	342.83 ± 94.59	336.79 ± 74.91	.251	.553	.042*
Medial Heel	173.95 ± 64.24	160.25 ± 104.58	158.63 ± 104.66	148.38 ± 36.28	128.75 ± 49.86	134.29 ± 30.3	.266	.507	.939
Lateral Heel	160.42 ± 57.27	144.38 ± 84.76	146.38 ± 96	132.67 ± 39.95	120.75 ± 54.85	127.08 ± 34.35	.445	.521	.930
Medial Midfoot	150.94 ± 30.92	141.69 ± 32.26	140.08 ± 30.45	134.08 ± 18.53	138.58 ± 30.6	140.5 ± 23.65	.909	.667	.343
Lateral Midfoot	162.62 ± 22.24	149.87 ± 17.59	157.58 ± 17.44	141.75 ± 26.66	142.42 ± 29.12	142.92 ± 20.04	.771	.127	.735
Medial Forefoot	239.37 ± 37.56	231.42 ± 54.21	235.33 ± 44.97	220.96 ± 53.76	261.08 ± 62.54	262 ± 38.07	.048*	.651	.007*
Central Forefoot	220.89 ± 32.63	207.54 ± 43.08	213.29 ± 35.27	218.83 ± 50.65	235.58 ± 51.56	238.67 ± 42.55	.621	.489	.054
Lateral Forefoot	202.64 ± 33.23	188.07 ± 41.14	200.38 ± 27.43	206.75 ± 38.9	217.46 ± 58.61	213.79 ± 58.79	.912	.512	.458
Great Toe	272.79 ± 65.43	260.48 ± 61.86	255.04 ± 61.92	250.96 ± 83.23	326.88 ± 102.49	331.75 ± 80.53	.090	.345	.009*
Lesser Toes	206.25 ± 42.35	204.75 ± 36.14	193.71 ± 37.35	186.71 ± 49.95	201.79 ± 47.95	217.54 ± 44.77	.494	.985	.038*

Table A3.23. Maximum force in each region of the foot within each group across time during step down

	Control			AudFB			Time Main Effect P Value	Group Main Effect P Value	Group x Time Interaction P Value
	Baseline	Immediate	1-week Post	Baseline	Immediate	1-week Post			
Total	209.26 ± 11.45	189.43 ± 18.34	193.97 ± 14.92	193.26 ± 34.62	199.69 ± 12.86	202.97 ± 11.07	.701	.862	.200
Medial Heel	38.1 ± 17.49	35.27 ± 29.49	33.73 ± 26.42	32.76 ± 13.11	26.79 ± 11.75	26.89 ± 7.32	.204	.531	.872
Lateral Heel	27.19 ± 11.06	23.76 ± 17.31	23.44 ± 17.75	25.23 ± 14.67	20.94 ± 11.19	20.41 ± 7.52	.180	.733	.974
Medial Midfoot	22.66 ± 8.88	18.51 ± 5.12	18.54 ± 8.04	22.55 ± 6.19	23.38 ± 4.61	25.38 ± 5.71	.425	.299	.032*
Lateral Midfoot	35.05 ± 5.51	31 ± 3.8	32.25 ± 5.99	30.79 ± 13.01	30.5 ± 6.58	31.66 ± 4.84	.584	.616	.593
Medial Forefoot	28.14 ± 5.21	27.31 ± 6.79	28.75 ± 5.92	23.55 ± 4.54	29.41 ± 4.08	29.86 ± 3.83	.021*	.866	.020*
Central Forefoot	28.17 ± 1.66	26.2 ± 4.32	28.43 ± 5	28.52 ± 6.93	31.61 ± 6	31.16 ± 5.46	.444	.317	.104
Lateral Forefoot	26.1 ± 3.09	23.83 ± 4.73	24.54 ± 6.38	25.01 ± 8.35	24.61 ± 3.64	24.78 ± 4.64	.651	.992	.776
Great Toe	20.74 ± 4.56	20.77 ± 4.44	21.06 ± 5.75	19.68 ± 6.38	25.41 ± 5.2	25.93 ± 7.38	.014*	.376	.022*
Lesser Toes	22.02 ± 3.62	21.62 ± 4.47	19.81 ± 5.65	19.08 ± 6.28	19.76 ± 4.69	20.76 ± 3.8	.934	.618	.213

Table A3.24. Pressure time integral in each region of the foot within each group across time during step down

	Control			AudFB			Time Main Effect	Group Main Effect	Group x Time Interaction
	Baseline	Immediate	1-week Post	Baseline	Immediate	1-week Post	P Value	P Value	P Value
Total	130.28 ± 24.81	120.98 ± 25.8	120.25 ± 22.33	119.74 ± 28.32	139.55 ± 32.34	136.64 ± 23.33	.540	.579	.010*
Medial Heel	25.88 ± 15.49	19.81 ± 12.42	21.45 ± 16.16	21.83 ± 7.1	15.16 ± 10.05	14.91 ± 7.86	.089	.419	.910
Lateral Heel	25.41 ± 13.69	18.24 ± 10.52	19.46 ± 14.24	20.04 ± 10.22	14.89 ± 11.05	20.39 ± 21.17	.350	.699	.743
Medial Midfoot	43.29 ± 14.93	39.02 ± 12.52	40.84 ± 18.01	36.37 ± 7.43	36.03 ± 13.79	32.98 ± 13.23	.790	.347	.847
Lateral Midfoot	52.98 ± 10.45	43.69 ± 4.93	46.94 ± 10.03	46.42 ± 19.13	38.9 ± 15.1	36.54 ± 11.97	.229	.104	.865
Medial Forefoot	104.86 ± 20.06	102.06 ± 29.15	100.62 ± 24.09	96.47 ± 29.04	108.39 ± 17.57	112.19 ± 13.43	.393	.800	.118
Central Forefoot	99.02 ± 17.7	93.26 ± 23.21	92.61 ± 19.6	97.03 ± 32.01	99.07 ± 19.89	102.72 ± 19.69	.794	.710	.327
Lateral Forefoot	89.49 ± 20.78	79.84 ± 18.93	81.99 ± 17.93	89.21 ± 30.05	86.87 ± 25.77	86.17 ± 23.24	.466	.767	.779
Great Toe	111.84 ± 29.67	107.15 ± 30.42	104.1 ± 30.26	96.89 ± 38.44	122.81 ± 37.49	128.3 ± 25.8	.084	.646	.005*
Lesser Toes	92.12 ± 25.53	89.03 ± 23.9	83.93 ± 23.54	85.21 ± 36.25	89.06 ± 18.71	97.41 ± 22.49	.834	.876	.130

Table A3.25. Force time integral in each region of the foot within each group across time during step down

	Control			AudFB			Time Main Effect	Group Main Effect	Group x Time Interaction
	Baseline	Immediate	1-week Post	Baseline	Immediate	1-week Post	P Value	P Value	P Value
Total	70.06 ± 7.23	62.24 ± 6.68	63.09 ± 4.67	65.57 ± 18.19	62.63 ± 7.05	62.98 ± 5.59	.275	.700	.755
Medial Heel	4.33 ± 2.43	3.43 ± 2.52	3.71 ± 2.91	3.63 ± 1.67	2.47 ± 1.54	2.34 ± 1.16	.105	.371	.810
Lateral Heel	3.19 ± 1.59	2.32 ± 1.52	2.57 ± 1.99	3.09 ± 2.37	2.1 ± 1.62	2.07 ± 1.5	.146	.761	.859
Medial Midfoot	3.31 ± 1.78	2.57 ± 1.63	2.95 ± 2.87	3.5 ± 1.2	2.46 ± 0.76	2.54 ± 0.75	.057	.901	.704
Lateral Midfoot	7.43 ± 2.23	5.75 ± 1.77	5.85 ± 2.95	7.7 ± 5.59	5.05 ± 2.87	4.82 ± 1.94	.093	.734	.729
Medial Forefoot	11.59 ± 2.43	11.31 ± 3.57	11.41 ± 2.47	9.57 ± 2.67	11.38 ± 1.6	12.09 ± 1.55	.184	.741	.104
Central Forefoot	12.17 ± 1.11	11.25 ± 2.14	11.6 ± 1.81	12.56 ± 4.17	12.83 ± 2.77	12.79 ± 1.75	.876	.418	.635
Lateral Forefoot	10.37 ± 2.21	8.92 ± 1.96	8.93 ± 1.91	9.79 ± 4.17	8.57 ± 2.12	8.08 ± 1.57	.163	.592	.916
Great Toe	8.14 ± 2.11	7.96 ± 2.3	8.03 ± 3	7.45 ± 3.18	9.53 ± 2.7	9.62 ± 3.05	.059	.597	.032
Lesser Toes	9.5 ± 2.65	8.7 ± 2.81	8.01 ± 3.46	8.24 ± 3.68	8.2 ± 1.83	8.59 ± 0.94	.517	.790	.303

TableA3.26. Peak pressure in each region of the foot within each group across time during lateral hop

	Control			AudFB			Time Main Effect P Value	Group Main Effect P Value	Group x Time Interaction P Value
	Baseline	Immediate	1-week Post	Baseline	Immediate	1-week Post			
Total	323.44 ± 70.89	331.24 ± 83.01	354.78 ± 68.17	345.45 ± 81.4	361.88 ± 76.95	388.26 ± 120.22	.054	.528	.867
Medial Heel	135.17 ± 31.58	118.54 ± 45.95	116.34 ± 46.15	118.45 ± 47.29	101.44 ± 56.55	109.3 ± 55.54	.134	.590	.734
Lateral Heel	128.29 ± 29.31	110.75 ± 41.18	107.78 ± 40.56	101.3 ± 53.74	99.79 ± 53.88	104.51 ± 41.91	.472	.541	.401
Medial Midfoot	152.38 ± 23.59	144.39 ± 23.33	153.43 ± 38.96	140.04 ± 34.57	146.4 ± 36.57	151.33 ± 46.23	.518	.818	.450
Lateral Midfoot	187.12 ± 16.39	172.46 ± 13.8	180.89 ± 31.47	139.13 ± 24.43	158.24 ± 18.43	153.25 ± 10.23	.915	<0.001*	.215
Medial Forefoot	271.88 ± 46.75	280.31 ± 57.82	302.92 ± 63.39	290.29 ± 100.76	307.51 ± 101.73	332.8 ± 141.79	.025*	.605	.894
Central Forefoot	242.48 ± 38.76	252.62 ± 44.16	265.53 ± 45.19	248.14 ± 52.52	278.04 ± 64.86	290.08 ± 59.48	.005	.496	.472
Lateral Forefoot	230.54 ± 36.23	233.36 ± 36.39	239.59 ± 59.84	207.89 ± 53.38	247.69 ± 55.63	244.68 ± 76.68	.117	.969	.283
Great Toe	284.64 ± 88.69	286.57 ± 106.89	307.12 ± 73.71	306.23 ± 65.38	309.81 ± 67.17	334.14 ± 59.72	.132	.577	.978
Lesser Toes	206.36 ± 56.68	217.53 ± 69.55	221.4 ± 65.39	217.52 ± 63.97	231.56 ± 69.61	257.87 ± 56.17	.041*	.552	.412

TableA3.27. Maximum force in each region of the foot within each group across time during lateral hop

	Control			AudFB			Time Main Effect P Value	Group Main Effect P Value	Group x Time Interaction P Value
	Baseline	Immediate	1-week Post	Baseline	Immediate	1-week Post			
Total	206.49 ± 13.27	197.48 ± 16.08	202.15 ± 20.59	198.52 ± 34.3	209.56 ± 20.27	219.26 ± 25.68	.352	.505	.113
Medial Heel	29.94 ± 6.96	24.13 ± 12.97	23.75 ± 12.86	24.02 ± 14.46	20.22 ± 13.53	21.63 ± 15.54	.122	.560	.650
Lateral Heel	23.37 ± 5.47	18.56 ± 9.73	17.77 ± 9.12	19.7 ± 13.46	18.7 ± 10.95	17.88 ± 10.31	.194	.826	.494
Medial Midfoot	20.8 ± 6.13	18.44 ± 6.92	19.1 ± 7.56	20.82 ± 4.94	19.75 ± 6.4	21.81 ± 6.34	.271	.697	.475
Lateral Midfoot	35.64 ± 4.07	30.42 ± 5.28	30.03 ± 4.06	29.12 ± 14.59	31.29 ± 11.19	31.45 ± 8.05	.606	.746	.071
Medial Forefoot	32.93 ± 7.33	32.74 ± 7.05	35.83 ± 9.64	30.58 ± 5.38	33.3 ± 4.85	35.02 ± 8.4	.063	.820	.625
Central Forefoot	32.46 ± 2.76	33.08 ± 5.66	33.66 ± 3.09	32.42 ± 5.04	37.66 ± 5.87	37.38 ± 5.04	.020*	.247	.120
Lateral Forefoot	30.17 ± 4.89	30.66 ± 5.22	30.1 ± 4.74	25.58 ± 5.73	30.06 ± 3.93	29.4 ± 4.49	.157	.405	.232
Great Toe	21.95 ± 4.28	22.15 ± 5.04	23.69 ± 2.52	25.28 ± 7.51	25.6 ± 5.99	26.41 ± 6.17	.336	.275	.928
Lesser Toes	19.9 ± 3.06	20.88 ± 7.44	20.33 ± 4.57	22.83 ± 6.1	23.64 ± 3.76	25.88 ± 4.1	.367	.157	.442

TableA3.28. Pressure time integral in each region of the foot within each group across time during lateral hop

	Control			AudFB			Time Main Effect	Group Main Effect	Group x Time Interaction
	Baseline	Immediate	1-week Post	Baseline	Immediate	1-week Post	P Value	P Value	P Value
Total	153.86 ± 64.97	133.55 ± 54.05	134.06 ± 30.58	118.42 ± 31.06	129.87 ± 66.32	132.39 ± 62.99	.910	.629	.208
Medial Heel	47.73 ± 31.54	36.56 ± 33.1	31.35 ± 28.55	33.71 ± 28.84	32.48 ± 49.57	32.4 ± 48.97	.268	.779	.361
Lateral Heel	47.35 ± 29.44	37.23 ± 32.65	30.73 ± 28.24	31.12 ± 26.85	31.95 ± 47.05	33.89 ± 42.65	.414	.746	.221
Medial Midfoot	64.25 ± 36.81	50.17 ± 27.48	48.17 ± 18.36	41.45 ± 13.57	43.41 ± 25.53	40.36 ± 30.08	.303	.369	.294
Lateral Midfoot	83.37 ± 40.94	69.13 ± 42.03	63.02 ± 22.55	47.33 ± 21.58	50.62 ± 31.9	47.78 ± 33.77	.410	.188	.329
Medial Forefoot	115.47 ± 47.44	103.05 ± 32.69	105.69 ± 24.04	93.79 ± 20.63	98.49 ± 30.28	103.69 ± 34.6	.733	.587	.275
Central Forefoot	109.94 ± 42.52	98.19 ± 31.36	98.22 ± 19.81	87.92 ± 24.84	91.53 ± 23.29	94.33 ± 24.71	.724	.472	.293
Lateral Forefoot	105.67 ± 39.16	93.89 ± 41.1	88.32 ± 22.7	77.07 ± 26.87	83.52 ± 28.84	81.06 ± 33.12	.673	.360	.325
Great Toe	115.44 ± 42.94	99.66 ± 35.36	100.88 ± 24.68	98.22 ± 32.48	102.17 ± 48.04	109.64 ± 47.44	.670	.924	.160
Lesser Toes	90.81 ± 33.81	84.54 ± 34.48	82.77 ± 28.84	75.24 ± 23.27	76.27 ± 23.98	80.74 ± 17.82	.831	.573	.306

TableA3.29. Force time integral in each region of the foot within each group across time during lateral hop

	Control			AudFB			Time Main Effect	Group Main Effect	Group x Time Interaction
	Baseline	Immediate	1-week Post	Baseline	Immediate	1-week Post	P Value	P Value	P Value
Total	94.02 ± 43.86	77.26 ± 38.22	71 ± 25.3	62.6 ± 17.63	54.58 ± 8	53.3 ± 5.83	.014	.126	.431
Medial Heel	8.88 ± 6.97	6.53 ± 6.66	5.43 ± 5.57	4.08 ± 3.44	1.67 ± 1.06	1.67 ± 1.4	.024	.108	.711
Lateral Heel	7.67 ± 5.74	5.96 ± 6.49	4.69 ± 5.24	3.85 ± 3.18	1.96 ± 1.00	1.75 ± 0.83	.021	.153	.737
Medial Midfoot	5.19 ± 2.26	3.59 ± 1.94	3.25 ± 1.64	3.7 ± 1.26	2.23 ± 0.63	2.19 ± 0.64	.002	.112	.753
Lateral Midfoot	14.41 ± 7.28	10.82 ± 7.06	8.96 ± 4.62	8.09 ± 4.79	5.83 ± 1.84	5.34 ± 1.29	.003	.081	.477
Medial Forefoot	13.57 ± 6.77	11.36 ± 4.46	11.69 ± 3.56	8.72 ± 1.1	9.14 ± 1.58	8.77 ± 1.63	.511	.110	.328
Central Forefoot	13.98 ± 5.19	12.25 ± 3.95	11.82 ± 1.91	11.31 ± 3.52	11.51 ± 2.51	10.84 ± 2.11	.234	.412	.361
Lateral Forefoot	13.35 ± 5.35	11.74 ± 5.73	10.51 ± 2.69	8.69 ± 3.26	8.42 ± 1.94	8.31 ± 2.66	.229	.109	.413
Great Toe	8.77 ± 3.38	7.56 ± 2.37	7.76 ± 1.82	6.93 ± 1.59	7.00 ± 2.00	6.95 ± 1.6	.351	.373	.302
Lesser Toes	8.13 ± 2.96	7.4 ± 3.14	6.86 ± 2.49	7.18 ± 1.98	6.78 ± 1.61	7.46 ± 1.44	.300	.802	.133

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Danielle Torp <dtorp@uncc.edu>

FW: [External] Fwd: Author Iss: Other/General Question

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To: Danielle Torp <dtorp@uncc.edu>

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