Impairment-based Rehabilitation and Gait Training for Chronic Ankle Instability

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A Dissertation

Presented to

The Faculty of the Curry School of Education

University of Virginia

In Partial Fulfillment

of the Requirement for the Degree

Doctor of Philosophy

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by

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August 2015

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APPROVAL OF THE DISSERTATION

This dissertation, "*Impairment-based Rehabilitation and Gait Training for Chronic Ankle Instability*", has been approved by the Graduate Faculty of the Curry School of Education in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

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Acknowledgements

I would like to thank the NATA Research and Education Foundation for the doctoral research grants that funded these projects.

First, I would like to thank my advisor Dr. Jay Hertel. Jay, I cannot express how much I have learned from you about research, mentoring, and life. The selflessness and humility that you display in both your professional and personal life has been truly inspiring and I hope to be able to exemplify similar qualities throughout my own personal and professional endeavors. I could not have gotten to where I am today without your tremendous guidance and I will never forget the things I have been fortunate enough to learn throughout my time working with you.

I would also like to thank my dissertation committee (Dr. Joseph Hart, Dr. Susan Saliba and Dr. Mark Abel). I sincerely appreciate all of your help and guidance over the last few years and throughout this dissertation process. You have each individually taught and inspired me on countless occasions and I will carry all that I have learned with me throughout medical school and my career in academic medicine.

Luke and Collin, there is no question that these projects would not have been completed without the tremendous teamwork and dedication from both of you. Our time collaborating and working together has only just begun and I look forward to continuing our professional collaborations and great friendships throughout our careers. I would like to also acknowledge all the amazing doctoral students I have been fortunate enough to share this experience with. The willingness to help and encourage others is truly an amazing dynamic that culminates individual and group success. I could not be more thankful for the opportunity to work with and learn from every one of you.

I would also like to thank my beautiful fiancé Hailey Love. Hailey, I could not have asked for more love and support than you provided throughout this process and in all aspects of life. You have been both a tremendous source of motivation and the prefect reminder of how amazing life truly can be when you have the right person to share it with.

Finally, I would like to thank all of my family and friends that have provided so much support over the last few years. The encouragement and support you have been able to provide from a distance will never be forgotten and I cannot thank you all enough!

ABSTRACT

Following a lateral ankle sprain, many patients develop chronic ankle instability (CAI). CAI is a heterogeneous condition that characterizes lateral ankle sprain patients who still have decreased self-reported function, recurrent sprains and feelings of instability for greater than one year following their initial sprain. CAI is a multi-faceted condition and thus researchers have developed a rehabilitation algorithm to aid in the assessment and treatment of the most common CAI impairments. Within the 'assess – treat – reassess' paradigm there are four broad areas that encompass the primary clinical manifestations CAI patients exhibit. These impairment domains include deficits in range of motion, strength, postural control, and altered biomechanics during functional tasks such as walking, running, or landing from a jump. Range of motion deficits are related to arthro- or osteokinematic restrictions and joint mobilization or calf stretching are highly efficacious at restoring normal range of motion in CAI patients. Strength deficits with CAI are associated with smaller shank muscle volumes and rehabilitation is effective at improving muscle strength. However, there is currently no evidence to suggest whether improved ankle strength with rehabilitation is related to muscle hypertrophy. Therefore we aimed to analyze the effects of impairment-based rehabilitation on muscle strength and foot and ankle muscle volumes in CAI patients as part of this dissertation (Study 2).

Furthermore, it has been theorized that targeting the less functional impairments of range of motion, strength, and postural control might be a sufficient approach to rehabilitation and that gains in those impairment domains may translate into improved gait and jump landing mechanics in CAI patients. We previously demonstrated that those

less functional improvements do not translate into improved gait patterns and as part of this dissertation we aimed to assess whether impairment-based rehabilitation could improve jump-landing mechanics in CAI patients (Study 1). Lastly, since impairment-based rehabilitation is insufficient at restoring normal gait mechanics, our final aim was to analyze the effects of gait training with a novel gait training device on measures of plantar pressure and surface electromyography in CAI patients (Study 3).

Following impairment-based rehabilitation, CAI patients demonstrated large and meaningful improvements in shank muscle volumes and four-way ankle strength. Unfortunately, we only identified minimal improvements in landing biomechanics and none of the improvements were prior to or during ground contact, which have been shown to be very important factors that will dictate whether or not an ankle sprain occurs. The CAI patients who received gait retraining demonstrated large and meaningful improvements in the location of their center of pressure during the stance phase of gait due to increased peroneus longus muscle activity during midstance. Furthermore, comprehensive impairment-based rehabilitation and gait training alone were both able to substantially improve self-reported outcomes for CAI patients. Based on these collective results, we recommend supplementing impairment-based rehabilitation with gait training to maximize improvements in self-reported function. Furthermore, we recommend future research analyze the effect of augmented biofeedback on jump-landing strategies in CAI patients as the improvements in range of motion, strength, and postural control seen in these same CAI patients did not manifest into meaningful improvements in landing strategies post-rehabilitation.

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SECTION II: MANUSCRIPT I

EFFECTS OF 4-WEEK IMPAIRMENT-BASED REHABILITATION ON JUMP LANDING BIOMECHANICS IN CHRONIC ANKLE INSTABILITY PATIENTS

ABSTRACT

Context: Chronic ankle instability (CAI) patients demonstrate an inverted and plantar flexed foot position when landing that may predispose them to recurrent sprain. **Objective:** To determine if 4-weeks of progressive impairment-based rehabilitation could improve lower extremity frontal and sagittal plane kinematics and kinetics and surface electromyography (sEMG) amplitudes of shank muscles during bilateral jump-landing. **Design:** Descriptive laboratory study. **Setting**: Laboratory. **Patients or Other Participants:** Twenty-six CAI subjects (age=21.4±3.1 sex=(M=7,F=19), height=169.0±8.8cm, weight=71.0±13.8kg) participated. **Interventions:** CAI subjects completed 15 baseline jump-landing trials. Subjects then completed 12 supervised rehabilitation sessions for range of motion, strength, balance and functional exercises with a certified athletic trainer. Subjects then completed 15 post-rehabilitation jump-landing trials. **Main Outcome Measures:** Dependent variables were frontal and sagittal ankle, knee, and hip kinematics and kinetics and sEMG amplitudes of the anterior tibialis, peroneus brevis, peroneus longus, and medial gastrocnemius. For each measure, means and 90% confidence intervals (CIs) were calculated for 100ms prior to and 200ms following ground contact. Areas where pre- and post-rehabilitation CIs did not overlap were considered significantly different. Frontal and sagittal kinematic and kinetic peaks and total kinematic excursion were compared with paired t-test with a level of significance set *a priori* at $P \leq 0.05$. **Results:** Following rehabilitation, CAI subjects exhibited less frontal plane excursion at the ankle (2.1° (0.8, 3.4), P=.003) and hip (2.0° (0.5, 3.7), P=.013) and lower peak hip abduction (2.5° (0.0, 5.0), P=.050). There was also less sagittal plane excursion at the ankle (5.0° (1.7, 8.3), P=.005) and knee (3.4° (0.8, 6.0), P=.013) following rehabilitation. There was a decrease in peroneus longus activity from 9ms-135ms post ground contact and a decreased peak plantar flexion moment (0.08N*m/kg (0.01, 0.13), P=.021) following rehabilitation. There were no other significant changes following rehabilitation for kinematics, kinetics, or sEMG amplitudes. **Conclusion:** Progressive impairment-based rehabilitation resulted in moderate reductions in frontal and sagittal plane kinematic excursion and peroneus longus muscle activity, suggesting a more efficient landing strategy. The lack of significant changes prior to or at ground contact may suggest other methods of jump-landing training such as augmented biofeedback may need to be implemented to effectively improve landing biomechanics in CAI patients for injury prevention.
Word Count: 355

Key Words: ankle sprain, kinematics, surface electromyography, therapeutic exercise

INTRODUCTION:

Ankle sprains are the most common musculoskeletal pathology and present a large financial and healthcare burden.[1-5] Chronic ankle instability (CAI) is a condition that develops in up to 40% of all individuals who sustain an acute lateral ankle sprain.[6] CAI patients are characterized by having a history of at least one significant ankle sprain and residual symptoms of decreased self-reported function, 'giving way', and recurrent sprains that persist for greater than one year following the initial sprain.[7] Individuals with a history of ankle sprain and CAI may develop early onset osteoarthritis,[8] become less physically active,[9] and have lower general health when compared to individuals with upper extremity injuries.[10]

Many initial and recurrent sprains occur during functional activities such as running, cutting, jumping, and landing.[3] A commonality amongst these activities is that each requires ankle stabilization when transitioning from an aerial or flight phase to ground contact or stance phase. To effectively complete this transition without sustaining an ankle sprain, individuals must have appropriate foot and ankle alignment prior to landing and adequate pre-initial contact muscle activity to control joint motion during the dissipation of the ensuing ground reaction forces.[11-13]

In order to understand the motor control strategies that predispose CAI patients to recurrent sprain, many researchers have analyzed jump-landing strategies in CAI patients and in individuals with no history of ankle sprains.[14-17] CAI patients are more inverted prior to landing and more plantar flexed following landing.[16] Increased inversion positioning prior to landing may predispose the ankle to inversion injury and the plantar flexed position may prevent CAI patients from achieving the more stable closed packed ankle position following landing.[16] Delahunt et al.[16] also identified decreased preparatory muscle activity in the peroneus longus, which may contribute to the inverted foot position identified during the same phase of landing. These deficits are likely related to the increased vertical ground reaction forces (vGRF)[18] and increased time to stabilization also seen with CAI during jump-landing tasks.[17]

There is clear evidence of altered motor control strategies with CAI during jump-landing that may contribute to recurrent sprain, however, the ability of rehabilitation to improve these motor control strategies has not been thoroughly investigated. Rehabilitation protocols have been shown to improve range of motion,[19-21] strength,[22,23] and postural control[24] deficits in CAI patients, and these physiologic parameters are required to safely land from a jump. However, it is important to investigate jump-landing biomechanics following rehabilitation to determine if improvements in range of motion, strength, and postural control are effectively integrated into non-pathological jump-landing strategies. Therefore, the purpose of this study was to analyze the effects of a 4-week progressive impairment-based rehabilitation protocol on lower extremity kinematics and kinetics and surface electromyography (sEMG) during a drop jump-landing task in CAI patients.

METHODS:

Study Design

We performed a descriptive laboratory study to analyze the effects of 4 weeks of supervised progressive impairment-based rehabilitation on frontal and sagittal plane ankle, knee, and hip kinematics and kinetics and sEMG activity (anterior tibialis, peroneus brevis, peroneus longus, and medial gastrocnemius) during a jump-landing task in young adults with CAI. These methods have previously been reported in detail in a previous study,[25] with the same subjects, in which we report the effects of the rehabilitation program on subjective function, strength, balance, and associated sEMG measures.[25] The methods were approved by the University's institutional review board and all subjects provided informed consent prior to participation.

Participants

Twenty-six young adults with CAI volunteered to participate in this study (Table 1). Inclusion criteria for CAI subjects was a history of more than one significant ankle sprain with the initial sprain occurring greater than one year prior to study onset, current self reported functional deficits due to ankle symptoms that was quantified by a score of <85% on the Foot and Ankle Ability Measure (FAAM) Sport scale and a score of ≥10 on the Identification of Functional Ankle Instability scale (IdFAI). Subjects were excluded if they had a history of ankle fracture, ankle surgery, an ankle sprain within 6 weeks of study onset, or any other current lower extremity pathology. Subjects were also required to be physically active (20 minutes/day at least 3 days/week) and could not have a history of neurological or vestibular disorders.

Instruments

Three Dimensional Motion Capture System

Three-dimensional joint kinematics of the ankle, knee, and hip were measured using the *TrackSTAR* (Ascension Technologies, Inc., Burlington, Vermont) electromagnetic motion analysis system and Motion Monitor software (Version 8, Innovative Sports Training, Inc., Chicago, Illinois) at a sampling rate of 144 Hz. A non-conductive force plate (Bertec Corporation, Columbus, Ohio) with a sampling rate of 1440 Hz was used to collect ground reaction forces and for determination of initial contact of the involved limb during the jump-landing task.

Surface Electromyography

Surface EMG was collected using 2 parallel bar rectangular sensors. Each bar was 1 mm wide and 1 cm long with an inter-electrode distance of 1 cm. The sensors were DE 2.1 differential EMG sensors (Delsys, Boston, MA). The signal was amplified with a gain of 1000 and digitized with a 4 channel acquisition system (Bagnoli EMG system, Delsys, Boston, MA) at 1000 Hz. Input impedance was $>10^{15}\Omega/0.2pF$ with a signal to noise ratio of 1.2uV. Data was collected with Motion Monitor software (Innovative Sports Training, Inc., Chicago, Illinois).

Procedures

Subjects completed a general health history questionnaire, Godin Leisure-Time Exercise Questionnaire, [26] FAAM Activities of Daily Living [27] and Sport scale, [28] and the IdFAI questionnaire. [29] Next, surface electrodes were placed over the midline of each muscle belly that was determined via manual palpation during a voluntary contraction. To minimize skin impedance, the skin was shaved, abraded, and then cleansed with isopropyl alcohol. Proper sensor placement was visually inspected for crosstalk by having subjects perform voluntary contractions against manual resistance.

Next, 10 electromagnetic sensors were placed bilaterally on the subjects' posterior calcaneus, dorsal aspect of the first metatarsal, lateral mid-shank and lateral mid-thigh. The final 2 sensors were placed on the base of the sacrum and the 4th thoracic vertebrae. All sensors were secured with double-sided tape, Leuokotape and elastic wraps to minimize movement during the jump-landing task. All sensors were placed directly on the skin with the exception of the dorsal aspect of the first metatarsal, which was secured to the outer surface of the standardized lab shoes (Brooks Defyance 3, Brooks Sports Inc., Seattle, WA). For the sensor on the calcaneus, a hole was cut from the shoe to ensure the sensor accurately captured calcaneal motion, however we worked with the manufacturer to ensure that this hole would not compromise the shoe integrity. An 11th moveable sensor was attached to a stylus and used to for digitization of each joint. Digitization of the segments and joints were completed by pointing out proximal and distal longitudinal and horizontal landmarks. Specific anatomic landmarks included the 7th cervical vertebrae, 12th thoracic vertebrae, 5th lumbar vertebrae, and bilateral landmarks of the anterior superior iliac spines, medial and lateral knee joint lines, medial and lateral malleoli, and the tip of the 2nd toes.

Jump-landing Task

Subjects performed double limb jump-landing from a 30cm tall box that was positioned half of their height away from the center of the force plate. Subjects were instructed to jump forward toward the force plate and to minimize vertical displacement when leaving the box. The box was positioned so that the involved limb would land on the center of the force plate and the uninvolved limb would not contact the force plate.

Upon ground contact, subjects were instructed to land as normal as possible and transition into a maximal vertical jump. A target was provided directly above the force plate to ensure the subjects' maximal vertical jump had minimal forward or lateral trajectory. The initial landing, prior to the maximal vertical jump, was utilized for analysis. Subjects performed as many practice trials as needed to ensure proper form and data was not collected until subjects self-reported they were comfortable with the task, and the assessor verified the subject was performing the task correctly. No subject required more than 5 practice trials. A total of 15 jump-landing trials were collected and utilized for analysis. Each trial was monitored to ensure proper form, as previously described and subjects were given adequate rest between each trial while the assessor visually inspected the previously collected trial. After the 15 trials, subjects were informed to return to the lab 2 days later for the first rehabilitation session. Subjects completed 12 supervised rehabilitation sessions and then returned to the lab for post-rehabilitation jump-landing trials 2 to 7 days following the 12th rehabilitation visit.

Rehabilitation Program

All rehabilitation was supervised and progressed by a certified athletic trainer as previously described in detail.[25] Briefly, the rehabilitation program consisted of exercises to improve ankle range of motion, strength, balance, and functional activity performance. Each session was approximately 1 hour in duration and the athletic trainer used clinical judgment for the initial intensity of each exercise as well as when to progress each subject based on our pre-established progression criteria.[25] The rehabilitation program was designed to continuously challenge each subject from rehab day 1 until rehab day 12 for all impairment domains presented by Donovan and Hertel [30] for the rehabilitation of CAI patients.

Data Reduction

All analyses were performed for the 100ms immediately prior to and 200ms following initial contact on the force plate. Initial contact was defined as the time at which the vertical ground reaction force vector exceeded 20N. Using the Motion Monitor software, the 300ms epoch (100ms pre through 200 ms post) for the 15 jump-landing trials was re-sampled to 100 frames so that each frame represents one percent of the 300ms epoch. This was completed for all ankle, knee, and hip kinematics and kinetics and for the sEMG activity of the anterior tibialis, peroneus brevis, peroneus longus, and medial gastrocnemius.

Ankle, Knee and Hip Kinematics and Kinetics

The kinematic data were filtered with a low-pass 4^{th}-order, Butterworth filter at a cut-off frequency of 14.5 Hz. Joint rotations for the ankle, knee, and hip were calculated using the Euler rotation method (Y, X, Z) and are presented as flexion/extension, adduction/abduction, and internal/external rotation, respectively. . Vertical ground reaction force was normalized to each subject's body mass (N/kg) and internal joint moments were normalized to the subject's height and mass (N*m/kg).

Surface Electromyography Amplitudes

Data was filtered using a 10-500 band-pass filter and smoothed using a 50-sample moving window root mean square (RMS) algorithm. Jump-landing muscle activity was normalized to the corresponding mean muscle activity during quiet standing.

Statistical Analysis

Confidence Interval Analysis

For ankle, knee, and hip frontal and sagittal plane kinematics and kinetics and for normalized sEMG activity we calculated group means and associated 90% confidence intervals (CIs) across all 100 points of the jump-landing task. A time series CI analysis was performed to determine any increments where the CIs did not overlap between the two groups (pre and post rehabilitation). If CIs did not overlap for at least 3 consecutive data points, those increments were considered statistically significant.

Discrete Analysis

We also extracted discrete ankle, knee, and hip kinematic and kinetic peaks (maximum and minimums) and calculated ankle, knee, and hip total kinematic excursion (difference between peaks in frontal or sagittal planes) during the 300ms epoch. Discrete variables were compared pre to post rehabilitation using paired t-tests. The level of significance was set *a priori* at $P \leq 0.05$ for all discrete analyses and per contemporary statistical recommendations we chose not to control for multiple comparisons.[31] In addition to inferential statistics, Cohen's *d* effect sizes and associated 95% confidence intervals were calculated to estimate the magnitude and precision of treatment effect post-rehabilitation. Effect sizes were interpreted as ≥0.80 large, 0.50-0.79 moderate, 0.20-0.49 small, and <0.20 trivial.[32] Data was analyzed using Statistical Package for Social Sciences (SPSS) Version 20.0 (SPSS, Inc, Chicago, IL).

RESULTS:

Frontal Plane Kinematics and Kinetics

There were no significant changes in frontal plane kinematics or kinetics in our time series CI analysis following rehabilitation during the jump-landing task (Figure 1). Discrete analysis revealed a significant, albeit small (Mean Difference (95% CI) = 2.1° (0.8, 3.4) P=.003), reduction in ankle frontal plane kinematic excursion following the rehabilitation program (Table 2). There was also a moderate reduction in peak hip abduction (Mean Difference (95% CI) = 2.5° (0.0, 5.0), P=.050) and hip frontal plane kinematic excursion (Mean Difference (95% CI) = 2.0° (0.5, 3.7), P=.013) post-rehabilitation (Table 4). There were no significant changes in peak frontal plane moments following rehabilitation (Tables 2-4). There were no other significant discrete frontal plane kinematic or kinetic changes following rehabilitation.

Sagittal Plane Kinematics and Kinetics

There were no significant changes in sagittal plane kinematics or kinetics in our time series CI analysis following the rehabilitation program (Figure 2). Rehabilitation did result in small reductions in total ankle (Mean Difference (95% CI) = 5.0° (1.7, 8.3), P=.005) and knee (Mean Difference (95% CI) = 3.4° (0.8, 6.0), P=.013) sagittal plane kinematic excursion (Tables 2 & 3). There was also a small reduction in the peak plantar flexion moment following rehabilitation (Mean Difference (95% CI) = 0.08N*m/kg (0.01, 0.13), P=.021, Table 2). There were no other discrete sagittal plane kinematic or kinetic changes following rehabilitation.

Surface EMG Amplitudes

There was a significant reduction in normalized peroneus longus muscle activity 9ms post-IC to 135ms post-IC during the jump-landing task after subjects completed rehabilitation (Figure 3). There were no other significant changes in sEMG amplitudes following rehabilitation.

Vertical Ground Reaction Force

There were no significant changes in the vGRF time series CI analysis (Figure 4) or for peak vGRF following rehabilitation (Mean Difference (95% CI) = -0.4N/kg (-1.0, 0.2), P = .175). The effect size for the peak vGRF was -0.11 with a CI crossing zero, suggesting no meaningful treatment effect.

DISCUSSION:

Four weeks of progressive impairment-based rehabilitation resulted in small to moderate reductions in frontal plane excursion at the ankle and hip and peak hip abduction, as well as sagittal plane excursion at the ankle and knee during bilateral jump-landing in CAI patients. There was a concurrent reduction in normalized peroneus longus muscle activity and peak plantar flexion moment following ground contact, but no other meaningful reductions in sEMG amplitudes or frontal or sagittal plane kinematics or kinetics as indicated by our time series CI analyses. Our results were similar to a case report [33] which demonstrated 6 weeks of comprehensive rehabilitation decreased the amount of plantarflexion during landing in a single subject with ankle instability. However, to our knowledge, this is the first study to analyze the effects of a comprehensive rehabilitation program on jump-landing biomechanics and sEMG amplitudes in a group of CAI patients.

Previous rehabilitation studies for CAI have analyzed the effects of rehabilitation on range of motion, [19-21] strength, [22,23] balance, [24] and self-reported function [24,25] are effective at increasing ankle dorsiflexion motion, invertor and evertor strength, postural control, and patient reported outcomes. As reported previously,[25] the CAI patients in the current study also exhibited improvements in all three of these impairment domains as well as the largest documented improvements in self-reported function following a rehabilitation program for CAI patients. However, the current results suggest that improved range of motion, strength, and postural control that these patients exhibited only translated into small to moderate reductions in total joint excursion at the ankle, knee, and hip during jump landing. Previous studies have suggested that improper (inverted/plantar flexed) foot and ankle alignment at ground contact[12,13] and inadequate preparatory muscle activity[11,16] are predisposing factors for recurrent ankle sprain. Unfortunately, we did not identify any meaningful improvements in joint position or sEMG amplitudes prior to or at ground contact following rehabilitation.

It is important to note, however, that post-initial contact muscle activity is dependent upon how well the preparatory muscle activity was able to control and decelerate the rapid joint movements utilized to dissipate the ground reaction forces during landing.[11] In the current study, the vGRF did not change following rehabilitation, but CAI patients were able to reduce the total frontal plane excursion at the ankle with less peroneus longus muscle activity. This finding, coupled with the other reductions in total joint excursion in the frontal and sagittal planes and the reduced peak plantar flexion moment may suggest that the improved strength or balance seen in these same patients[25] translates into a more efficient landing strategy. A more efficient landing strategy may better equip CAI patients to tolerate or cope with the injurious foot position during landing.

Our speculation is in line with the results presented by Janssen et al.,[34] which demonstrated that 8 weeks of home-based neuromuscular training is only half as effective at preventing injury when compared to patients that wore ankle braces. It is not surprising that ankle braces, which have been shown to improve foot and ankle position prior to landing[12,35,36] are more effective at injury prevention than current methods of rehabilitation, which we have now shown have little effect of foot positioning prior to landing. While our rehabilitation program was quite comprehensive when compared to other rehabilitation protocols utilized for CAI in research settings,[22-24,37] we did not utilize any form of specific biofeedback or jump-landing instruction during the 12 rehabilitation sessions.

Healthy participants, when instructed to land in a manner that would decrease the sound of impact or when instructed to land softly, have been able to reduce the vGRF after training.[38-40] In the aforementioned treatment algorithm for CAI,[30] the fourth and final impairment domain includes functional exercises such as jump-landing and the authors suggest that specific impairments should be identified and then treated with targeted interventions. We assert that clinical methods to assess poor landing biomechanics with CAI be identified and that rehabilitation programs begin to implement biofeedback or landing instruction in the latter phases of rehabilitation when range of motion, strength, and balance have been adequately restored in an attempt to translate these physiological improvements into safer landing strategies. Furthermore, it is possible that 12 sessions of rehabilitation was adequate for range of motion, strength and postural control improvements, but perhaps more sessions are required for improvements in jump-landing biomechanics or it may take longer for the sensorimotor system to re-organize and develop new movement patterns during landing.

Limitations

This study is not without limitations. First, a bilateral jump-landing is not as demanding on an unstable ankle as a single limb landing task may have been and it is possible the effects of rehabilitation may have been more apparent with a single limb landing task. Another limitation is the short follow-up period following rehabilitation, and thus we cannot identify if the small to moderate improvements in jump-landing efficiency translate into longstanding ankle sprain prevention during sport. Lastly, it is more difficult to identify improvements in a group of patients that may not all exhibit poor landing strategies at baseline, which underscores the importance of future research identifying methods of screening for injurious movement patterns during functional activities so that meaningful improvements can be documented following rehabilitation for functional pathomechanics with CAI.

CONCLUSION:

Four weeks of progressive impairment-based rehabilitation for CAI that addressed range of motion, strength, postural control, and functional rehabilitation resulted in small to moderate improvements in total frontal and sagittal plane kinematic excursion at the ankle, knee, and hip during bilateral jump-landing. Frontal plane ankle stability was achieved with less peroneus longus muscle activity following ground contact, which may indicate more efficient landing strategies following rehabilitation. Clinicians should be aware of the lack of substantial improvements in joint positioning or muscle activity prior to or at ground contact during jump-landing after completing 12 comprehensive supervised rehabilitation sessions in CAI patients.

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TABLES:

Table 1.1: Subject Demographics (n=26)

	Mean (SD)
Age (years)	21.4 (3.1)
Sex	Male: 7, Female: 18
Height (centimeters)	169.0 (8.8)
Mass (kilograms)	71.0 (13.8)
Godin Leisure-Time Exercise Questionnaire Score	69.3 (26.9)
FAAM ADL %	86.4 (7.3)
FAAM Sport %	66.0 (15.5)
idFAI	23.0 (3.8)
Number of Ankle Sprains	4.7 (4.1)
Time Since Last Sprain (months)	16.6 (18.1)

FAAM = Foot and Ankle Ability Measure
ADL = Activities of Daily Living
IdFAI = Identification of Functional Ankle Instability

Table 1.2: Paired t-test statistical results, effect sizes and associated 95% confidence intervals for discrete ankle kinematic (degrees) and kinetic (N*m/kg) variables pre and post rehabilitation

	Pre-Rehab Mean (SD)	Post-Rehab Mean (SD)	Mean Difference (95% CI)	P-value	Effect Size (95% CI)
Ankle Kinematics					
Peak Plantarflexion	43.6 (8.6)	40.1 (10.9)	3.5 (0.1, 7.1)	.059	0.32 (-0.24, 0.88)
Peak Dorsiflexion	11.8 (5.8)	10.3 (5.5)	1.5 (-0.5, 3.5)	.139	0.27 (-0.28, 0.83)
Ankle Sagittal Excursion	55.4 (7.6)	50.4 (10.0)	5.0 (1.7, 8.3)	.005*	0.49 (-0.07, 1.05)
Peak Inversion	12.6 (6.3)	10.9 (6.5)	1.7 (-0.1, 3.5)	.068	0.26 (-0.30, 0.82)
Peak Eversion	2.4 (3.9)	2.0 (3.8)	0.4 (-0.7, 1.5)	.483	0.08 (-0.48, 0.63)
Ankle Frontal Excursion	14.9 (6.3)	12.8 (6.0)	2.1 (0.8, 3.4)	.003*	0.35 (-0.21, 0.91)
Ankle Internal Moments					
Peak Plantarflexion	1.03 (0.31)	0.95 (0.27)	0.08 (0.01, 0.13)	.021*	0.30 (-0.27, 0.84)
Peak Dorsiflexion	0.03 (0.02)	0.03 (0.04)	-0.01 (-0.02, 0.01)	.469	0.00 (-0.55, 0.55)
Peak Inversion	0.06 (0.05)	0.10 (0.10)	-0.04 (-0.09, 0.01)	.056	-0.50 (-1.06, 0.06)
Peak Eversion	0.16 (0.16)	0.11 (0.12)	0.05 (-0.01, 0.11)	.101	0.42 (-0.14, 0.98)

* = significant difference between pre- and post-rehabilitation kinematics or kinetics at $P \leq 0.05$

Abbreviations: N=Newton, m=Meter, kg=Kilogram, SD=Standard Deviation, CI=Confidence Interval

Table 1.3: Paired t-test statistical results, effect sizes and associated 95% confidence intervals for discrete knee kinematic (degrees) and kinetic (N*m/kg) variables pre and post rehabilitation

	Pre-Rehab Mean (SD)	Post-Rehab Mean (SD)	Mean Difference (95% CI)	P-value	Effect Size (95% CI)
Knee Kinematics					
Peak (Max) Flexion	80.4 (11.2)	77.1 (11.6)	3.3 (-0.4, 7.0)	.075	0.28 (-0.27, 0.84)
Peak (Min) Flexion	4.9 (7.5)	5.0 (7.8)	-0.1 (-3.3, 3.1)	.958	-0.01 (-0.57, 0.54)
Knee Sagittal Excursion	75.5 (12.3)	72.1 (12.0)	3.4 (0.8, 6.0)	.013*	0.28 (-0.27, 0.84)
Peak Adduction	5.5 (7.7)	3.8 (5.7)	1.7 (-1.4, 4.5)	.267	0.30 (-0.26, 0.86)
Peak Abduction	7.3 (7.3)	6.8 (6.9)	0.5 (-3.2, 4.2)	.793	0.07 (-0.48, 0.63)
Knee Frontal Excursion	12.8 (5.8)	10.6 (3.2)	2.2 (-0.6, 4.9)	.115	0.69 (0.12, 1.26)
Knee Internal Moments					
Peak Flexion	0.27 (0.17)	0.34 (0.15)	-0.07 (-0.15, 0.02)	.119	-0.47 (-1.03, 0.10)
Peak Extension	1.73 (0.37)	1.83 (0.36)	-0.10 (-0.21, 0.02)	.088	-0.25 (-0.81, 0.31)
Peak Adduction	0.34 (0.21)	0.34 (0.19)	0.00 (-0.09, 0.09)	.968	0.00 (-0.55, 0.55)
Peak Abduction	0.22 (0.25)	0.23 (0.21)	-0.01 (-0.12, 0.10)	.849	-0.05 (-0.60,0.51)

* = significant difference between pre- and post-rehabilitation kinematics or kinetics at $P \leq 0.05$

Abbreviations: N=Newton, m=Meter, kg=Kilogram, SD=Standard Deviation, CI=Confidence Interval

Table 1.4: Paired t-test statistical results, effect sizes and associated 95% confidence intervals for discrete hip kinematic (degrees) and kinetic (N*m/kg) variables pre and post rehabilitation

	Pre-Rehab Mean (SD)	**Post-Rehab Mean (SD)**	**Mean Difference (95% CI)**	**P-value**	**Effect Size (95% CI)**
Hip Kinematics					
Peak (Max) Flexion	78.2 (18.2)	73.3 (19.1)	4.9 (-0.5, 10.3)	.074	0.26 (-0.30, 0.81)
Peak (Min) Flexion	25.8 (16.7)	20.0 (11.5)	5.8 (-0.1, 11.6)	.054	0.50 (-0.06, 1.07)
Hip Sagittal Excursion	52.4 (17.0)	53.2 (16.9)	-0.9 (-5.4, 3.7)	.697	-0.05 (-0.60, 0.51)
Peak Adduction	2.6 (5.3)	2.2 (4.9)	0.4 (-1.9, 2.6)	.723	0.08 (-0.47, 0.64)
Peak Abduction	12.2 (6.2)	9.7 (4.6)	2.5 (0.0, 5.0)	.050*	0.54 (-0.02, 1.11)
Hip Frontal Excursion	9.5 (4.5)	7.5 (3.3)	2.0 (0.5, 3.7)	.013*	0.61 (0.04, 1.17)
Hip Internal Moments					
Peak Flexion	1.03 (0.38)	1.00 (0.34)	0.03 (-0.16, 0.22)	.761	0.12 (-0.44, 0.67)
Peak Extension	1.43 (0.44)	1.45 (0.45)	-0.02 (-0.21, 0.18)	.878	-0.04 (-0.60, 0.51)
Peak Adduction	0.40 (0.36)	0.39 (0.24)	-0.01 (-0.17, 0.13)	.837	0.04 (-0.51, 0.60)
Peak Abduction	0.50 (0.41)	0.54 (0.33)	-0.40 (-0.99, 0.19)	.518	-0.15 (-0.71, 0.40)

* = significant difference between pre- and post-rehabilitation kinematics or kinetics at $P \leq 0.05$

Abbreviations: N=Newton, m=Meter, kg=Kilogram, SD=Standard Deviation, CI=Confidence Interval

FIGURES:

Figure 1.1: Time series 90% confidence interval analysis for frontal plane joint kinematics and kinetics pre and post rehabilitation

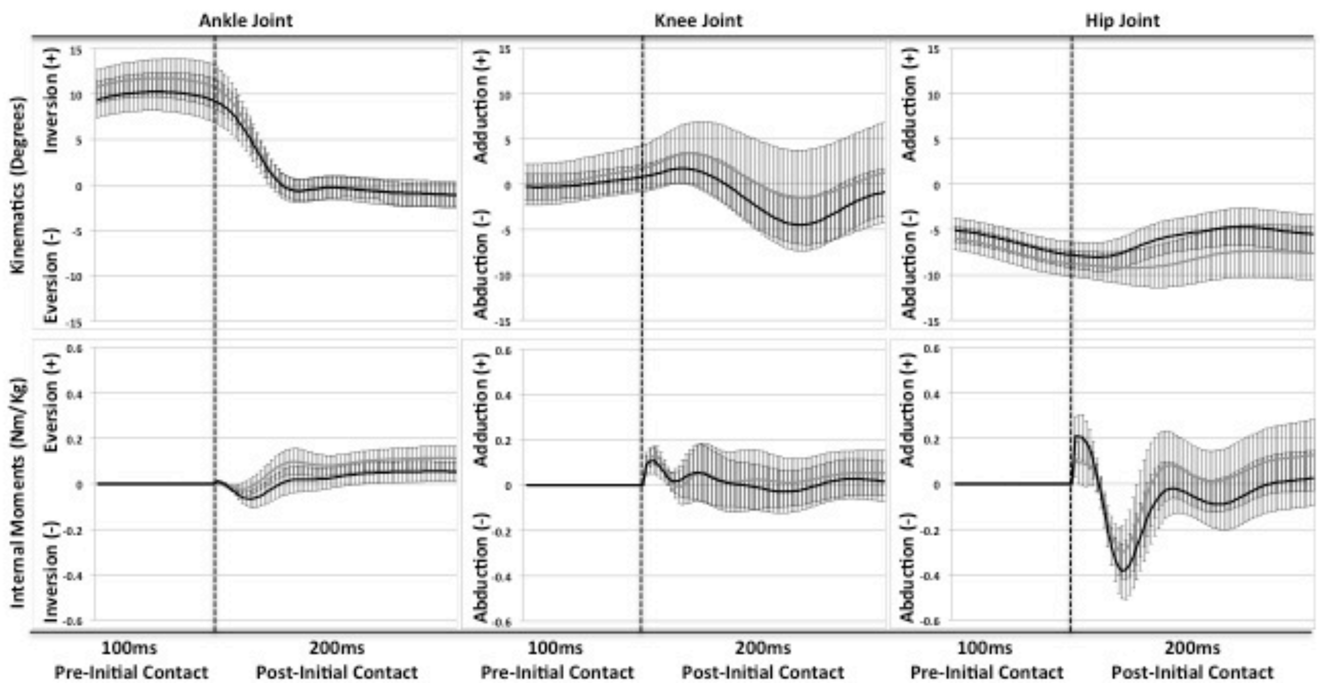


Figure 1.2: Time series 90% confidence interval analysis for sagittal plane joint kinematics and kinetics pre and post rehabilitation

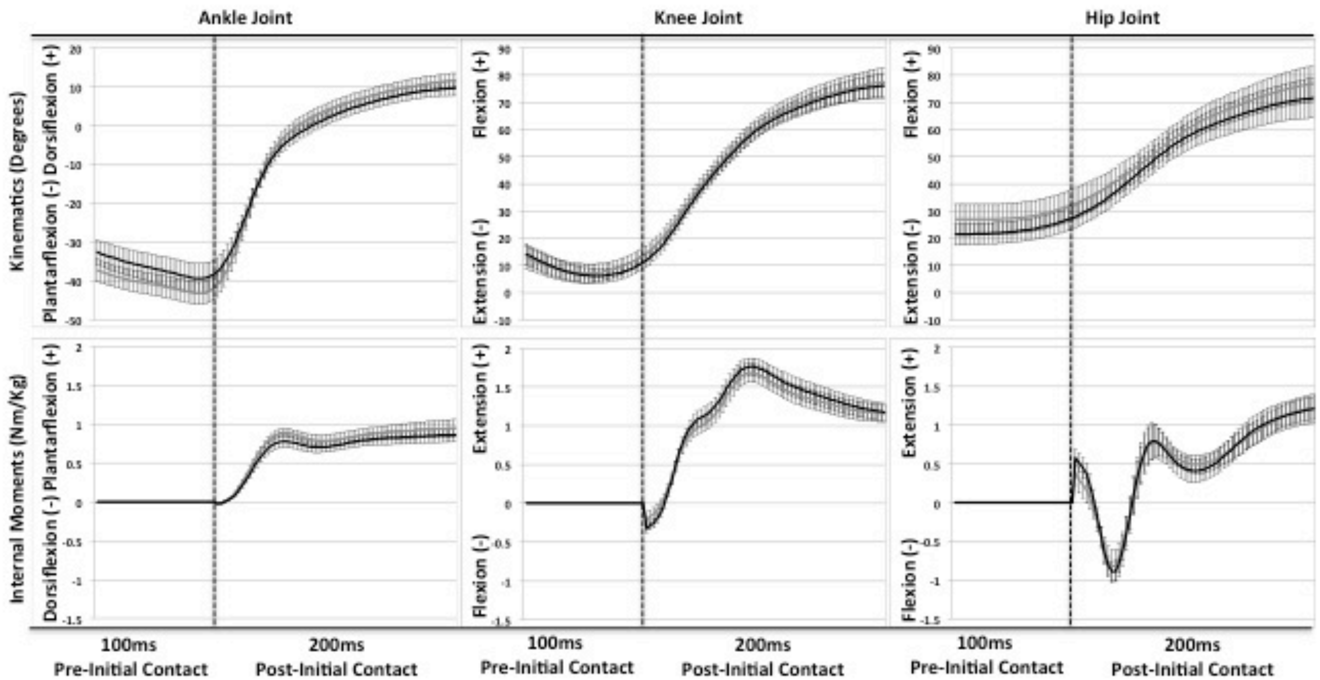
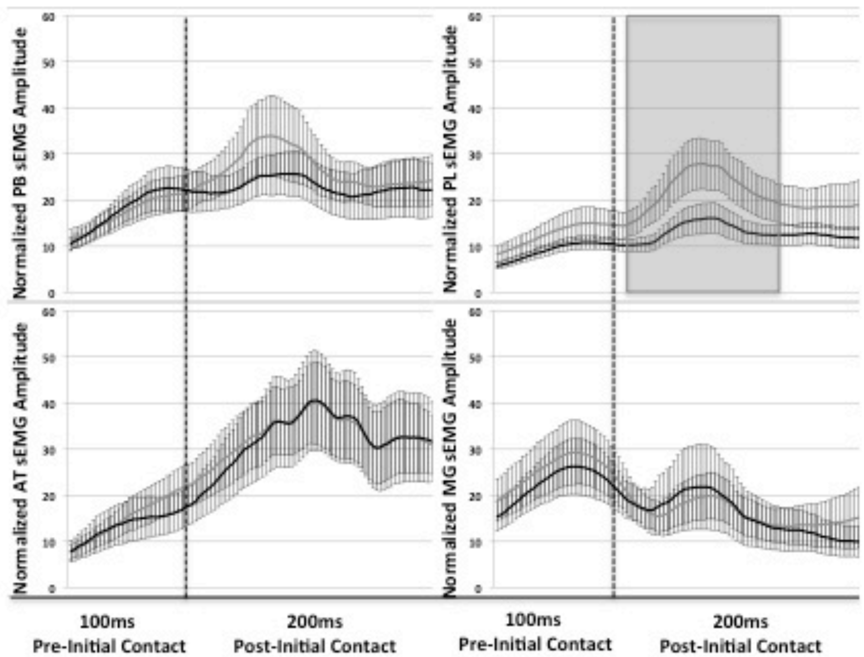
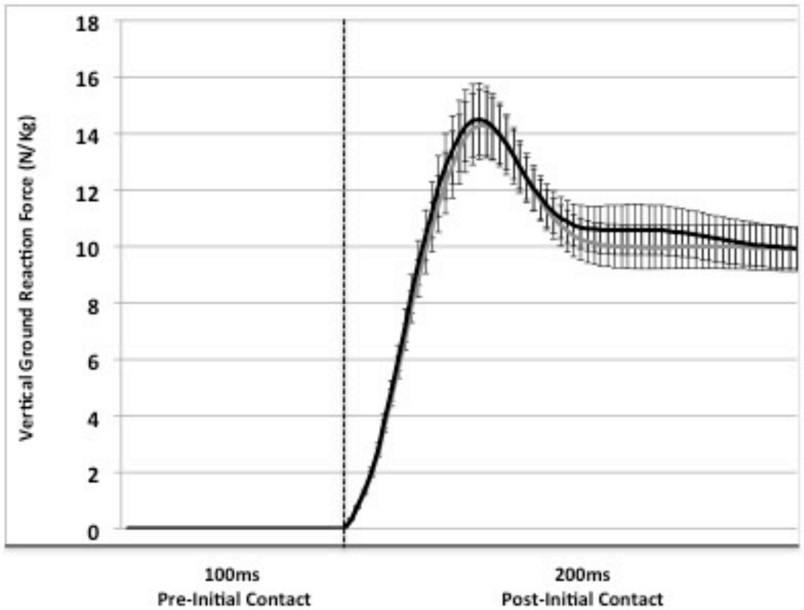


Figure 1.3: Time series 90% confidence interval analysis for normalized surface electromyography (sEMG) amplitudes pre and post rehabilitation



*Surface EMG amplitudes are normalized to the mean amplitude during quiet standing

Figure 1.4: Time series 90% confidence interval analysis for normalized vertical ground reaction force pre and post rehabilitation



SECTION II: MANUSCRIPT II

IMPAIRMENT-BASED REHABILITATION INCREASES LOWER LEG MUSCLE VOLUMES AND STRENGTH IN CHRONIC ANKLE INSTABILITY PATIENTS

ABSTRACT

Study Design: Controlled laboratory study **Objective:** To analyze the effect of impairment-based rehabilitation on intrinsic and extrinsic foot and ankle muscle volumes and strength in chronic ankle instability (CAI) patients. **Background:** CAI patients have demonstrated atrophy of foot and ankle musculature and deficits in ankle strength. The effect of rehabilitation on muscle morphology and ankle strength has not previously been investigated in CAI patients. **Methods:** Five young adults with CAI had measures of extrinsic and intrinsic foot muscle volume and ankle strength measured before and after 4 weeks of supervised rehabilitation. Novel fast-acquisition MRI was used to scan from above the femoral condyles through the entire foot. The perimeter of each muscle was outlined on each axial slice and then the 2D area was multiplied by the slice thickness (5mm) to calculate muscle volume. Plantar flexion, dorsiflexion, inversion, and eversion isometric strength were measured using a hand-held dynamometer. All measures were recorded before and after 12 sessions of supervised impairment-based rehabilitation that included range of motion, strength, balance, and functional exercises. **Results:** Rehabilitation resulted in hypertrophy of all extrinsic foot muscles except for the flexor hallucis longus and peroneals. Large improvements were seen in inversion, eversion, and plantar flexion strength following rehabilitation. Effect sizes for significant differences following rehabilitation were all large and ranged from 1.54 to 3.35. No significant differences were identified for intrinsic foot muscle volumes. **Conclusion:** Impairment-based rehabilitation for CAI can induce hypertrophy of extrinsic foot and ankle musculature with corresponding increases in ankle strength.
Word Count: 249

Key words: Muscle morphology, therapeutic exercise, magnetic resonance imaging

INTRODUCTION:

Lateral ankle sprains occur at a rate of 2.15 sprains per 1000 person years in the general public [37] and the rate is substantially higher in athletic and physically active populations. [36] Over 55% of all ankle sprain patients do not seek care for their injury [28] and of those patients that do seek care, less than 7% are prescribed therapeutic exercises for the restoration of function and prevention of subsequent ankle sprain. [10] Inadequate management of acute LAS has been hypothesized as a potential mechanism of self-reported disability and recurrent ankle sprain. [10] Recurrent sprain, giving way, and self-reported disability for greater than 1 year following an initial sprain characterize the 40% of all lateral ankle sprain patients that develop chronic ankle instability (CAI). [13,15] Long-term consequences of recurrent ankle sprain include post-traumatic osteoarthritis, [33] decreased physical activity, [23] and lower overall quality of life. [2]

Invertor [39] and evertor [3] muscle weakness has been reported as a potential ankle sprain risk factor and four-way ankle strength deficits have been identified in CAI patients. [20,21] We have also recently elucidated corresponding muscle volume deficits of numerous extrinsic and intrinsic foot and ankle muscles in CAI patients. [11] Our previous results [11] suggest that inversion, dorsiflexion, and plantar flexion strength deficits are related to smaller muscles and that eversion strength deficits appear to be more neuromuscular, rather than due to muscle size, in nature. Supervised rehabilitation programs [8,16,17,30] emphasizing neuromuscular and balance training for CAI patients have been associated with improved patient-reported outcomes and sensorimotor measures, but the effects of such interventions on muscle volume have not been previously studied.

Resistance band strength training and proprioceptive neuromuscular facilitation are both effective interventions for increasing ankle strength and decreasing perceived disability in CAI patients.[18] Strength training alone has been shown to improve not only strength measures, but also sensorimotor function (joint position sense)[6] and functional performance (balance and hopping tests).[34] Up to this point, however, there is no evidence to suggest whether the improvements in ankle strength commonly seen following rehabilitation are also related to muscle hypertrophy.

Improving our understanding of the mechanisms by which CAI patients generate more force following rehabilitation will allow for more informed decisions regarding the prescription of therapeutic exercise for the treatment of lateral ankle sprain and CAI. Analyzing muscle morphological changes in response to rehabilitation will also provide insight into the muscular adaptability of CAI patients who demonstrate both impaired neuromuscular function[24,26] and smaller muscles[11] when compared to healthy counterparts. Therefore, the purpose of the current investigation is to analyze the effect of progressive, impairment-based rehabilitation on extrinsic and intrinsic foot and ankle muscle volumes and four-way ankle strength in CAI patients. We hypothesized that CAI patients would demonstrate muscle hypertrophy and corresponding increases in muscle strength.

METHODS:

Study Design

We performed a descriptive laboratory study with a pre-post design to compare intrinsic and extrinsic foot and ankle muscle volumes and ankle strength prior to and following a 4-week progressive, impairment-based rehabilitation program for CAI patients. Our independent variable was time (pre- and post-rehabilitation) and our dependent variables were mass*height normalized muscle volumes and mass normalized four-way ankle strength (normalized force output for dorsiflexion, plantar flexion, inversion, and eversion). The study methods were approved by the University's institutional review board and all subjects provided informed consent prior to study participation.

Participants

Five young adults with CAI volunteered to participate in this study (Table 1). We have previously published the baseline muscle volume and strength data on these same five CAI patients compared to age-, sex-, and limb-matched healthy controls. [11] In the current investigation, we analyze the effect of rehabilitation on these measures in the same cohort. Additionally, these 5 subjects were part of a larger sample of CAI patients in an intervention study that assessed the effects of rehabilitation on patient-reported outcomes, range of motion, balance, strength, and electromyographic measures, but not muscle volume measures. [8] Inclusion criteria was a history of more than one significant ankle sprain with the initial sprain occurring more than one year prior to study onset and current self-reported functional deficits due to ankle symptoms that was quantified by a score of <75% on the Foot and Ankle Ability Measure (FAAM) Sport scale and a score of ≥10 on the Identification of Functional Ankle Instability scale (IdFAI). Exclusion criteria included a history of lower extremity surgery, lower extremity fracture, foot or ankle immobilization greater than 48 hours within 6 months of study onset, an ankle sprain within 6 weeks of study onset, or any other condition known to affect muscle volumetric measurements (muscular dystrophy, multiple sclerosis, etc.). Subjects were required to be physically active at least 20 minutes/day for at least 3 days/week.

Instruments

Magnetic Resonance Imaging for Foot and Ankle Muscle Volumes

Subjects were scanned on a 3 Tesla Siemens Trio MRI scanner as previously described [11,19] from just superior of the medial and lateral femoral condyles through the entire foot. Images were acquired using a 2-D multi-slice non-Cartesian spiral gradient echo sequence with a scan time of 15 minutes per subject. Scan parameters for the shank were as follows: TE/TR/α: 3.8ms/800ms/90°, field of view: 400mm x 400mm, slice thickness: 5mm, in plane spatial resolution: 1.1mm x 1.1mm. Scan parameters were identical for the foot with the exception of a smaller field of view (250mm x 250mm) and commensurately higher resolution. Due to the smaller field of view for the intrinsic foot muscles, a Siemans 4-channel large flex coil was utilized to increase the signal-to-noise ratio.

Four-way Ankle Strength Testing

Ankle strength (dorsiflexion, plantar flexion, inversion, and eversion) was measured using a hand-held dynamometer (Accelerated Care Plus Corp, Reno, NV).

Procedures

Subjects completed a general health history questionnaire, Godin Leisure-Time Physical Activity Questionnaire, [14] FAAM Activities of Daily Living [27] and Sport scale, [4] and IdFAI questionnaire. [7] Prior to strength testing, subjects performed a 5-minute warmup by walking on a treadmill at a self-selected pace. For each testing position, subjects were instructed to complete practice trials at 50% and then 75% of maximal effort against the tester's resistance.[8] Three 5-second maximal voluntary isometric contractions (MVICs) were completed with a 15 second rest period between trials. All three trials for an individual ankle motion were completed before transitioning to the 50% and 75% practice trials of the next tested ankle motion. The MRI was scheduled within 1 week of strength testing for both pre- and post-rehabilitation time points.

Subjects were positioned in the MRI scanner supine and feet first. Axial slices for the shank were obtained contiguously in sets of 20 images from just superior to the femoral condyles distally through the most inferior aspect of the calcaneus. The research team then applied the flex coil around the feet and axial slices were then obtained in sets of 20 contiguous images from just posterior to the calcaneus anteriorly through the entire foot.

Rehabilitation Protocol

We utilized the same progressive, impairment-based rehabilitation protocol as a previous study that demonstrated large improvements in strength, balance, range of motion, and self-reported function in CAI patients.[8] A detailed description of the rehabilitation protocol and individualized progression algorithm has previously been published as a supplement to the aforementioned study.[8] Briefly, the rehabilitation protocol was developed based on Donovan and Hertel's paradigm for each of the four common CAI impairment domains of range of motion, strength, balance, and functional activities.[9] Subjects completed 12 sessions of supervised rehabilitation with a certified athletic trainer. Sessions were one hour in duration and subjects completed 3 sessions per week for four consecutive weeks. Each subject's daily progression was individualized based on pre-determined criteria and the clinician's clinical expertise.[8] The progressions were individualized to ensure that each subject was challenged within each impairment domain[9] from day 1 until they completed the 12th session. Following the 12th rehabilitation session, subjects returned to the lab within 48 hours for follow-up strength testing and within 7 days for the post-rehabilitation MRI.

Data Reduction

Magnetic Resonance Image Processing

A detailed and technical description of the data processing technique has been published previously.[19] Briefly, each intrinsic and extrinsic foot and ankle muscle was segmented using in-house segmentation software written in Matlab (The Mathworks Inc., Natick, MA, USA). The segmentation process required the investigator to specify 2-D contours, which define the perimeter of each muscle in each axial slice. The segmentation analysis was performed by three trained research assistants who utilized a detailed slice-by-slice segmentation atlas created from a previous data set using similar scanning parameters and segmentation procedures. The research assistants were blinded to whether a scan was a pre- or post-rehabilitation scan during segmentation of all axial slices. The final images were then screened by a single highly trained investigator to ensure consistency across all segmented images. The 2-D area of each muscle for each axial slice was multiplied by the slice thickness (5mm) to get the muscle volume for that slice and the segmentation software created 3-D *in-vivo* reconstructions of all intrinsic and extrinsic foot and ankle muscles and calculated the associated muscle volumes. Muscle volumes were normalized to each subjects mass*height. [19] Normalized muscle volumes (cm^3/m*kg) were utilized to compare pre- and post-rehabilitation muscle volumes. We compared pre- and post-rehabilitation individual muscle volumes as well as summed compartmental (anterior, lateral, deep posterior, superficial posterior) and total muscle volume for the extrinsic muscles and total intrinsic plantar muscle volumes. For extrinsic muscle volume comparisons we also compared normalized muscle volumes prior to and following rehabilitation to a normative database as described in our statistical analysis section (see below).

Four-way Ankle Strength

Strength was recorded as the maximal force (N) output during the individual MVIC trials for each ankle motion. The average over the three trials was computed for each of the four tested motions and normalized to each subject's mass (kg) and the normalized force output (N/kg) was utilized to compare pre- and post-rehabilitation strength measures.

Statistical Analysis

All dependent variables (muscle volume and strength) were compared pre- and post-rehabilitation with group means and associated 90% confidence intervals (CIs). For dependent variables where the CIs between pre- and post-rehabilitation did not overlap, it was determined there was a significant difference following rehabilitation. We also calculated Cohen's d effect sizes and associated 90% CIs to estimate the magnitude and precision of the effect due to rehabilitation. Effects sizes were interpreted as follows:

≥ 0.80 was large, 0.50-0.79 was moderate, 0.20-0.49 was small, and <0.20 was trivial.[5] Positive effect sizes indicate an improvement in muscle size (hypertrophy) or an increase in ankle strength. Data was analyzed using Microsoft Excel Version 14.1.0 (Microsoft, Redmond, WA).

Normative Database Comparison

Pre- and post-rehabilitation extrinsic muscle volumes were also compared to a previously established normative database for lower extremity muscle volumes.[19] The database was created as part of another project that quantified the relationship between lower extremity muscle volumes to body mass and height in 24 healthy subjects.[19] To compare muscle volumes for the subjects in our current study to the previously published normative values,[19] we calculated z-scores for each extrinsic muscle, individually for all 5 CAI subjects prior to and following rehabilitation. We then calculated the z-score change by subtracting the pre-rehabilitation z-score from the post-rehabilitation z-score for each extrinsic muscle volume. To our knowledge, our current study is only the second study to quantify the intrinsic foot muscle volumes using this technique and thus it was not possible to compare the CAI intrinsic foot muscles to normative values.[11] Clinical interpretation of z-scores was determined *a priori* as follows: $z \geq 3.0$ = extreme hypertrophy, $3 > z \geq 2$ = moderate hypertrophy, $2 > z \geq 1$ = slight hypertrophy, $1 > z > -1$ = normal, $-1 \geq z > -2$ = slight atrophy, $-2 \geq z > -3$= moderate atrophy, and $-3 \geq z$ = extreme atrophy.[11]

RESULTS:

Muscle Volumes

Extrinsic Foot and Ankle Muscle Volumes

Rehabilitation resulted in significant hypertrophy of overall extrinsic foot and ankle muscle volume (PRE: 9.62±0.39 cm^3/m*kg; POST: 11.87±0.86 cm^3/m*kg). This overall improvement was driven by large increases in the superficial posterior and anterior compartments (PRE: 5.15±0.55 cm^3/m*kg; POST: 6.62±0.45 cm^3/m*kg and PRE: 1.55±0.11 cm^3/m*kg; POST: 1.94±0.17 cm^3/m*kg, respectively, Figure 3). Rehabilitation resulted in large increases in all foot and ankle extrinsic muscle volumes, except for the flexor hallucis longus and peroneals (PRE: 0.87±0.22 cm^3/m*kg; POST: 0.66±0.18 cm^3/m*kg and PRE: 0.91±0.11cm^3/m*kg; POST: 1.17±0.19 cm^3/m*kg, respectively, Table 2). Effect sizes for all significant hypertrophic gains following rehabilitation were large and ranged from 1.75 to 3.35 with 90% CI that were entirely positive, indicating meaningful improvements in muscle size following rehabilitation for CAI.

Extrinsic Foot and Ankle CAI Muscle Volume Normative Database Comparisons

Prior to rehabilitation, CAI patients presented with slight atrophy (average z-scores of $-1 \geq z > -2$) of the flexor digitorum longus (average z=-1.23) and soleus (average z=-1.45) and moderate atrophy (average z-scores of $-2 \geq z > -3$) of the medial gastrocnemius (average z=-2.00), lateral gastrocnemius (average z=-2.16), phalangeal extensors (average z=-2.06), and the popliteus (average z=-2.64) (Figure 1a). Following rehabilitation, the average z-score for every extrinsic foot and ankle muscle was within a normal range (average z-scores of $-1 > z > 1$) compared to the normative values (Figure 1b). The z-score change is illustrated individually for each patient in Figure 2.

Intrinsic Foot Muscle Volumes

There were no significant differences following rehabilitation for any intrinsic foot muscle volumes (Table 3). Effect sizes ranged from -0.56 to 1.05 with 90% CIs that all crossed zero suggesting uncertainty about the effect of rehabilitation on intrinsic foot muscle volumes for CAI patients.

Four-way Ankle Strength

Rehabilitation significantly improved inversion and eversion ankle strength (Figure 4). Effect sizes for significant strength gains ranged from 2.03 to 2.61 with 90% CIs that were entirely positive suggesting meaningful improvements in ankle strength following rehabilitation.

Self-Reported Function:

Following rehabilitation, CAI subjects demonstrated a 5.1% increase in FAAM-ADL scores and a 31.0% increase in FAAM-Sport scores (FAAM-ADL: PRE: 89.9±3.6%, POST: 94.9±7.8%; FAAM-Sport: PRE: 54.4±22.1%, POST: 85.4±5.5%).

DISCUSSION:

Following 4 weeks of progressive, impairment-based rehabilitation CAI patients demonstrated meaningful improvements in extrinsic foot and ankle muscle volumes and concurrent improvements in ankle strength and self-reported function. We did not identify any improvements in intrinsic foot muscle volumes post-rehabilitation. This is the first study to quantify muscle morphological adaptations to rehabilitation for CAI patients. These results increase our understanding of the physiological mechanism by which CAI patients can increase force output with rehabilitation.

Previously, we identified moderate to large deficits in muscle volumes and strength of these same subjects to age-, sex-, and limb-matched healthy counterparts. [11] We have now demonstrated that those morphological deficiencies can be overcome with progressive, impairment-based rehabilitation in accordance with Donovan and Hertel's [9] recommendations for the rehabilitation of CAI patients. It has been shown that strength training and subsequent improvements in force output are associated with improved joint position sense [6] and functional performance [34] and we have expanded upon this knowledge by demonstrating muscle hypertrophy following just four-weeks of rehabilitation for CAI.

Identifying muscle hypertrophy with only four weeks of rehabilitation is counterintuitive to the central dogma of resistance training for hypertrophic gains. [25,31] Conventional theory would suggest that strength improvements in the first weeks of training should be neuromuscular in nature followed by a progression to morphological and architectural adaptations. [32,38] This theory is based on studies of untrained individuals in which neural adaptations would be expected to be the largest. [32] In CAI patients, we have previously demonstrated that traditional rehabilitation exercises (forward lunge, single limb balance, dynamic balance, and lateral hopping tasks) can result in up to 121% motor recruitment when compared to maximal voluntary isometric contractions. [12] We posit that the large neuromuscular demand placed on the shank musculature during simple functional tasks in CAI patients [12] may limit the potential for further neural adaptations prior to demonstrating hypertrophic gains with the progressive rehabilitation prescribed in our study. Non-pathological populations have seen approximately a 12%

increase in quadriceps cross-sectional area after just three weeks of training, [1] compared to a 23% increase in total shank muscle volume seen in our study following 4 weeks of progressive rehabilitation for CAI. Large improvements in quadriceps femoris cross sectional area, fascicle length, and pennation angle have also been seen after 20 and 35 days of resistance training, collectively adding credence to the increased muscle size seen in our CAI patients after four weeks of rehabilitation. [35]

Our previous results [11] on muscle volumes demonstrated a disproportional deficit in eversion ankle strength when considering the relatively normal peroneal muscle volumes seen in the CAI subjects. We postulated that this uncoupling of peroneal muscle size and eversion weakness supported the theory of peroneal neuromuscular dysfunction with CAI. [11] Similarly, in our current investigation, there were minimal increases in peroneal muscle size but very large and meaningful improvements in eversion strength. This may further substantiate the hypothesis that in muscles where the potential for neural adaptations to resistance training is the greatest, there will be lower hypertrophic gains when compared to muscles where the potential for neural adaptations are minimal.

This same rationale may help explain how none of the intrinsic foot muscles increased in muscle size following rehabilitation. We did utilize short foot exercises in this rehabilitation protocol, but we suspect that initial adaptations to the novel exercise, if any, were neuromuscular in nature. Future studies should evaluate the effectiveness of intervention programs specifically aimed at improving plantar intrinsic muscle function to assess whether hypertrophy of these muscles may be accomplished. [29]

Limitations

Limitations of the current investigation include the relatively small sample size due to the high time demands of the MRI data segmentation process and analysis as well as the lack of surface electromyography of intrinsic and extrinsic foot and ankle musculature to elucidate the neural and morphological adaptations to therapeutic exercise for CAI. Furthermore, the lack of long-term outcomes after the cessation of rehabilitation limits our understanding of the duration of which hypertrophic and strength gains will be maintained without continued rehabilitation.

Conclusion

Four weeks of progressive, impairment-based rehabilitation for CAI can increase extrinsic foot and ankle muscle volumes with concurrent improvements in ankle strength and self-reported function. Rehabilitation was unable to increase intrinsic foot muscle volumes. Clinicians should be aware of both the neural and morphological adaptations that can occur in response to rehabilitation for CAI patients.

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TABLES:

Table 2.1: Subject Demographics

	CAI Mean ± SD N=5
Age	23.0 ± 4.0
Gender	1M:4F
Height (cm)	165.4 ± 8.8
Mass (kg)	66.5 ± 7.3
Number of ankle sprains	3.2 ± 1.6
Time from last sprain (months)	27.8 ± 21.2
FAAM ADL	89.9 ±3.6
FAAM sport score	54.4 ± 22.1
IdFAI	24.0 ± 3.8
Godin Leisure Time Physical Activity Scale	51.8 ± 23.0

Abbreviations: CAI=Chronic Ankle Instability, SD=Standard Deviation, FAAM=Foot and Ankle Ability Measure, ADL=Activities of Daily Living, IdFAI=Identification of Functional Ankle Instability

Table 2.2: Extrinsic Foot and Ankle Muscle Volumes $\left(\frac{cm^3}{m*kg}\right)$ and Associated Cohen's d Effect Sizes

Extrinsic Muscles	Pre-Rehabilitation Mean (90% CI)	Post-Rehabilitation Mean (90% CI)	Cohen's d Effect Size (90% CI)
Tibialis Anterior	0.92* (0.90, 0.95)	1.09* (1.01, 1.18)	1.93 (0.67, 3.19)
Phalangeal Extensors	0.63* (0.53, 0.72)	0.84* (0.75, 0.96)	1.75 (0.52, 2.97)
Peroneals	0.91 (0.80, 1.02)	1.17 (0.98, 1.35)	1.24 (0.10, 2.38)
Flexor Digitorum Longus	0.16* (0.15, 0.18)	0.23* (0.21, 0.25)	2.82 (1.35, 4.29)
Flexor Hallucis Longus	0.87 (0.71, 1.02)	0.66 (0.53, 0.79)	-1.04 (-2.14, 0.07)
Tibialis Posterior	0.86* (0.79, 0.92)	1.05* (0.96, 1.14)	1.84 (0.60, 3.08)
Popliteus	0.13* (0.12, 0.14)	0.19* (0.17, 0.21)	2.56 (1.16, 3.96)
Gastrocnemius Medial Head	1.62* (1.50, 1.75)	2.03* (1.87, 2.18)	2.12 (0.82, 3.42)
Gastrocnemius Lateral Head	0.90* (0.78, 1.03)	1.34* (1.19, 1.49)	2.38 (1.02, 3.74)
Soleus	2.62* (2.40, 2.84)	3.25* (3.09, 3.41)	2.42 (1.05, 3.79)

* Denotes significant difference as indicated by group means and associated 90% confidence intervals that do not overlap
Abbreviations: CI=Confidence Interval
Positive effect size indicates increased muscle volume following rehabilitation

Table 2.3: Intrinsic Foot Muscle Volumes $\left(\frac{cm^3}{m*kg}\right)$ and Associated Cohen's d Effect Sizes

Intrinsic Foot Muscles	Pre-Rehabilitation Mean (90% CI)	Post-Rehabilitation Mean (90% CI)	Cohen's d Effect Size (90% CI)
Abductor Hallucis	0.21 (0.17, 0.25)	0.21 (0.18, 0.24)	0.01 (-1.03, 1.05)
Adductor Hallucis Obliqus	0.07 (0.06, 0.08)	0.06 (0.05, 0.08)	-0.56 (-1.62, 0.50)
Adductor Hallucis Transversus	0.02 (0.01, 0.02)	0.03 (0.02, 0.03)	1.05 (-0.06, 2.16)
Flexor Hallucis Brevis	0.06 (0.05, 0.07)	0.09 (0.06, 0.12)	0.90 (-0.19, 1.99)
Abductor Digiti Minimi	0.16 (0.14, 0.18)	0.16 (0.13, 0.18)	-0.18 (-1.22, 0.87)
Flexor Digiti Minimi	0.08 (0.06, 0.10)	0.07 (0.06, 0.08)	-0.45 (-1.50, 0.61)
Extensor Digitorum Brevis	0.08 (0.06, 0.10)	0.10 (0.07, 0.14)	0.64 (-0.53, 1.70)
Flexor Digitorum Brevis	0.20 (0.16, 0.23)	0.21 (0.17, 0.24)	0.19 (-0.85, 1.23)
Interosseus	0.17 (0.14, 0.20)	0.20 (0.18, 0.23)	0.81 (-0.27, 1.89)
Quadratus Plantae	0.13 (0.10, 0.16)	0.14 (0.12, 0.16)	0.40 (-0.65, 1.45)
Total Plantar Intrinsic Foot Muscle Volume	1.09 (0.95, 1.23)	1.16 (1.05, 1.27)	0.39 (-0.66, 1.44)

* Denotes significant difference as indicated by group means and associated 90% confidence intervals that do not overlap
Abbreviations: CI=Confidence Interval
Positive effect size indicates increased muscle volume following rehabilitation

FIGURES:

Figure 2.1a: Normative database z-score comparisons for each muscle, individually for each CAI subject, prior to (2.1a) and following (2.1b) impairment-based rehabilitation.

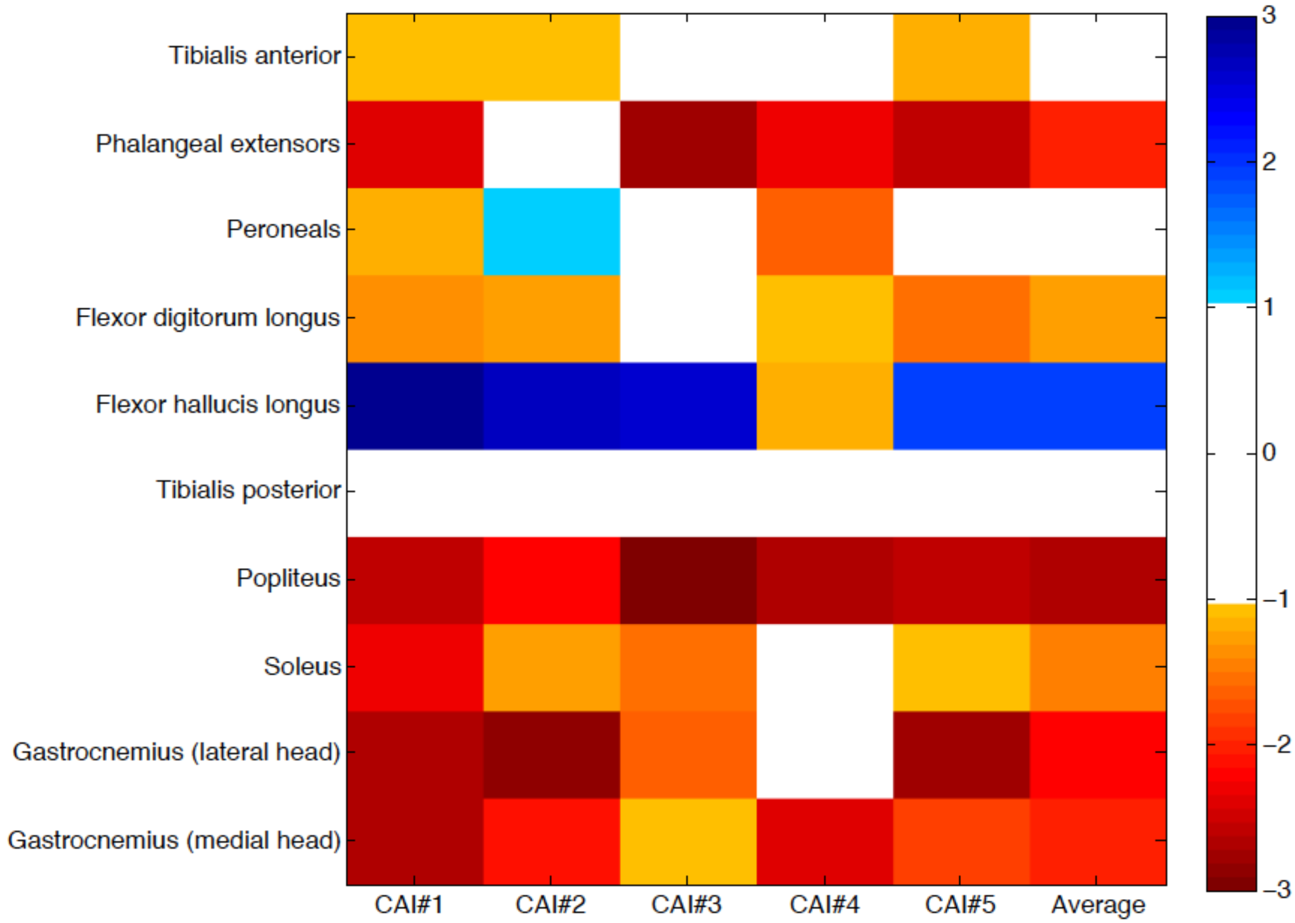


Figure 2.1b: Normative database z-score comparisons for each muscle, individually for each CAI subject, prior to (2.1a) and following (2.1b) impairment-based rehabilitation.

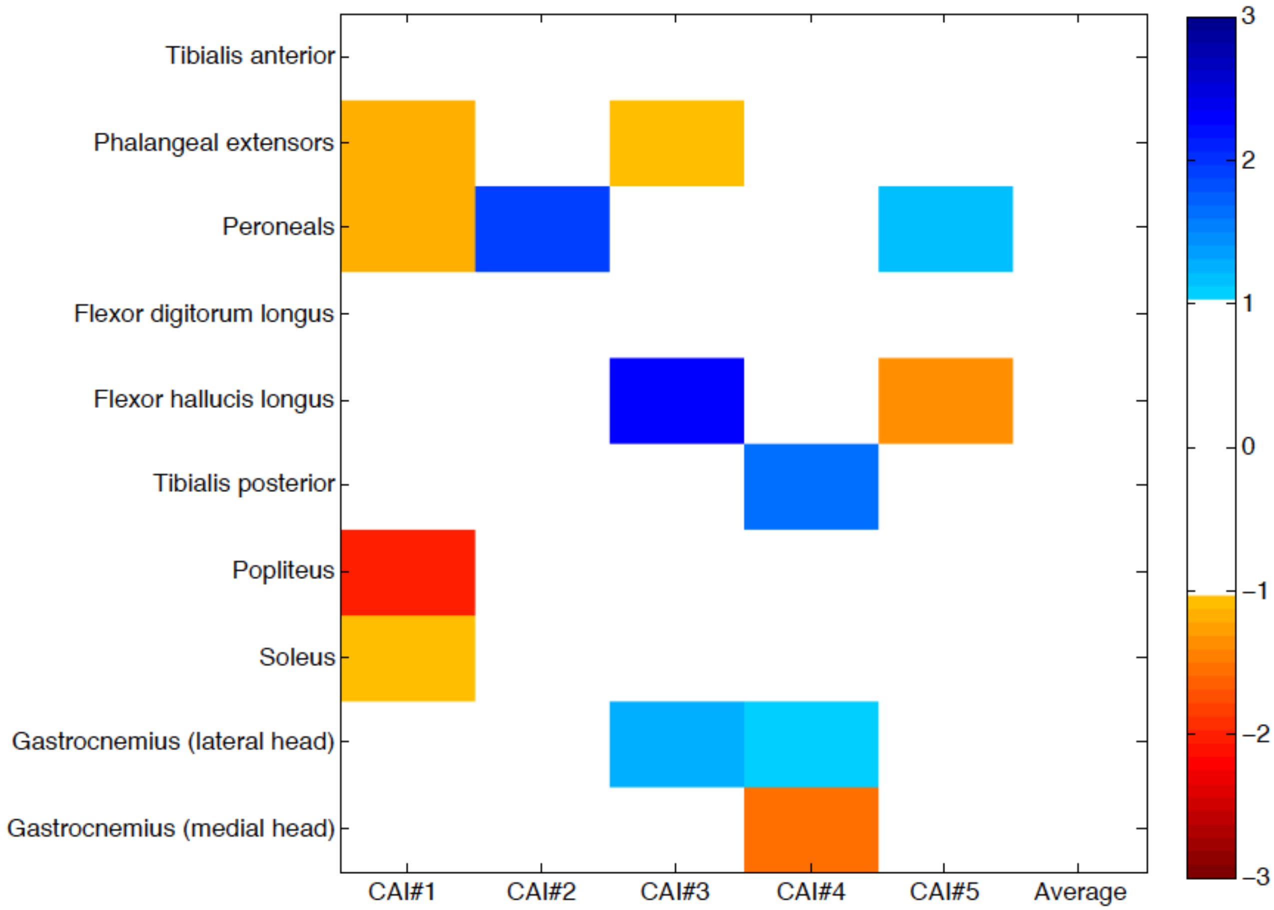


Figure 2.2: Change in z-score (post z-score – pre z-score) due to rehabilitation for all extrinsic foot and ankle muscles individually for each subject

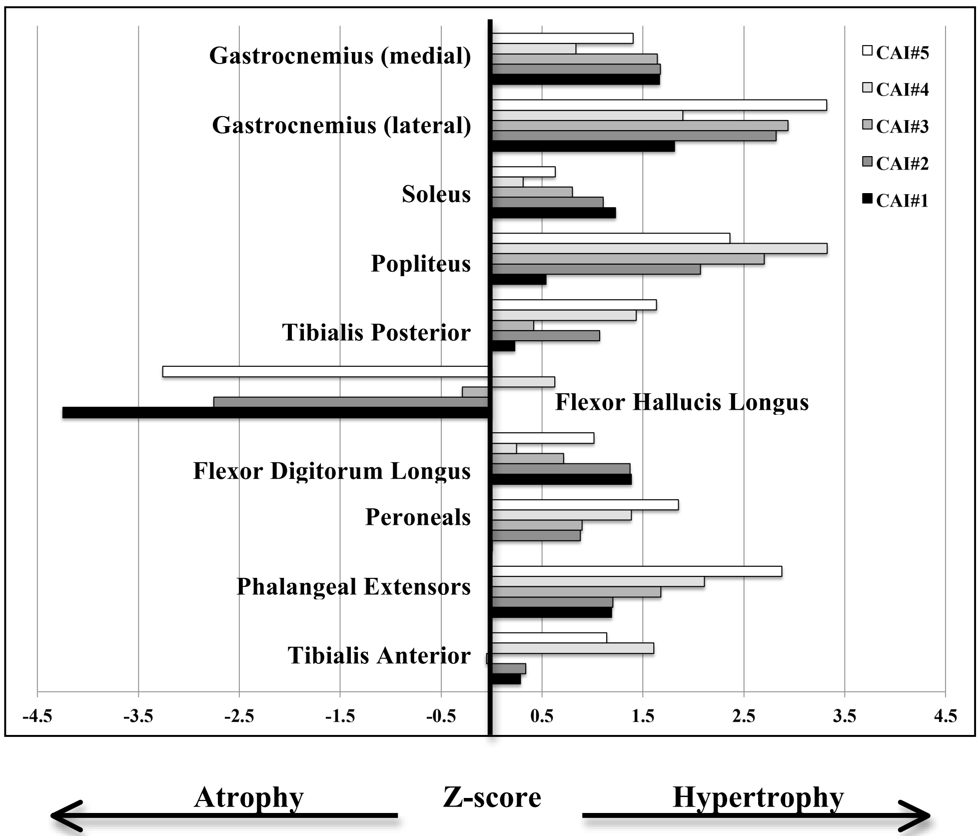
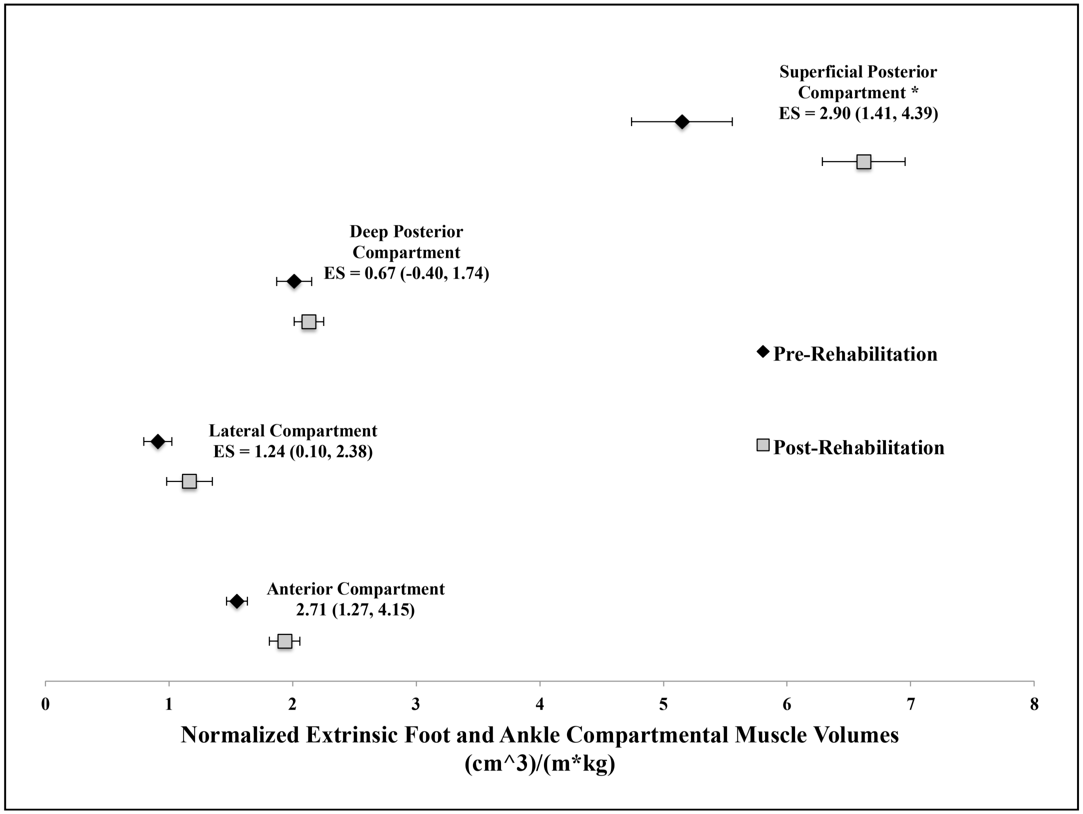
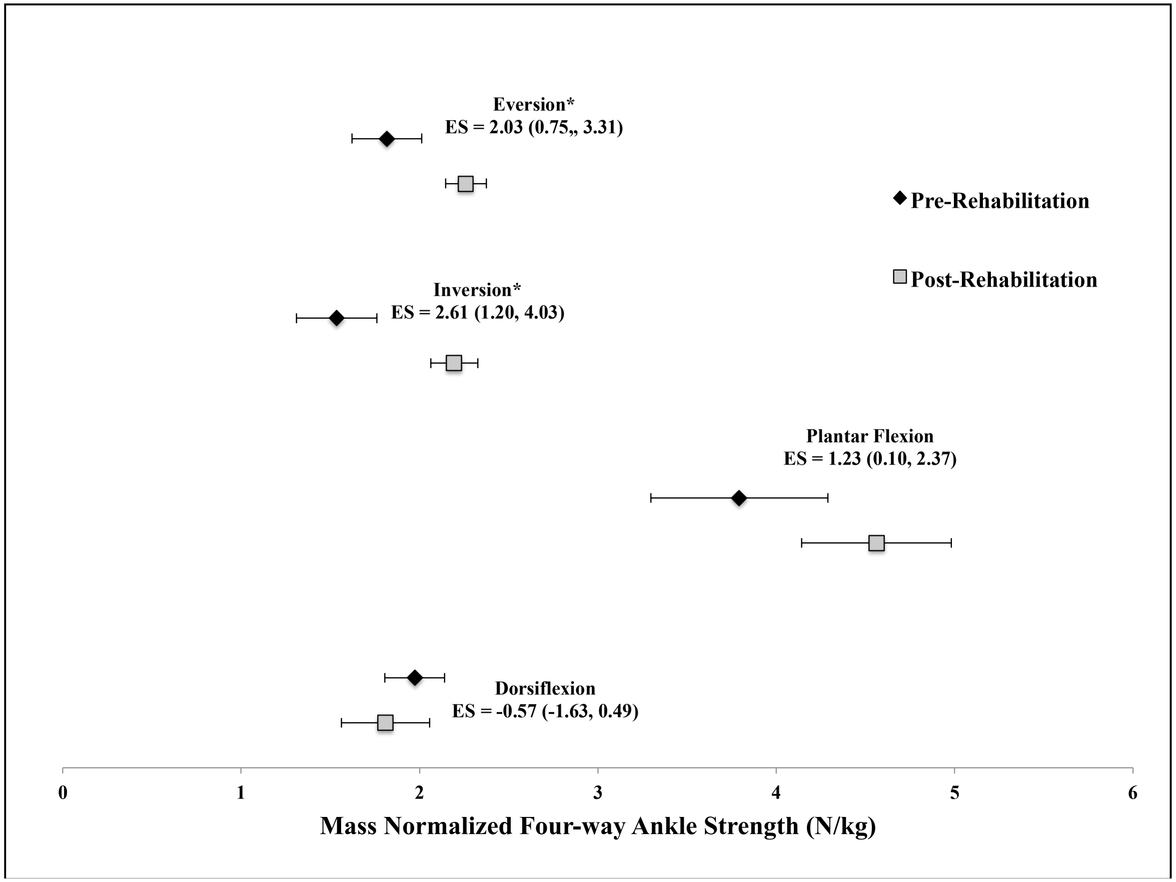


Figure 2.3: Extrinsic Foot and Ankle Muscle Compartment Volumes $\left(\frac{cm^3}{m*kg}\right)$ and Associated Cohen's d Effect Sizes and 90% Confidence Interval



*Denotes significant difference as indicated by group means and associated 90% confidence intervals that do not overlap
Positive effect size indicates lower muscle volumes with CAI

Figure 2.4: Four-way Ankle Strength Measures N/kg and Associated Cohen's d Effect Size and 90% Confidence Interval



*Denotes significant difference as indicated by group means and associated 90% confidence intervals that do not overlap
Positive effect size indicates lower muscle volumes with CAI

SECTION II: MANUSCRIPT III

GAIT TRAINING FOR CHRONIC ANKLE INSTABILITY IMPROVES NEUROMECHANICS DURING TREADMILL WALKING

ABSTRACT

Purpose: To analyze the effect of gait training with a novel gait training device on measures of plantar pressure and surface electromyography (sEMG) in chronic ankle instability (CAI) patients. **Methods:** Sixteen CAI patients participated. In-shoe plantar pressure and sEMG were collected simultaneously during treadmill walking at 3.0mph prior to and following supervised gait training. Measures of plantar pressure **(**pressure time integral, peak pressure, time to peak pressure, contact area, contact time and center of pressure trajectory) of the entire foot and 9 specific regions of the foot were recorded concurrently with sEMG root mean square amplitudes from the anterior tibialis, peroneus longus, medial gastrocnemius, and gluteus medius. Five gait training sessions were performed over 5-10 days with each session lasting approximately 15 minutes. Pre- and post-gait training measures of self-reported function, plantar pressure, and sEMG were compared using paired t-tests with *a priori* level of significance of $P \leq 0.05$ and results were supplemented with Cohen's d effect sizes and associated 95% confidence intervals (CI). **Results:** Gait training improved self-reported function (FAAM-Sport scale: Pre=75.1±7.1%, Post=85.7±12.2%, $P<.001$). There was a significant medial shift in the location of the COP gait line from 10% of stance through toe-off ($P<.05$ for all analyses). The medial shift in COP following gait training was driven by concurrent increases in peroneus longus muscle activity from 21-60% and 81-90% of stance ($P<.05$ for all analyses). There was also a corresponding reduction in gluteus medius muscle activity during 71-100% of stance ($P<.05$ for all analyses).**Conclusion:** Gait training with a device that targets the peroneus longus and gluteus medius throughout the gait cycle is effective at restoring normal gait patterns in CAI patients.
Word Count: 273

Key Words: rehabilitation, therapeutic exercise, walking, self-reported function

INTRODUCTION:

Lateral ankle sprains are common amongst physically active individuals.[34,35] Time lost from sport,[26] cost associated with treatment,[22,31] chronicity of symptoms,[24] joint degeneration,[30] and decreased physical activity[20,33] are some of the commonly reported short- and long-term consequences of lateral ankle sprain. Furthermore, 40% of lateral ankle sprain patients will go on to experience recurrent ankle sprain,[13] residual instability and decreased self-reported function for greater than one year following their initial sprain.[15] These symptoms characterize patients who have developed chronic ankle instability (CAI).[15]

Within two weeks of sustaining an initial ankle sprain, patients exhibit altered gait patterns with increased ankle joint inversion during toe-off.[6] In CAI patients, there is a similar increase in ankle joint inversion prior to and following heel strike.[5,29] It has been theorized that this improper foot position during swing provides a stimulus for earlier onset and increased peroneus longus muscle activity in an attempt to correct the frontal plane alignment at heel-strike.[12] Unfortunately, this coping mechanism seen in CAI patients is ineffective at restoring normal foot and ankle biomechanics as CAI patients maintain a laterally deviated center of pressure (COP) throughout the entire stance phase of gait.[23] The lateral deviation in the COP is thought to be related to the inability of the peroneus longus to effectively pronate the foot following ground contact.[12] Increased gluteus medius muscle activity identified during the latter half (last 50%) of stance and early (first 25%) swing phase may be a proximal adaptation to help stabilize the involved limb while the foot maintains a supinated position throughout stance.[23]

Clinical researchers have prescribed both progressive balance training [28] and comprehensive impairment-based rehabilitation [8] for CAI patients, but have been unable to restore normal ankle frontal plane motion during gait. Contemporary recommendations [9] for the treatment of altered gait patterns with CAI recommend the implementation of gait training, however, there is no current evidence-based recommendations as to what gait training should entail for this pathological population. We previously tested a novel gait training device (Figure 1) in CAI patients and identified that the increased peroneus longus and gluteus medius muscle activity induced by the device resulted in large medial shifts in CAI patients' COP throughout the entire stance phase. [11] The previous investigation analyzed CAI gait patterns while the participants were using the device, [11] but there is a need to assess whether the improved gait pattern can be maintained following a series of gait training sessions. Therefore, the purpose of the current study is to analyze the effects of gait training for CAI patients with a novel gait training device on measures of plantar pressure and surface electromyography (sEMG).

METHODS:

Study Design

A descriptive laboratory study was performed to compare measures of plantar pressure and sEMG during treadmill walking prior to and following supervised gait training with a novel gait training device in young adults with CAI. Our independent variables were time: pre- and post-gait training. For dependent plantar pressure variables we analyzed peak pressure, pressure time integral, time to peak pressure, contact area and contact time of the entire foot and 9 specific regions of the foot (medial heel, lateral heel, medial midfoot, lateral midfoot, medial forefoot, central forefoot, lateral forefoot, hallux, and toes 2-5) as well as the medial-lateral position of the COP gait line over the entire stance phase. For sEMG dependent variables, we compared root mean square (RMS) amplitudes during the entire gait cycle for the anterior tibialis, peroneus longus, medial gastrocnemius and gluteus medius muscles.

Participants

Sixteen young adults with CAI volunteered for this study. The inclusion criteria was a history of more than one ankle sprain with the initial sprain occurring greater than one year prior to study onset and no history of ankle sprain within 6 weeks of data collection. Subjects also had to have current self-reported functional deficits due to ankle symptoms that was quantified by a score of <85% on the Foot and Ankle Ability (FAAM) Sport scale and a score ≥10 on the Identification of Functional Instability scale (IdFAI). All subjects were physically active (at least 20 minutes of exercise per day at least 3 days per week) and had no other lower extremity injuries or pathologies that would affect outcome measures. This study was approved by the Institutional Review Board for Health Sciences Research and all subjects provided written informed consent prior to participation.

Instruments

Plantar Pressure

Plantar pressure was measured using the Pedar-x plantar pressure system (Novel Inc, St Paul MN) with in-shoe plantar pressure insoles that had a sampling rate of 100 Hz. Subjects used a standard athletic shoe for both pre- and post-gait training data collection sessions (Brooks Defyance 3, Brooks Sports Inc., Seattle, WA). All trials were completed on a standard laboratory treadmill (Gait Trainer™ 3, Biodex, Shirley, NY).

Surface Electromyography

Surface EMG was collected using 2 parallel bar rectangular sensors. Each bar was 1mm wide and 1cm long and inter-electrode distance was 1cm. The sensors were DE 2.1 differential EMG sensors (Delsys, Boston, MA). The signal was amplified with a gain of 1000 and digitized with a 4 channel acquisition system (Bagnoli EMG system, Delsys, Boston, MA) at 1000 Hz. Input impedance was $>10^{15}\Omega/0.2$pF with a signal to noise ratio of 1.2uV. Data was collected with Motion Monitor software (Innovative Sports Training, Inc., Chicago, Illinois) and processed with EMGworks software (version 4.1.1, Delsys, Boston, MA). Data was filtered using a 10-500 Hz band-pass filter and smoothed using a 50-sample moving window root mean square (RMS) algorithm. Initial contact was identified with a foot switch that was placed beneath the heel of the subject's involved limb (Delysis, Boston, MA).

Procedures

Subjects completed a general health history questionnaire, Godin Leisure-Time Exercise Questionnaire, [14] FAAM Activities of Daily Living [25] and Sport scale, [3] and IdFAI questionnaire. [7] Next, surface electrodes were placed over the midline of each muscle belly that was determined via manual palpation during a voluntary contraction. To minimize skin impedance, the skin was shaved, abraded, and then cleansed with isopropyl alcohol prior to electrode placement. Proper sensor placement was visually inspected for crosstalk by having subjects perform voluntary contractions against manual resistance. Subjects were then fitted with standard lab shoes and in-shoe pressure insoles.

On each data collection day (pre- and post-gait training), quiet stance sEMG was recorded while subjects stood with feet shoulder width apart and their hands on their hips. The mean quiet standing value for each muscle was utilized for normalization of sEMG RMS amplitudes during gait trials. Subjects walked on the treadmill at a standardized walking pace of 3.0mph. Data was not collected until subjects reported they had achieved their self-perceived normal gait pattern. At this point, the tester collected 30 seconds of baseline gait. After completing baseline data collection, subjects returned within 48 hours for their first gait training session.

Subjects performed five gait training sessions over five to ten days. Subjects were allowed to come in on consecutive days for gait training, but were not allowed to take more than three full days between gait training sessions. For each gait training session, subjects were asked to stand with feet shoulder width apart, with the gait training device tracks positioned between their legs at a height of approximately the distal 1/3 of the subject's lower leg (Figure 1). The device utilized elastic resistance to provide a medial force to each subject's lower leg independently of the contralateral limb. Elastic bands were secured bilaterally around the lower leg of each subject by the athletic training supervising the gait training sessions. Elastic bands were stretched to approximately 150% of their resting length and tied around the lower leg. Subjects then began walking at a self-selected walking pace while hitting foot strike targets that were placed approximately shoulder width apart for each subject. Subjects were allowed to hold onto the treadmill handrails during gait training.

Subjects completed a minimum of seven gait training repetitions but no more than ten repetitions per gait training session. Each repetition consisted of one minute of walking with the gait training resistance followed by one minute of rest. After the 7th repetition, subjects determined when they wanted to discontinue gait training for that day based on how tired they perceived the muscles in their legs had become. If a subject reached the 10th repetition, they were allowed to continue walking against resistance up to five total minutes. This was the maximal amount of gait training allowed for that day. We elected to have subjects self-select when to discontinue the gait training each day to ensure that each subject was progressively challenged over the five gait training sessions. Through pilot testing we identified that 7-10 repetitions was a range of repetitions that would be obtainable but challenging for most subjects. We also collected the rate of perceived exertion (RPE)[2] at the end of each gait training session to provide an estimate of perceived effort during gait training. If a subject reached the 10th repetition, they were progressed to a heavier resistance band for their next gait training session. All subjects began with a blue resistance band (approximately 3.25kg of resistance per limb at 150% of resting length) and only two subjects progressed to a grey band (approximately 5.75kg of resistance per limb at 150% of resting length) by the end of the five gait training sessions. Following the 5th gait training session, subjects returned to the lab for post-gait training data collection 24-72 hours following the last gait training session. Subjects also completed self-reported questionnaires (FAAM Activities of Daily Living [25] and Sport scale, [3] and Global Rating of Change [21] (GROC)), post-gait training.

Data Reduction

Plantar Pressure

The mean peak pressure, pressure time integral, time to peak pressure, contact area and contact time over 15 consecutive steps of the involved limb were processed using Novel Database Pro 1/14 and Automask software packages (Novel Inc, St Paul, MN). This was completed for the entire foot and all 9 regions of the foot (medial heel, lateral heel, medial midfoot, lateral midfoot, medial forefoot, central forefoot, lateral forefoot, hallux, and toes 2-5). Peak pressure represented the highest point of pressure (kPa) in a given region of the foot during stance phase of gait. The pressure time integral was defined as the total plantar pressure applied to a specific region of the foot multiplied by the time spent in stance (kPa*s). Time to peak pressure was the percentage of stance when the peak pressure occurred for that specific region. Contact area and contact time indicated how large of an area (cm^2) and how long (ms) each region was in contact with the ground during the stance phase of gait.

Center of Pressure Gait Line

The medial to lateral location of the COP was measured as the distance from the most medial location of each participant's involved heel (mm). We condensed each subjects gait line into increments that represented 10% of the stance phase. Data points that represented 1-10% of stance were averaged and considered to represent average location of the COP during the first 10% of stance (graphically, this increment is presented as the average location of the COP at 5% of stance in Figure 1). Similarly, data points that represented 11-20% of stance were averaged and considered to represent the average location of the COP during the second 10% of stance (graphically, this increment is presented as the average location of the COP at 15% of stance in Figure 1). This process was repeated for the entire stance phase. The ten resulting data points were then treated as separate dependent variables and compared pre- and post-gait training.

Surface Electromyography

Using EMGworks software (version 4.1.1, Delsys, Boston, MA) sEMG RMS amplitudes during the entire stride cycle were resampled to 100 data points for 15 consecutive strides. We then took the first 60 data points and condensed them into 10 increments that corresponded to the same 10 plantar pressure increments described above for the COP gait line. Data points that represented 1-10% of stance were averaged and considered to represent the mean sEMG RMS amplitude during the first 10% of stance. Similarly, data points that represented 11-20% of stance were averaged and considered to represent the mean sEMG RMS amplitude during the next 10% of stance. This process was repeated for the entire stance phase. Additionally, the last 40 data points were condensed to represent four distinct increments of the swing phase. Data points that represented 1-25% of the swing phase were averaged and considered to represent the mean sEMG RMS amplitude for the first 25% of the swing phase. Similarly, data points that represented 26-50% of the swing phase were averaged and considered to represent the mean sEMG RMS amplitude for the second 25% of the swing phase. This process was completed for the entire swing phase. This data reduction process resulted in 14 separate sEMG dependent variables (10 for stance, 4 for swing) for each muscle (anterior tibialis, peroneus longus, medial gastrocnemius, and gluteus medius). Surface EMG RMS amplitudes were normalized to the mean quiet standing RMS amplitude.

Statistical Analysis

Paired t-tests were used to for all dependent variables to compare pre- and post-gait training. The level of significance set *a priori* at P≤0.05 for all analyses and per contemporary statistical recommendations we chose not to control for multiple comparisons.[19] In addition to inferential statistics, Cohen's *d* effect sizes and associated 95% confidence intervals were also calculated to estimate the magnitude and precision of effect due that gait training had on CAI patients. Effect sizes were interpreted as ≥0.80 was large, 0.50-0.79 was moderate, 0.20-0.49 was small, and <0.20 was trivial.[4] Data was analyzed using Statistical Package for Social Sciences (SPSS) Version 20.0 (SPSS, Inc, Chicago, IL).

RESULTS:

Self-reported Outcomes

There was a significant improvement in self-reported function on the FAAM-Sport scale (Pre=75.1±7.1%, Post=85.7±12.2%, P<.001), but not a significant change in FAAM-ADL scores (Pre=92.9.1±3.7%, Post=94.7±4.7%, P=.065), following gait training. The significant improvement in FAAM-Sport scores resulted in a large effect size of 1.06 with a CI that was entirely positive (0.32, 1.80), suggesting meaningful improvements in self-reported function following gait training. On average, the GROC following rehabilitation was a 3±1 (2=a little bit better, 3=somewhat better, 4=moderately better). The average RPE reported immediately following gait training trials was 13±2 (11=light, 13=somewhat hard, 15=hard).

Plantar Pressure

Following gait training, CAI subjects demonstrated significant improvements via a medial shift in the location of their COP from 10% through 100% of the stance phase ($P<.005$ for all 9 dependent variables, Figure 2). Effect size point estimates for 7 of the 9 significant differences for the COP gait line were large with CIs that were entirely positive, suggesting meaningful improvements in the location of the COP following gait training for CAI (Figure 2). There was not a significant improvement in the location of the COP during the first 10% of stance ($P=.07$).

There was a significant increase in the medial midfoot contact area following gait training (Pre=12.3±7.1cm^2, Post=15.3±6.6cm^2; $P=.006$, Table 2). There was also an increase in the medial forefoot pressure time integral (Pre=48.4±15.2kPa*s, Post=52.8±16.4kPa*s; $P=.004$) and hallux peak pressure (Pre=200.9±39.5kPa, Post=216.2±45.9kPa; $P=.024$) following gait training for CAI (Table 2). Effect size point estimates for these significant differences were all small and ranged from 0.28-0.43 with CIs that crossed zero, suggesting uncertainty about the clinical meaningfulness of these small post-gait training changes. There were no other significant changes in plantar pressure following gait training (Table 2).

Surface Electromyography

CAI subjects utilized significantly more peroneus longus muscle activity during 21-60%, and 81-90% of the stance phase following gait training (Table 3). Conversely, there were significant reductions in gluteus medius muscle activity post-gait training during 71-100% of stance (Table 3). Effect size point estimates ranged from small to large for the significant increases in peroneus longus muscle activity and from moderate to large for the significant reductions in gluteus medius muscle activity (Table 4). There were no other significant changes in sEMG activity following gait training for CAI (Table 3).

DISCUSSION:

Five sessions of supervised gait training with a novel gait training device resulted in large improvements in CAI gait patterns and self-reported function. Improvements in the location of COP throughout stance were driven by large increases in peroneus longus muscle activity and there were corresponding reductions in gluteus medius muscle activity during late stance. To our knowledge, this is the first study to elicit meaningful improvements in frontal plane foot and ankle mechanics during gait in CAI patients. These results are important for sports medicine clinicians and researchers involved in the analysis and rehabilitation of gait pathomechanics with CAI.

Following gait training, the average FAAM-Sport score (85.7%) for the entire sample would have been greater than the threshold for inclusion into this study. This finding illustrates how important the restoration of normal gait patterns may be in the rehabilitation for CAI patients. It is very important to note however, that the percent improvement in self-reported function following gait training was roughly half as large when compared to our previous study [8] that employed a 4 week comprehensive rehabilitation program (11% vs. 20% on FAAM-Sport). We believe this underscores the multi-faceted nature of CAI pathophysiology [16,17] and the importance of incorporating gait training into a comprehensive impairment-based rehabilitation program. [9]

This same CAI cohort, in comparison to healthy subjects, demonstrated a laterally deviated COP during the entire stance phase. [23] Furthermore, the CAI subjects demonstrated an increased pressure distribution for the lateral forefoot. [23] Gait training shifted the COP medially for the last 90% of the stance phase but was unable to significantly reduce the peak pressure or the pressure time integral of the lateral forefoot. It is possible our current study was under-powered to detect improvements in the COP location during the first 10% of stance or in the amount of pressure transmitted through the lateral forefoot (which all had p-values <.01 but >.05 with effect size point estimates that ranged from small (0.45) to moderate (0.7)). It is also possible that more than five gait training sessions would be required to elicit those changes.

We previously speculated that an earlier onset and increased activation of the peroneus longus was an inefficient coping mechanism that would not allow CAI patients to effectively pronate during midstance. [12] We have now demonstrated that without changing pre-initial contact peroneus longus muscle activity, CAI patients can increase peroneus longus activation enough during stance to cause meaningful medial shifts in their COP, refuting our previous hypothesis. [12] We have also previously speculated that increased gluteus medius muscle activity during late stance was a coping mechanism to stabilize the lower limb due to the supinated foot position seen with CAI. [23] Our current results support that hypothesis, as the medial shift in the location of the COP following gait training resulted in corresponding reductions in gluteus medius muscle activity during the latter half of stance.

Previous studies have utilized progressive hop to stabilization [28] and comprehensive impairment-based rehabilitation [8] protocols for CAI with the expectation that the improvements in strength and postural control commonly seen with rehabilitation would translate into improved gait biomechanics as inferred from Hertel's [16] spectrum of sensorimotor dysfunction with ankle instability. However, emerging evidence [8,10] suggests that sensorimotor deficits on the more functional end of the spectrum [16] (walking, running, and jump-landing) may require targeted gait or jump-landing interventions in conjunction with traditional rehabilitation for CAI.

The gait training protocol utilized in the current investigation has distinct features that provide insight into gait pathomechanics associated with CAI and for rehabilitation of CAI patients. First, gait training sessions were 7-15 minutes per day over five days for a combined 1-2 hours of gait training, which was enough to elicit meaningful improvements in CAI gait patterns and self-reported function. These improvements were seen without adjunctive therapeutic exercises for range of motion, strength, postural control or other functional tasks. These results provide valuable insight in that gait pathomechanics with CAI are likely the result of poor neuromuscular or inter-segmental coordination and not because of deficits in range of motion, [17,18,32] strength, [1,37] or postural control. [27] We did not record outcome measures on these other physiological parameters and therefore cannot speculate if the gait training influenced any of these other impairment domains. [9] However, previous investigations have demonstrated that improving range of motion, strength and postural control does not manifest into non-pathological gait patterns. [8,28]

The gait training device utilized in this study targets the peroneus longus and gluteus medius muscles while CAI patients perform each stride cycle. These two muscles have been of great interest in the study of CAI pathophysiology and rehabilitation due to their ability to correct hip and ankle frontal plane postural deviations during the gait cycle. [36] Traditionally, strengthening exercises or unstable surfaces are utilized to target these muscles during the rehabilitation of CAI patients. Up to this point however, there has not been an evidence-based approach for transitioning CAI patients from less functional rehabilitation exercises to gait training for the restoration of normal gait patterns. We have now demonstrated that stimulating these muscles throughout the gait cycle can incite the motor learning that may be required to restore non-pathological gait patterns in CAI patients.

Limitations:

Limitations of the current study include the relatively small sample size and potential type II statistical error for outcome measures such as the location of COP during the first 10% of stance and peak pressure and pressure time integral of the lateral midfoot which had low p-values ($P<.01$) and moderate effect sizes (0.50-0.79) that might have been significant and meaningful differences following gait-training with additional subjects. Additionally, this was one of the first studies to perform gait training for CAI and there was no precedent to follow when prescribing an appropriate volume (5 sessions) of gait training sessions. Five sessions was selected based off of pilot testing and it is possible that more sessions or maintenance sessions may be required to fully restore and maintain normal gait patterns in CAI patients. Lastly, gait deficits are only one aspect of CAI pathomechanics and gait training would not commonly be performed in isolation, so these results should be replicated in a larger study that includes comprehensive impairment-based rehabilitation for CAI supplemented with gait training.

Conclusion:

Gait training for CAI with a novel gait training device was able to improve the COP location during the stance phase of gait. The improved gait pattern was driven by increased peroneus longus activity during the majority of stance. Percent improvements in self-reported function were lower than comprehensive rehabilitation protocols and thus we recommend adding gait training that targets the peroneus longus and gluteus medius muscles during gait to existing impairment-based treatment algorithms for CAI.

Acknowledgements
The authors would like to thank Neal Glaviano, Rachel Koldenhoven, and John Fraser for their contributions to supervising gait training (NG), data collection (RK and JF), and data processing (RK).

Conflicts of Interest
Two authors (MF) and (JH) have a patent pending for the novel gait training device utilized in this study. The results of the present study do not constitute endorsement by ACSM.

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TABLES:

Table 3.1: Subject Demographics (n=16)

	Mean (SD)
Age (years)	20.0 (2.6)
Sex	Male: 6, Female: 10
Height (centimeters)	171.3 (10.8)
Mass (kilograms)	68.3 (15.9)
Godin Leisure-Time Exercise Questionnaire Score	63.6 (22.7)
Pre FAAM ADL %	92.9 (3.7)
Pre FAAM Sport %	75.1 (7.1)
idFAI	21.2 (5.3)
Number of Ankle Sprains	5.0 (5.6)
Time Since Last Sprain (months)	16.9 ± 18.4

Abbreviations: FAAM=Foot and Ankle Ability Measure, ADL=Activities of Daily Living, IdFAI=Identification of Functional Ankle Instability

Table 3.2: Plantar pressure measures for the total foot and nine regions of the foot for pre- and post-gait training

		Total Foot	Lateral Heel	Medial Heel	Lateral Midfoot	Medial Midfoot	Lateral Forefoot	Central Forefoot	Medial Forefoot	Toes 2-5	Hallux
Pressure Time Integral	Pre-Gait Training Mean±SD	102.6±20.8	60.9±16.8	52.8±10.0	55.7±24.2	31.3±10.4	62.2±23.2	53.2±11.3	48.4±15.2	50.2±12.7	50.7±15.2
kPa*s	Post-Gait Training Mean±SD	101.7±13.8	58.8±11.0	55.3±7.5	46.7±6.9	33.3±8.1	53.9±11.7	52.9±11.6	52.8±16.4	47.8±14.4	54.5±16.1
	Mean Difference	0.9	2.1	-2.6	9.1	-2.0	8.3	0.3	-4.4	2.4	-3.8
	(95% CI)	(-8.3, 10.1)	(-7.2, 11.5)	(-7.0, 1.8)	(-1.4, 19.5)	(-5.6, 1.6)	(-0.9, 17.5)	(-2.4, 3.0)	(-7.1, -1.6)	(-2.3, 7.0)	(-7.8, 0.2)
	P-value	.837	.637	.232	.085	.263	.074	.818	.004*	.295	.062
	Effect Size	-0.05	-0.15	0.29	-0.51	0.21	-0.45	-0.03	0.28	-0.17	0.24
	(95% CI)	(-0.74, 0.64)	(-0.84, 0.54)	(-0.41, 0.99)	(-1.21, 0.19)	(-0.48, 0.91)	(-1.15, 0.25)	(-0.72, 0.67)	(-0.42, 0.97)	(-0.87, 0.52)	(-0.45, 0.94)
Peak Pressure	Pre-Gait Training Mean±SD	231.8±30.6	209.0±21.9	211.4±20.8	131.5±49.1	87.7±30.9	173.5±41.1	181.2±27.4	174.6±38.7	178.0±29.0	200.9±39.5
kPa	Post-Gait Training Mean±SD	238.9±28.3	215.2±22.3	219.4±17.3	111.6±18.9	93.9±27.8	157.1±30.6	179.0±26.6	180.7±41.1	171.3±34.3	216.2±45.9
	Mean Difference	-7.1	-6.3	-8.0	19.9	-6.2	16.5	2.2	-6.1	6.8	-15.3
	(95% CI)	(-18.4, 4.3)	(-17.8, 5.3)	(-16.1, 0.2)	(-1.0, 40.9)	(-17.8, 5.4)	(-3.3, 36.2)	(-4.7, 9.0)	(-12.5, 0.4)	(-6.8, 20.4)	(-28.3, -2.4)
	P-value	.203	.269	.055	.060	.274	.096	.506	.063	.306	.024*
	Effect Size	0.24	0.28	0.42	-0.54	0.21	-0.45	-0.08	0.15	-0.21	0.36
	(95% CI)	(-0.46, 0.94)	(-0.41, 0.98)	(-0.28, 1.12)	(-1.24, 0.17)	(-0.48, 0.91)	(-1.16, 0.25)	(-0.77, 0.61)	(-0.54, 0.85)	(-0.91, 0.48)	(-0.34, 1.06)
Time to Peak Pressure	Pre-Gait Training Mean±SD	44.5±22.8	15.2±1.9	15.5±1.6	47.7±21.1	32.7±15.9	72.0±9.4	75.9±5.9	76.0±5.5	77.3±5.3	79.3±6.3
% of Stance	Post-Gait Training Mean±SD	45.9±25.1	16.3±3.5	16.7±3.9	46.5±22.3	38.6±20.8	73.7±8.4	76.8±3.4	76.3±3.5	79.3±3.9	81.0±3.9
	Mean Difference	-1.4	-1.1	-1.2	1.2	-5.9	-1.7	-0.9	-0.4	-2.0	-1.8
	(95% CI)	(-10.4, 7.6)	(-2.7, 0.5)	(-3.1)	(-5.0, 7.5)	(-13.4, 1.6)	(-4.1, 0.7)	(-3.3, 1.4)	(-3.0, 2.3)	(-4.5, 0.4)	(-4.4, 0.9)
	P-value	.746	.171	.186	.678	.113	.153	.414	.780	.094	.175
	Effect Size	0.06	0.39	0.40	-0.06	0.32	0.19	0.20	0.08	0.44	0.34
	(95% CI)	(-0.64, 0.75)	(-0.31, 1.09)	(-0.30, 1.10)	(-0.75, 0.64)	(-0.38, 1.02)	(-0.50, 0.88)	(-0.50, 0.89)	(-0.62, 0.77)	(-0.26, 1.14)	(-0.36, 1.03)
Contact Area	Pre-Gait Training Mean±SD	145.4±21.1	19.0±2.8	21.0±2.8	24.9±3.5	12.3±7.1	13.7±1.5	14.2±1.4	12.2±1.4	17.6±2.3	10.4±1.2
cm^2	Post-Gait Training Mean±SD	150.7±21.8	19.3±2.9	21.5±2.9	25.3±3.9	15.3±6.6	14.0±1.4	14.4±1.5	12.3±1.7	18.0±2.2	10.7±1.1
	Mean Difference	-5.2	-0.2	-0.5	-0.4	-2.9	-0.3	-0.2	-0.1	-0.3	-0.3
	(95% CI)	(-11.2, 0.8)	(-1.3, 0.8)	(-1.2, 0.2)	(-1.4, 0.7)	(-4.9, -1.0)	(-0.7, 0.1)	(-0.8, 0.4)	(-0.9, 0.6)	(-1.2, 0.5)	(-0.7, 0.2)
	P-value	.084	.651	.179	.457	.006*	.173	.519	.665	.412	.246
	Effect Size	0.24	0.08	0.17	0.10	0.43	0.20	0.12	0.10	0.15	0.22
	(95% CI)	(-0.45, 0.94)	(-0.61, 0.77)	(-0.52, 0.87)	(-0.59, 0.79)	(-0.27, 1.13)	(-0.50, 0.89)	(-0.57, 0.82)	(-0.60, 0.79)	(-0.55, 0.84)	(-0.47, 0.92)
Contact Time	Pre-Gait Training Mean±SD	690.3±96.6	644.6±135.1	557.1±174.7	683.0±103.4	628.1±131.8	672.5±107.9	630.1±125.9	588.1±143.9	619.9±133.7	586.1±150.6
ms	Post-Gait Training Mean±SD	665.8±52.3	631.7±85.5	571.9±118.8	665.1±52.4	610.0±92.0	656.4±54.3	605.8±98.0	587.6±103.6	601.1±102.3	602.7±104.5
	Mean Difference	24.5	12.9	-14.8	17.9	18.1	16.1	24.3	0.5	18.8	-16.6
	(95% CI)	(-17.0, 65.9)	(-41.6, 67.4)	(-104.2, 74.7)	(-28.6, 64.3)	(-44.8, 81.0)	(-30.3, 62.5)	(-21.6, 70.2)	(-46.0, 47.1)	(-32.7, 70.3)	(-74.6, 41.4)
	P-value	.227	.620	.730	.425	.548	.471	.277	.981	.449	.551
	Effect Size	-0.32	-0.11	0.10	-0.22	-0.16	-0.19	-0.22	0.00	-0.16	0.13
	(95% CI)	(-1.01, 0.38)	(-0.80, 0.58)	(-0.59, 0.79)	(-0.91, 0.48)	(-0.85, 0.53)	(-0.88, 0.51)	(-0.91, 0.48)	(-0.70, 0.69)	(-0.85, 0.54)	(-0.57, 0.82)

kPa= kilopascals, s=second, SD = Standard Deviation, CI=Confidence Interval, cm=centimeter, ms=millisecond

* Indicates significant difference between pre- and post-gait training ($P \leq 0.05$)

Table 3.3: Paired t-tests statistical results and mean differences for pre- to post-gait training surface electromyography (sEMG)

	Anterior Tibialis		**Peroneus Longus**		**Medial Gastrocnemius**		**Gluteus Medius**	
Percent of Stance	Mean Difference (95% CI)	P-value	Mean Difference (95% CI)	P-value	Mean Difference (95% CI)	P-value	Mean Difference (95% CI)	P-value
1-10	-2.6 (-12.7, 7.6)	0.59	-0.4 (-3.0, 2.2)	0.73	-0.9 (-3.4, 1.6)	0.44	0.8 (-0.7, 2.2)	0.28
11-20	-5.7 (-12.0, 0.6)	0.07	-1.8 (-4.4, 0.7)	0.15	-0.9 (-3.4, 1.6)	0.46	1.2 (-0.3, 2.8)	0.12
21-30	-2.2 (-5.8, 1.4)	0.20	-2.8 (-5.2, -0.4)	0.03*	-1.4 (-5.6, 2.8)	0.49	1.0 (-0.6, 2.5)	0.21
31-40	-0.1 (-1.8, 1.6)	0.92	-2.1 (-4.0, -0.3)	0.03*	-3.2 (-11.2, 4.8)	0.40	1.5 (-1.3, 4.3)	0.28
41-50	0.4 (-1.0, 1.7)	0.55	-3.1 (-5.2, -1.1)	0.01*	-2.3 (-8.9, 4.3)	0.46	1.5 (-1.2, 4.2)	0.25
51-60	-0.2 (-1.3, 1.0)	0.77	-2.9 (-5.5, -0.2)	0.04*	0.1 (-2.5, 2.8)	0.91	0.6 (-1.2, 2.4)	0.51
61-70	-0.1 (-1.3, 1.1)	0.86	-2.8 (-6.0, 0.4)	0.08	1.1 (-2.1, 4.3)	0.48	0.6 (-0.4, 1.7)	0.21
71-80	-0.2 (-1.4, 1.0)	0.76	-1.7 (-5.1, 1.6)	0.28	2.1 (-2.6, 6.8)	0.36	0.9 (0.0, 1.7)	0.05*
81-90	-1.6 (-4.3, 1.1)	0.22	-2.1 (-3.9, -0.3)	0.03*	2.3 (-2.8, 7.3)	0.35	1.0 (0.2, 1.7)	0.01*
91-100	-1.8 (-6.7, 3.1)	0.44	-1.0 (-2.3, 0.4)	0.14	3.4 (-5.2, 12.0)	0.41	1.7 (0.4, 2.9)	0.01*
Percent of Swing								
1-25	-1.2 (-6.3, 4.0)	0.63	-0.5 (-1.3, 0.3)	0.22	3.3 (-3.7, 10.3)	0.34	7.3 (-0.2, 14.8)	0.06
26-50	-2.4 (-5.6, 0.8)	0.13	-0.5 (-1.4, 0.4)	0.28	-0.2 (-3.3, 2.8)	0.87	3.7 (-1.1, 8.4)	0.12
51-75	-1.2 (-3.8, 1.5)	0.36	-1.0 (-3.4, 1.3)	0.35	-0.9 (-3.3, 1.5)	0.45	1.4 (-1.1, 4.0)	0.25
76-100	0.2 (-7.1, 7.4)	0.96	-1.0 (-3.2, 1.2)	0.34	-1.0 (-3.7, 1.6)	0.41	0.6 (-0.5, 1.6)	0.26

Table 3.4: Group means and Cohen's d effect sizes for pre- to post-gait training surface electromyography (sEMG)

	Anterior Tibialis			Peroneus Longus			Medial Gastrocnemius			Gluteus Medius		
Percent of Stance	Pre-Gait Training Mean±SD	Post-Gait Training Mean±SD	ES (95% CI)	Pre-Gait Training Mean±SD	Post-Gait Training Mean±SD	ES (95% CI)	Pre-Gait Training Mean±SD	Post-Gait Training Mean±SD	ES (95% CI)	Pre-Gait Training Mean±SD	Post-Gait Training Mean±SD	ES (95% CI)
1-10	32.4±19.1	35.0±14.8	0.15 (-0.57, 0.87)	5.4±4.5	5.8±4.7	0.09 (-0.62, 0.81)	2.4±1.2	3.3±4.5	0.28 (-0.42, 0.97)	5.1±2.2	4.3±2.8	-0.30 (-1.02, 0.42)
11-20	17.1±9.4	22.8±9.6	0.60 (-0.13, 1.33)	4.2±2.8	6.0±4.3	0.51 (-0.22, 1.24)	2.3±1.1	3.2±4.5	0.27 (-0.42, 0.97)	6.7±3.8	5.4±2.9	-0.37 (-1.09, 0.35)
21-30	7.2±5.3	9.4±5.7	0.41 (-0.31, 1.13)	4.6±1.9	7.4±4.6	0.80* (0.06, 1.54)	3.6±2.2	5.0±7.7	0.25 (-0.45, 0.94)	4.8±3.0	3.9±1.4	-0.41 (-1.14, 0.31)
31-40	5.6±4.3	5.7±2.8	0.02 (-0.69, 0.74)	5.4±2.8	7.6±3.2	0.70* (-0.03, 1.44)	6.1±3.7	9.3±15.1	0.29 (-0.40, 0.99)	4.9±4.5	3.4±1.6	-0.43 (-1.15, 0.29)
41-50	4.7±3.6	4.3±1.8	-0.13 (-0.85, 0.58)	5.6±2.6	8.7±4.2	0.90* (0.15, 1.65)	9.2±5.7	11.5±14.6	0.21 (-0.48, 0.90)	4.7±4.2	3.2±1.7	-0.46 (-1.19, 0.26)
51-60	4.3±3.0	4.5±1.7	0.06 (-0.65, 0.78)	7.7±2.6	10.5±5.4	0.62* (-0.11, 1.35)	12.9±8.1	12.7±9.7	-0.02 (-0.71, 0.68)	3.9±2.8	3.3±1.4	-0.25 (-0.97, 0.46)
61-70	4.9±3.6	5.0±2.4	0.03 (-0.68, 0.75)	10.5±3.6	13.3±8.6	0.40 (-0.32, 1.12)	15.5±8.0	14.5±9.1	-0.13 (-0.82, 0.57)	3.4±1.6	2.7±1.3	-0.45 (-1.17, 0.27)
71-80	4.8±2.9	4.9±2.5	0.06 (-0.65, 0.78)	11.9±4.9	13.7±10.0	0.20 (-0.51, 0.92)	16.2±8.8	14.1±10.0	-0.22 (-0.91, 0.48)	3.0±1.6	2.1±0.9	-0.69* (-1.42, 0.05)
81-90	3.7±1.8	5.3±4.9	0.44 (-0.28, 1.17)	7.4±6.9	9.5±6.6	0.35* (-0.38, 1.07)	12.7±11.4	10.4±10.0	-0.21 (-0.91, 0.48)	2.8±1.2	1.8±0.9	-0.92* (-1.67, 0.17)
91-100	7.4±5.4	9.2±9.2	0.24 (-0.48, 0.96)	3.3±5.6	4.2±2.1	0.45 (-0.27, 1.18)	16.4±14.7	13.0±15.6	-0.22 (-0.92, 0.47)	3.7±2.4	2.1±1.0	-0.92* (-1.67, -0.16)
Percent of Swing												
1-25	13.6±7.8	14.8±9.5	0.14 (-0.58, 0.85)	2.5±2.1	3.0±1.9	0.29 (-0.43, 1.01)	12.5±11.1	9.2±12.6	-0.27 (-0.97, 0.42)	10.1±13.1	2.8±2.1	-0.78 (-1.52, -0.03)
26-50	11.0±5.5	13.5±5.0	0.46 (-0.26, 1.19)	2.0±1.4	2.5±1.7	0.31 (-0.41, 1.03)	2.8±3.6	3.0±4.4	0.06 (-0.64, 0.75)	6.3±7.9	2.6±1.8	-0.65 (-1.38, 0.09)
51-75	9.5±5.1	10.7±4.3	0.25 (-0.47, 0.97)	2.3±1.5	3.3±4.1	0.33 (-0.39, 1.05)	2.0±1.3	2.9±4.4	0.27 (-0.43, 0.96)	3.1±4.4	1.7±0.8	-0.45 (-1.18, 0.27)
76-100	22.3±13.7	22.1±10.8	-0.01 (-0.73, 0.70)	4.0±1.8	5.0±5.0	0.25 (-0.47, 0.97)	2.1±1.5	3.2±4.8	0.29 (-0.41, 0.99)	2.8±1.7	2.2±1.2	-0.38 (-1.10, 0.34)

FIGURES:

Figure 3.1: Gait training device

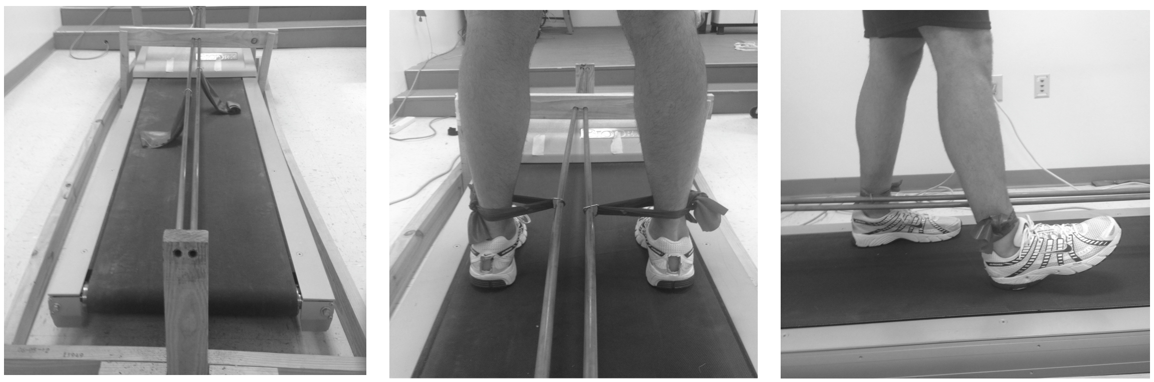
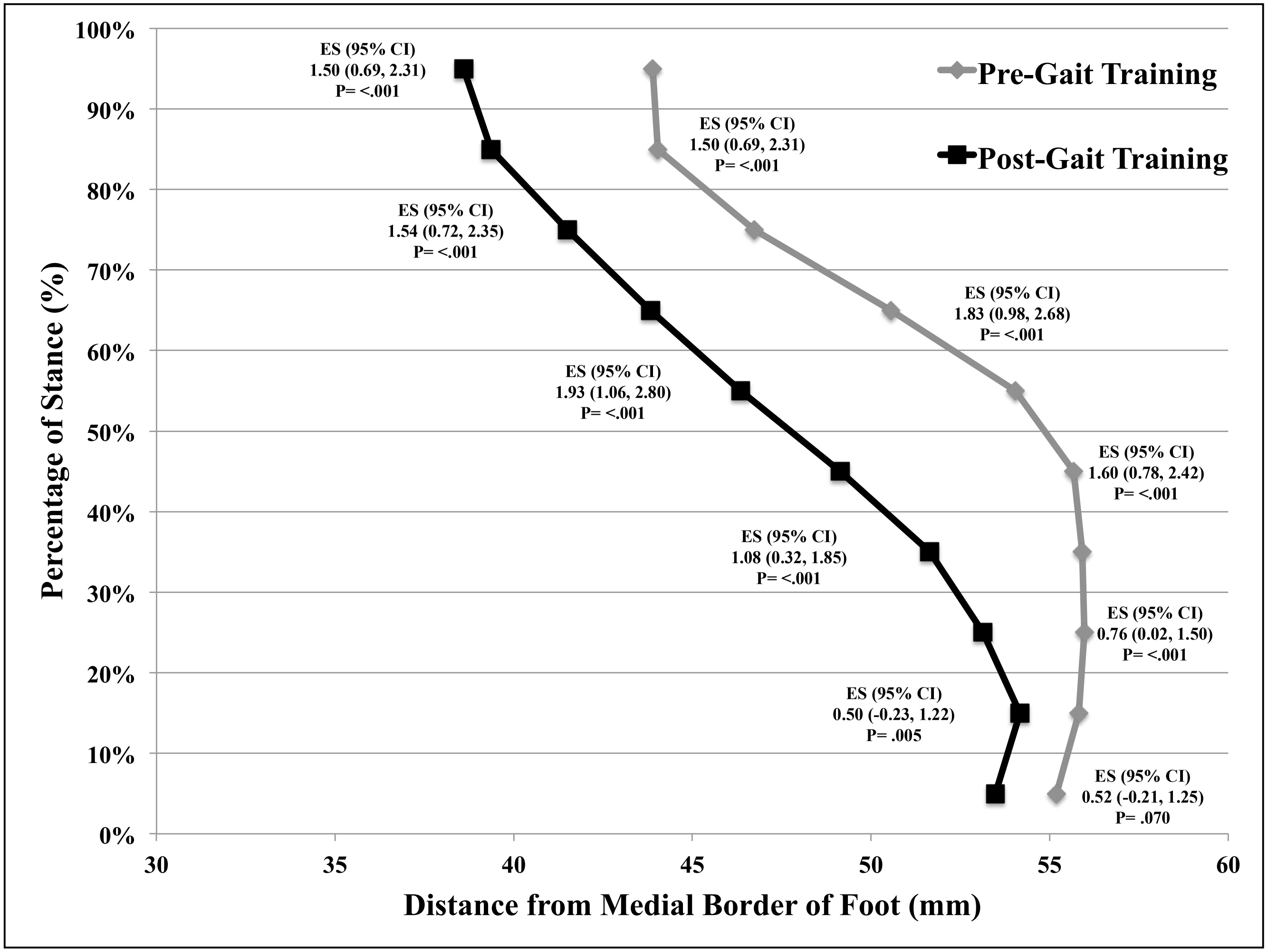


Figure 3.2: Paired t-test statistical results and Cohen's d effect sizes for COP gait line pre- and post-gait training



SECTION III: APPENDICES

APPENDIX A
The Problem

Ankle sprains are the most common musculoskeletal injury and are estimated to account for 15% of all sport related injuries. [1] Additionally, over 2 million ankle sprains occur per year in the United States. [3] Following an initial ankle sprain up to 40% of individuals develop chronic ankle instability (CAI). [80] CAI is characterized by recurrent sprains, multiple episodes of giving way, persistent symptoms and diminished self-reported function. [74] CAI has tremendous short- and long-term implications. Nearly 72% of individuals suffering from an ankle sprain are unable to maintain their previous physical activity level. [44] In addition, 70-85% of end-stage ankle osteoarthritis cases that result in surgery are post-traumatic cases, and many of these cases result in drastically diminished quality of life. [43,44]

Deficits in proprioception, [81] peroneal reaction time, [53] ankle strength, [45,77] muscle volume, [49] and postural control [78] have all been identified in patients with CAI. More functional impairments have been identified in lower extremity kinematics during gait [67,69,82] and jump landing, [15,16,83] that may predispose CAI patients to subsequent episodes of instability or recurrent sprain. [13] Specifically, the increased inversion prior to ground contact during gait and jump landing has been identified as an important factor that will dictate whether an ankle sprain occurs following ground contact. [13] There have been tremendous strides in the understanding of the pathophysiology and pathomechanics of lateral ankle sprain and residual ankle instability. [7,75] The large advancements in our understanding of CAI has led to evidence based recommendations for impairment-based treatments of the common clinical manifestations of this condition. [30] Specifically, clinicians are encouraged to screen for range of motion, strength, balance, and functional specific impairments in CAI patients. [30]

Evidence suggests that arthrokinematic and osteokinematic restrictions to ankle joint range of motion can be improved upon with joint mobilizations and calf-stretching. [19,21] In regards to strength, we have recently identified that CAI patients have smaller muscle volumes and corresponding decreases in ankle strength. [49] Rehabilitation is effective at restoring normal ankle strength, [25,37] however, there is currently no evidence to suggest whether the improvements in ankle strength are due to improved motor recruitment or muscle hypertrophy. Therefore one purpose (Study 2) of this dissertation is to analyze the effects of comprehensive impairment-based rehabilitation on muscle volume and ankle strength in CAI patients.

In regards to postural control, CAI patients consistently demonstrate deficits in postural control [78] and more importantly, balance training drastically improves postural control and self-reported function. [24,50,84] As the impairments associated with CAI become more functional, such as gait and jump landing, the ability of the clinician to identify and prescribe interventions to target the deficits becomes increasingly difficult. It has been hypothesized that restoring range of motion, strength, and balance may subsequently improve the more functional impairments without specifically targeting the improper (inverted) foot position prior to ground contact during both gait and jump landing tasks. [75] We have previously identified that improvements in range of motion, strength, and balance do not translate into meaningful improvements in foot and ankle gait mechanics in CAI patients. [25] However, up to this point, no one has assessed whether those improvements following rehabilitation translate into safer jump landing strategies. Therefore a second purpose (Study 1) of this dissertation is to analyze the effects of comprehensive rehabilitation on jump landing mechanics in CAI patients.

Due to the results of our aforementioned study that illustrated how comprehensive impairment-based rehabilitation does not improve gait patterns in CAI patients [25] we came to the conclusion that specifically targeting gait training may be required to restore normal gait mechanics. We have developed a novel gait training device that targets the peroneus longus and gluteus medius throughout the entire gait cycle. [71] CAI patients, when using this device have demonstrated meaningful improvements in the location of their center of pressure during the entire stance phase. [71] However, there is a need to assess whether this method of gait training can improve gait mechanics after CAI patients perform multiple gait training sessions. Therefore, the last purpose of this dissertation is to analyze the effects of gait training with a novel gait training device on measures of plantar pressure and motor recruitment in CAI patients.

Research Questions

Study 1. Do the effects of a 4-week impairment-based rehabilitation program improve jump landing kinetics, kinematics, and muscle activity in CAI patients?

Study 2. Do the effects of a 4-week impairment-based rehabilitation program increase intrinsic and extrinsic foot and ankle muscle volumes and four-way ankle strength in CAI patients?

Study 3. Does gait training with a novel gait training device improve gait patterns in CAI patients?

Experimental Hypothesis

Study 1. CAI patients will be less inverted and plantar flexed prior to landing and demonstrate a concurrent increase in peroneus longus, peroneus brevis and medial gastrocnemius muscle activity.

Study 2. CAI patients will exhibit hypertrophy of intrinsic and extrinsic foot and ankle muscles.

Study 3. CAI patients will demonstrate a medial shift in the location of their center of pressure with concurrent increases in peroneus longus and gluteus medius muscle activity prior to and following ground contact.

Assumptions

- Participants will be honest when answering questions related to inclusion/exclusion criteria
- Participants will give their best effort during rehabilitation and gait training sessions
- Participants will perform jump-landing and gait training tasks to the best of their ability
- Measurement techniques will accurately reflect the current state of each participant

Delimitations

- Participants were limited by our recruitment scope to the university setting, 18-40 years of age, and represent a sub-set of the CAI population that falls within a specific level of self-reported dysfunction per our inclusion criteria.
- Participants for jump-landing and gait training wore standardized lab shoes for data collection
- Participants in the muscle volume study represent CAI patients with a greater degree of self-reported disability (<75% FAAM-Sport) due to the small sample size utilized for that particular study

Limitations

Jump-landing (Study 1)

None of the participants reached the final progression during the rehabilitation protocol. Therefore, we do not know if continued rehabilitation may have improved jump-landing mechanics or if specific jump-landing training is required.

Muscle Volume (Study 2)

We do not have concurrent surface electromyography data from numerous foot and ankle muscles to increase our understanding of improved ankle strength, muscle size, and neuromuscular function following rehabilitation. Furthermore, participants were not familiar with short-foot exercises prior to rehabilitation and thus improvements in intrinsic foot muscle volumes may have been seen after a longer duration of rehabilitation that incorporates short foot exercises.

Gait Training (Study 3)

This study was the next step in proving the concept of gait training with our novel gait-training device and thus subjects only performed 5 gait training sessions. Very few of the subjects progressed to a higher level of resistance during gait training sessions and it is possible that more than 5 sessions would be required to truly restore gait patterns in CAI patients.

Overall (Studies 1-3)

We do not have long-term data on jump-landing mechanics, muscle volumes, strength, or plantar pressure during gait and thus we have no way of knowing if the improvements demonstrated at the initial follow-up will be maintained over time. Furthermore, we do not have long-term outcomes on self-reported function or history of subsequent ankle sprain following rehabilitation or gait training to know if improvements seen from our analyses translate into better outcomes or injury prevention over the long-term.

Significance of the Study

A 4-week progressive impairment based rehabilitation program increased shank muscle volumes and ankle strength but only demonstrated minimal improvements in jump-landing kinematics and kinetics. We have now demonstrated that even the most comprehensive rehabilitation programs for CAI patients are insufficient at restoring normal jump landing mechanics and thus future studies may need to supplement comprehensive rehabilitation with augmented bio-feedback to improve landing strategies. Lastly, we have demonstrated that by targeting the peroneus longus and gluteus medius muscles during gait training clinicians can improve the medial to lateral position of the center of pressure throughout the gait cycle in CAI patients. Furthermore, since we improved gait patterns with less than 2 hours of total gait training, we have provided evidence that altered gait patterns seen with CAI are likely related to poor neuromuscular or inter-segmental coordination as opposed to range of motion, strength or postural control deficiencies as previously hypothesized.

APPENDIX B

Literature Review

The purpose of this literature review is to: 1. Overview the etiology and epidemiology of lateral ankle sprains 2. Describe chronic ankle instability, associated functional pathomechanics, and long term effects of recurrent sprain and 3. Introduce the instrumentation and devices utilized in the assessment and treatment of functional insufficiencies for CAI.

Etiology and Epidemiology of Lateral Ankle Sprains

Lateral ankle sprains, as a result of an inversion mechanism, typically involve damage to the anterior talofibular (ATFL) and calcaneofibular ligament (CFL). [74,85] Injury occurs when the inversion stress exceeds the tensile strength of the lateral ankle ligaments. It has been shown that foot position at ground contact is an important factor that will dictate whether or not an ankle sprain is sustained during a given task. [13] Specifically, increased plantarflexion and inversion at ground contact increases the chance of ankle sprain. [13] Following a lateral ankle sprain, most patients experience pain, develop edema, and have various functional limitations. [86] Pain rapidly resolves during the first two weeks following injury and residual pain after this point diminishes more slowly. [86]

Nearly 2 million people in the United States sprain their ankle each year [4] and ankle sprains are the most common musculoskeletal injury in athletics. [1,87,88] Ankle sprains most commonly occur during functional tasks, such as, running, cutting, or landing from a jump. [2,3] A 16-year injury surveillance study of 15 NCAA men's and women's sports showed that 14.8% of all injuries were ankle sprains [1] and the rate of sprain appears to be greater in females (13.6 per 1000 exposures) than it is in males (6.94 per 1000 exposures). [89] Furthermore, the rate of ankle sprain appears to be highest in children (2.85 per 1000 exposures) and then decreases as children get older and become adolescents (1.94 per 1000 exposures) and then decreases even further as individuals become adults (0.72 per 1000 exposures). [89]

Chronic Ankle Instability – Definition and Long Term Effects of Recurrent Sprain

Nearly 40% of patients who sprain their ankle develop chronic ankle instability (CAI). [6] The definition of CAI has evolved over the years as the understanding of this complex heterogeneous condition improves. CAI is characterized by recurrent sprains, multiple episodes of ankle giving way, persistent symptoms, and diminished self-reported function for at least one year following a significant ankle sprain. [7] Seven out of every ten people that sprain their ankle are unable to maintain their previous level of physical activity and many of these patients may develop post-traumatic osteoarthritis. [43,44] It has been shown that 25% of all ankle sprain patients still report subjective instability and/or pain and only15-45% report full recovery 3 years post ankle sprain. [86] This is concerning, when considering over half of all ankle sprains go untreated [41] and 95% of all ankle sprain patients return to sport within 10-days. [63] Of those that to seek medical care, less than 7 percent actually receive the evidence based physical therapy for the restoration of normal function and preventions of re-injury. [42,90]

There is a wide spectrum of pathological characteristics that depict this heterogeneous condition known as CAI. [7,75] These characteristics range from structural deficits such as joint laxity to functional impairments in gait, landing and cutting mechanics.[75] Due to the wide range of potential deficits seen in CAI patients, Donovan and Hertel[30] developed a treatment algorithm that encourages clinicians to assess for and treat specific CAI impairments with targeted therapeutic interventions. This algorithm was instrumental in the development of the rehab protocol utilized in the dissertation (Study 1 and Study 2).

The four impairment domains were established for the most commonly described insufficiencies seen in the literature concerning CAI.[30] The algorithm encourages clinicians to assess for potential arthrokinematic and osteokinematic range of motion restrictions, muscle strength and endurance as well as more functional impairments during balance tasks, gait, running, cutting, and jump landing.[30] As the complexity and speed of the task increases, the ability of a clinician to identify the known insufficiencies becomes more challenging.

Chronic Ankle Instability – Known Functional Insufficiencies and Benefits of Rehabilitation

Strength

Evidence of strength deficits and its role in CAI has been conflicting in previous literature as many studies have failed to demonstrate concentric strength deficits in individuals with CAI,[91-93] while others[94,95] have clearly demonstrated the proposed impairments. The conflicting literature led Arnold and colleagues to perform a meta-analysis that indicated a concentric evertor weakness in participants with unstable ankles does in fact exist.[77] However, the authors concluded that the number of subjects to identify to deficit that is likely present is problematic from a research design perspective and other methods of muscle function should be identified for this patient population. [77] Furthermore, evidence suggests that deficits in both invertor and evertor strength [96,97] can effectively be addressed with strength training interventions. [22,23] While we will not be utilizing strength as a direct outcome measure in our study, we will be looking at muscle volume, which has been shown to be a good estimation of torque generating capacity and overall muscle health (hypertrophy vs. disuse atrophy).

Decreased physical activity, [44] neuromuscular dysfunction, [16,59,66,98] and decreased joint range of motion [74,99,100] are not only common characteristics of CAI patients, but these factors are well documented as potential causes of muscle atrophy. [101] Clinical manifestations of muscle atrophy could include muscle weakness, altered movement patterns and increased risk of injury, which have consistently been reported in CAI patients. [45,75,77] Atrophy of foot and ankle musculature has been identified in individuals with post-traumatic ankle osteoarthritis [102] and following foot and ankle immobilization, [103] and we have recently identified large and we recently identified meaningful deficits in muscle volume and concurrent four-way ankle strength weakness in CAI patients when compared to age-, sex-, and limb-matched healthy controls. [49] Interestingly, we did not identify any muscle volume differences between groups in the peroneal muscles (lateral compartment). [49] This finding was particularly interesting considering that the CAI eversion strength deficit was the largest group difference identified in the same subjects in regards to ankle strength. [49] This suggests that eversion strength deficits [77] may be related to neuromuscular mechanisms as opposed to muscle size and associated torque generating capacity.[49] We previously identified large and meaningful improvements in force output following comprehensive impairment-based rehabilitation[25] for CAI and we will be assessing the effects of the same rehabilitation protocol on intrinsic and extrinsic foot and ankle muscle volumes as part of this dissertation (study 2).

Postural Control

Postural control can be thought of as the ability to maintain the correct posture in order to carry out a specific or skilled task.[104] Postural control is typically assessed during single-limb stance.[105] Altered postural control has been identified during static[78,106,107] and dynamic[108,109] balance tasks in patients with CAI. Additionally, decreased postural stability has been identified as being a potential risk factor for sustaining an initial or recurrent ankle sprain.[78] Static balance deficits are usually identified with instrumented spatiotemporal measures such as time to boundary calculations,[106] whereas dynamic balance deficits can be detected clinically with the Star Excursion Balance Test (SEBT).[110,111] We recently identified that patients with CAI exhibit large decreases in anterior tibialis and total lower extremity muscle activity while performing both single limb balance and the SEBT exercises when compared to healthy subjects.[59] Mckeon et al.[24] found that 4-weeks of supervised single limb balance training can improve postural control and self-reported function in patients with CAI. Our impairment-based rehabilitation program resulted in large improvements in both static and dynamic balance measures in CAI patients[25] and we will be investigating how the collective improvements in range of motion, strength and balance influence jump-landing mechanics in the same subjects as part of this dissertation (study 1).

Gait

During walking, patients with CAI demonstrate moderate increases in ankle inversion just prior to and following initial contact. [66,67] The increased inversion positioning following initial contact is associated with increased lateral loading during stance. [67] Furthermore, the medial to lateral center of pressure (COP) in CAI subjects is significantly further lateral than in healthy counterparts. [69] In order to improve ankle joint position prior to ground contact, patients with CAI activate their peroneus longus prior to ground contact, whereas healthy counterparts do not activate their peroneus longus until the initiation of pronation during mid-stance. [98] Improper foot position prior to ground contact is theorized to play a role in the frequent rate of recurrence or the repetitive sensations of giving way in this pathological population. McKeon et al. [70] demonstrated that four weeks of supervised balance training significantly altered shank and rearfoot coupling during gait, but was ineffective at improving inversion/eversion kinematics in CAI patients. We recently utilized a 4-week comprehensive impairment-based rehabilitation program for CAI and unfortunately were also unsuccessful at restoring normal foot and ankle kinematics and kinetics during gait. [25] There is currently no evidence in regards to the ability of gait retraining at restoring a normal gait pattern in CAI patients, however, we aim to test a novel gait training device that has demonstrated promising outcomes while participants with CAI are using the device. [71] The increased peroneus longus and gluteus medius muscle activity seen while CAI participants use the device was capable of shifting their laterally deviated COP in the medial direction. [71] We are now investigating the effects of serial gait training with this novel device on plantar pressure and muscle activity as part of this dissertation (study 3).

Jump-Landing

Delahunt et al [16] identified that patients with CAI have increased inversion (~4° more inverted) prior to initial contact and they are less dorsiflexed following initial contact (~5° more plantar flexed). The increased inversion positioning identified prior to initial contact was likely related to the decreased peroneus longus muscle activity identified during that phase of landing. [16] The decreased dorsiflexion positioning following initial contact was associated with increased ground reaction forces and a slower time to the more stable closed packed ankle position. [16] Furthermore, Gribble et al [17] identified decreased knee flexion positioning at ground contact and increased time to stabilization after ground contact in CAI patients. Collectively, these jump-landing studies indicate that CAI patients land on a more rigid limb, which may increase the demand on static and dynamic lateral ankle stabilizers. Hertel's [75] spectrum of sensorimotor dysfunction in CAI patients suggests that functional impairments in jump-landing may be improved by concurrent improvements in range of motion, strength and postural control. We have demonstrated that these impairment domains [30] have been improved following rehabilitation [25] and with the current investigation we aim to see if those less functional improvements influence jump-landing strategies post-rehabilitation. (Study 1)

Dissertation Measurement Techniques

Electromagnetic Motion Capture (Study 1)

For our study, three-dimensional joint kinematics of the ankle, knee, and hip were measured using the *TrackSTAR* (Ascension Technologies, Inc., Burlington, Vermont) electromagnetic motion analysis system and Motion Monitor software (Version 8, Innovative Sports Training, Inc., Chicago, Illinois) at a sampling rate of 144 Hz. A non-conductive forceplate (Bertec Corporation, Columbus, Ohio) with a sampling rate of 1440 Hz was used to collect ground reaction forces and for determination of initial contact of the involved limb during the jump-landing task.

Surface Electromyography (Study 1 and Study 3)

Surface electromyography (sEMG) is a non-invasive way to measure and record electrical muscle activity. It has been demonstrated that sEMG can be used to record the initiation and cessation of electrical muscle activity as well as an estimate of motor recruitment when compared to a self normalized value. [112] Surface EMG has also been used clinically as an index of fatigue. [112,113] The signal recorded through the electrodes in known as a motor unit action potential (MUAP). [113] The sum of the electrical activity across all muscle fibers innervated by a single motor unit comprises the MUAP. [113] Processing of sEMG includes rectification, smoothing, digital filtering, and amplitude normalization. [114]

For our study, sEMG was collected using 2 parallel bar rectangular sensors. Each bar was 1 mm wide and 1 cm long with an inter-electrode distance of 1 cm. The sensors were DE 2.1 differential EMG sensors (Delsys, Boston, MA). The signal was amplified with a gain of 1000 and digitized with a 4 channel acquisition system (Bagnoli EMG system, Delsys, Boston, MA) at 1000 Hz. Input impedance was $>10^{15}\Omega/0.2$pF with a signal to noise ratio of 1.2uV. Data was collected with Motion Monitor software (Innovative Sports Training, Inc., Chicago, Illinois).

Magnetic Resonance Imaging for Foot and Ankle Muscle Volumes (Study 2)

For our study, subjects were scanned on a 3 Tesla Siemens Trio MRI scanner as previously described [54] from just superior of the medial and lateral femoral condyles through the entire foot and ankle. Images were acquired using a 2-D multi-slice non-Cartesian spiral gradient echo sequence and scan time was approximately 15 minutes per subject. Scan parameters for the shank were as follows: TE/TR/α: 3.8ms/800ms/90°, field of view: 400mm x 400mm, slice thickness: 5mm, in plane spatial resolution: 1.1mm x 1.1mm. Scan parameters were identical for the foot with the exception of a smaller field of view (250mm x 250mm) and commensurately higher resolution. Due to the smaller field of view for the intrinsic foot muscles, a Siemans 4-channel large flex coil was utilized to increase the signal-to-noise ratio.

Four-way Ankle Strength Testing (Study 2)

For our study, ankle strength (dorsiflexion, plantarflexion, inversion, and eversion) was measured using a hand-held dynamometer (Accelerated Care Plus Corp, Reno, NV).

In-Shoe Plantar Pressure (Study 3)

For our study, plantar pressure was measured using the Pedar-x plantar pressure system (Novel Inc, St Paul MN) with in-shoe insoles that had a sampling rate of 100 Hz.

Gait Training Device (Study 3)

For our study, we will be using the same gait training device as our previous investigation that analyzed the effects of the device while participants used the device. [71] The gait training device was designed for use with a treadmill and was developed to target activation of the hip abductors and lateral ankle musculature prior to and following ground contact in an effort to decrease plantar pressure on the lateral column of the foot during the stance phase of gait. [71] For set-up, participants stand with their feet shoulder width apart, with the gait training device tracks positioned between their legs at a height of approximately the distal 1/3 of the participant's shank. [71] Elastic bands are then secured bilaterally around the lower leg of each participant by the supervising clinician. Elastic bands are stretched to approximately 150% of their resting length and tied around the lower leg. [71] Heel strike targets are positioned at approximately shoulder width apart and the user is instructed to hit the target with the heel during each step. [71]

Conclusion

CAI is a multi-faceted condition that represents a very large healthcare burden to individual patients and the health care system. There have been significant advancements in the understanding of CAI pathophysiology and pathomechanics during functional tasks. Contemporary clinical recommendations emphasize an 'assess – treat – reassess' paradigm for the rehabilitation of CAI patients, however, there is limited evidence in regards to three important clinical questions we aim to address with this dissertation project: 1) Do the improvements in range of motion, strength, and postural control seen following rehabilitation for CAI patients translate into safer landing strategies? 2) Do the increases in four-way ankle force seen following rehabilitation for CAI coincide with improvements in intrinsic and extrinsic muscle volumes? 3) Can targeting the peroneus longus and gluteus medius during gait training with a novel gait training device improve the gait patterns in CAI patients?

APPENDIX C
Additional Methods

<u>Jump-Landing</u>

1. Questionnaires

1. Foot and Ankle Ability Measure ADL/Sport
2. Identification of FAI
3. Godin Leisure-time exercise questionnaire
4. Global Rating Change Score

2. Descriptive Measures

1. Age
2. Height
3. Weight

3. Motion Monitor Data Collection Procedures (Jump Landing)

<u>Subject Preparation</u>

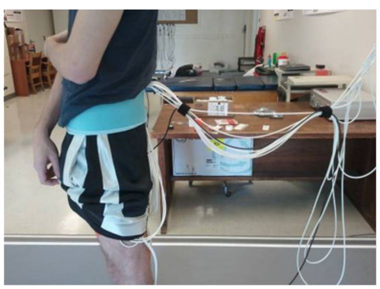
1. EMG Electrode Placement
    a. Double sided toupee tape was pre-applied to the active electrodes prior to subject arrival at the Exercise and Sport Injury Laboratory
2. EMG Electrode Placement
    i. This area was shaved using a disposable razor
    ii. The area was then lightly debrided using a brillo pad
    iii. The area was cleansed using isopropyl alcohol
    iv. A small mark was made at the location site for the electrode Subjects were instructed to leave the table and walk to the platform containing the Motion Monitor
3. The other side of the double-sided toupee tape covering was removed from the electrode
    a. The electrode was placed directly over the mark
    b. The electrode was secured in place with Leuokotape
4. The ground electrode was applied to the tibia of the nondominant limb
    a. This area was shaved using a disposable razor
    b. The area was then lightly debrided using a brillo pad
    c. The area was cleansed using isopropyl alcohol
5. Motion Monitor Sensor Placement (Figure C3)
    a. All areas were shaved as needed
    b. All sensors had double sided toupee tape attached to them
    c. Sensor 1 was placed on the dorsum of the right midfoot
        i. Sensor was secured in place using Leuokotape
        ii. Sensor cord was looped into the Leuokotape to avoid a tripping hazard
    d. Sensor 2 was placed on the dorsum of the left midfoot
        i. Sensor was secured in place using Leuokotape

    ii. Sensor cord was looped into the Leuokotape to avoid a tripping hazard

e. Sensor 3 was placed on the right lateral shank
    i. Sensor was secured in place using Leuokotape
    ii. Sensor cord from sensor number 1 was gathered together with the cord for sensor 3
    iii. Cords were not pulled taught in order to allow free movement of the joint and body segments
    iv. Sensor cords were looped into the Leuokotape to avoid a tripping hazard
f. Sensor 4 was placed on the left lateral shank
    i. Sensor was secured in place using Leuokotape
    ii. Sensor cord from sensor number 2 was gathered together with the cord for sensor 4
    iii. Cords were not pulled taught in order to allow free movement of the joint and body segments
    iv. Sensor cords were looped into the Leuokotape to avoid a tripping hazard
g. Sensor 5 was placed on the right lateral thigh
    i. Sensor was secured in place using Leuokotape
    ii. Sensor cords from sensor numbers 1 and 3 were gathered together with the cord for sensor 5
    iii. Cords were not pulled taught in order to allow free movement of the joint and body segments
    iv. Sensor cords were looped into the Leuokotape to avoid a tripping hazard
h. Sensor 6 was placed on the left lateral thigh
    i. Sensor was secured in place using Leuokotape
    ii. Sensor cords from sensor numbers 2 and 4 were gathered together with the cord for sensor 6
    iii. Cords were not pulled taught in order to allow free movement of the joint and body segments
    iv. Sensor cords were looped into the Leuokotape to avoid a tripping hazard
i. Sensor 7 was placed on the sacrum
    i. Sensor was secured in place using electric tape and an elastic wrap
    ii. Sensor cords from sensor numbers 1-6 were gathered together with the cord for sensor 7
    iii. The cord for sensor 8 was also gathered into this bundle
    iv. Cords were not pulled taught in order to allow free movement of the joint and body segments
    v. Sensor cords were looped into the elastic wrap to avoid a tripping hazard
        1. This created a tail of cords behind the subject

            2. Two Velcro straps were applied around the cords to keep them together

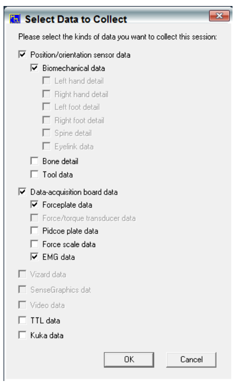
j. Sensor 8 was placed over the thorax
    i. Sensor was secured in place using electric tape
    ii. The cord for sensor 8 was gathered into the bundle of cords 1-7
k. Sensor 10 is placed on midline of the right calcaneus
l. Sensor 11 is placed on midline of the right calcaneus
m. Tape was placed on the calcaneus and traced to ensure the shoe fit properly over the sensor
n. The cords from the EMG electrodes were also gathered into the posterior tail (Figure C4)
o. The EMG box was clipped onto the elastic wrap at the subject's right hip (Figure C5)
p. Sensor 9 was the stylus
q. An overhead wiring system allowed free movement of the subject as the cords were suspended and slid freely (Figure C6)

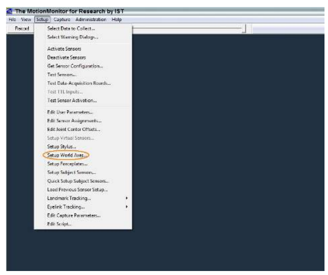


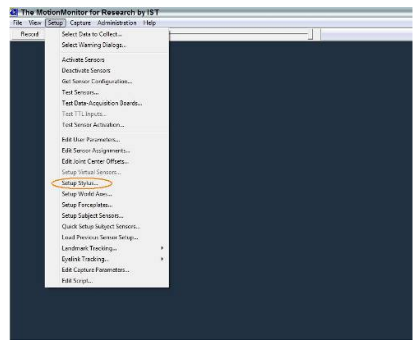
<u>Motion Monitor Hardware and Software Set-up</u>

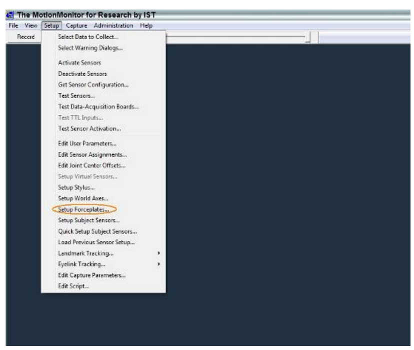
1. Prior to the subject arriving:
    a. The data to collect was chosen as biomechanical, forceplate, and EMG
    b. The stylus was set up
        i. Under the set-up tab, "set-up stylus" was selected
        ii. A new stylus was established
        iii. The stylus was placed on the force plate and rotated into ten different positions without moving the tip of the stylus
            1. If the error was 0.002 or less, the stylus set-up was accepted. If not, this process was repeated
    c. The world axes and force plate were then set up
        i. Under the set-up tab, "Set-up world axes" was selected
        ii. A new axis system was defined
        iii. The origin was designated as the bottom right corner of the forceplate

iv. The positive x-axis was defined as the direction the person faces
v. The positive y-axis was defined as the direction to the left side of the subject
vi. Under the set-up tab, “Set up forceplate” was selected
vii. The stylus was placed on the forceplate in 3 non-linear positions as cued by the Motion Monitor system
viii. The stylus was held aloft with 24 inches above the forceplate
    1. If the error was 0.002 or less, the forceplate set-up was accepted. If not, this process was repeated

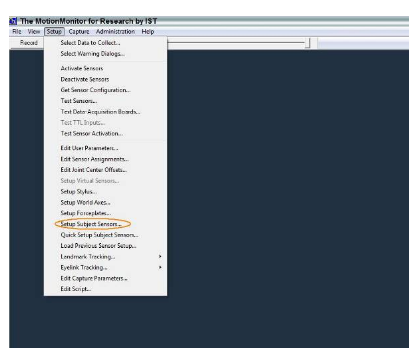








2. The subject stood next to, but not on the force plate
    a. Under the set-up tab, “Set up subject sensors” was selected
    b. The subject was asked to step onto the force plate
    c. The left anterior superior iliac spine (ASIS) was palpated by the researcher and the location was marked with the stylus.
        i. This process was repeated for the right ASIS
    d. A digital model of the subject was constructed by placing the stylus at the following locations when cued by the Motion Monitor system:
        i. Top of the head
        ii. C7/T1 vertebrae
        iii. T12/L1 vertebrae
        iv. L5/S1 vertebrae
        v. Left medial knee
        vi. Left lateral knee



vii. Left medial malleolus
viii. Left lateral malleolus
ix. Tip of the left second phalanx
x. Right medial knee
xi. Right lateral knee
xii. Right medial malleolus
xiii. Right lateral malleolus
xiv. Tip of right second phalanx

<u>Jump Landing Task Procedures</u>

1. Ten seconds of quiet, single limb stance on the dominant leg was recorded for EMG normalization purposes
2. Drop-Vertical Jump (DVJ) (C7-C8)
    a. Participants stand atop a 30cm box located in front of the force plate
        i. The box was placed a standardized distance from the force plate, at one-half of the participant's height
    b. A cue of "Ready? Go!" was given to signal to participants to begin the activity
        i. The participants dropped off the box onto the force plate, landing on both limbs
        ii. Participants landed on the force plate with their injured leg
    c. A maximal effort vertical jump was performed immediately upon landing from the initial drop
        i. Participants landed on the force plate following the vertical jump

<u>Gait-Training</u>

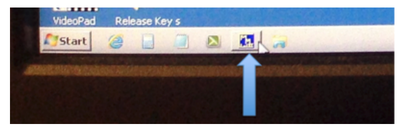
1. Questionnaires

1. Foot and Ankle Ability Measure ADL/Sport
2. Identification of FAI
3. Godin Leisure-time exercise questionnaire
4. Global Rating Change Score

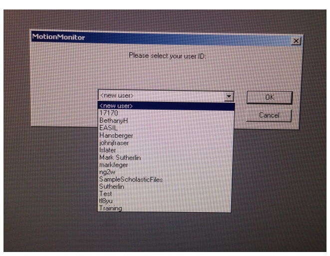
2. Descriptive Measures

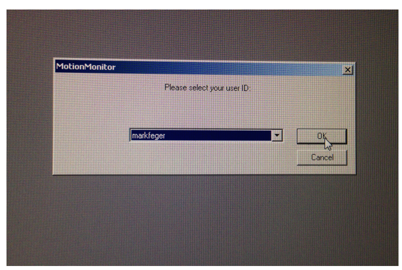
1. Age
2. Height
3. Weight

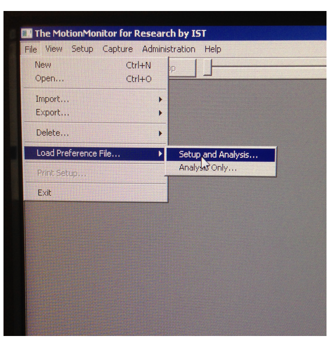
3. Motion Monitor sEMG and Pedar X Data Collection Procedures (Gait Training)

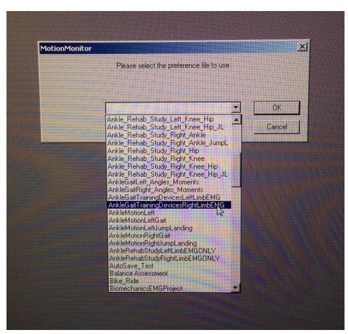


1. Surface Electromyography Software Set up
    a. Open motion monitor software on computer
    b. Select user ID
    c. Open/Load preference file
    d. AnkleGaitTrainingDevicesRightLimbEMG (or Left Limb)

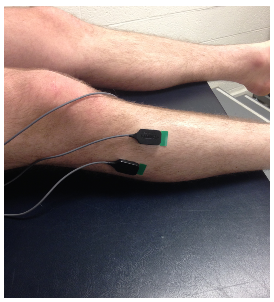
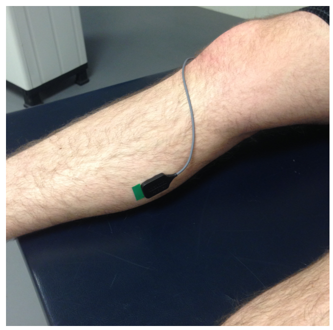
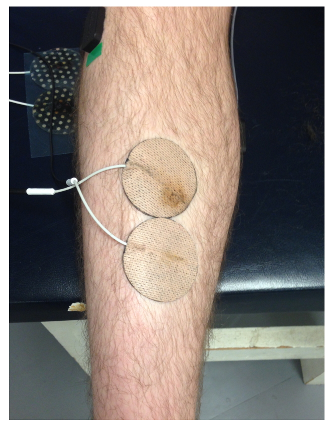


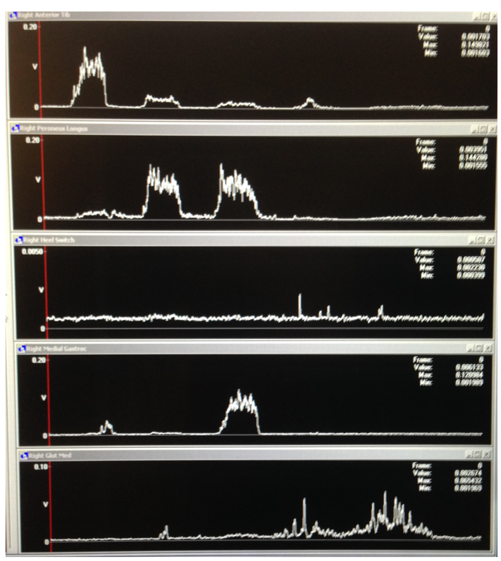




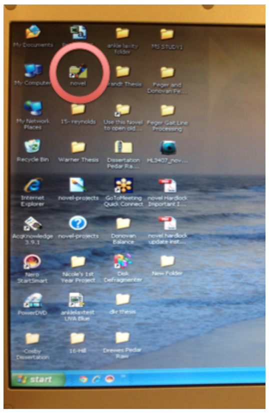
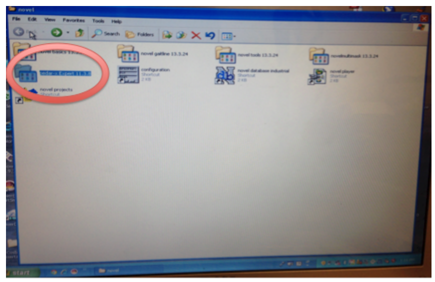
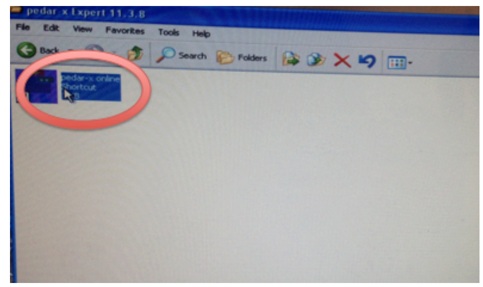


2. Surface Electromyography Subject Set up
    a. Shave
    b. Abrade
    c. Cleanse
    d. Place electrodes over muscle belly
        i. Tibialis anterior
        ii. Peroneus longus
        iii. Medial gastrocnemius
        iv. Gluteus medius
        v. Ground electrode on tibia
    e. Check for crosstalk via manual muscle test

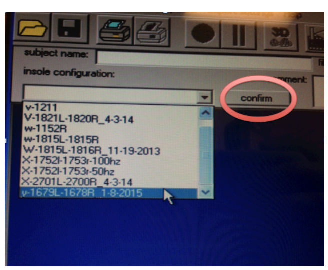






1. Plantar Pressure Software Set up
    a. Open Novel
    b. Select pedar-x Expert 11.3.8
    c. Select pedar-x online shortcut

2. Plantar Pressure Subject Set up
    a. Select appropriate size pressure insole
    b. Attach heel switch to lab shoes
    c. Insert pressure insole into lab shoes
    d. Subject puts shoes on and wires get secured to legs and waist
    e. Select calibration file that corresponds to the insoles being used
    f. Zero insoles

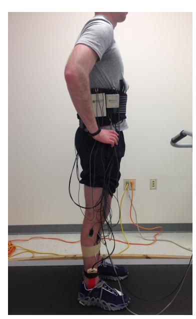
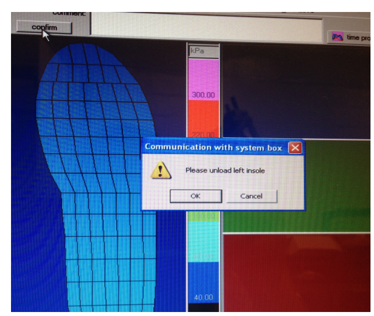



Table C1.

Foot and Ankle Ability Measure (FAAM)

Please answer **every question** with one response that most closely describes to 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	☐	☐	☐	☐	☐	☐

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 your 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 %

FAAM Sports Scale

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	☐	☐	☐	☐	☐	☐
Low impact activities	☐	☐	☐	☐	☐	☐
Ability to perform activity with your normal technique	☐	☐	☐	☐	☐	☐
Ability to participate in your desired sport as long as you would 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

Table C2.

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

Table C3.

Global Rating of Change

Please rate the overall condition of your ankle *FROM THE TIME YOU BEGAN TREATMENT UNTIL NOW* (Check only one)

□ A very great deal worse (-7)	□ About the same (0)	□ A very great deal better (7)
□ A great deal worse (-6)		□ A great deal better (6)
□ Quite a bit worse (-5)		□ Quite a bit better (5)
□ Moderately worse (-4)		□ Moderately better (4)
□ Somewhat worse (-3)		□ Somewhat better (3)
□ A little bit worse (-2)		□ A little bit better (2)
□ A tiny bit worse (-1)		□ A tiny bit better (1)

Table C4.

Godin Leisure-Time Exercise Questionnaire

1. During a typical **7-Day period** (a week), how many times on the average do you do the following kinds of exercise for **more than 15 minutes** during your free time (write on each line the appropriate number).

	Times Per Week
a) **STRENUOUS EXERCISE (HEART BEATS RAPIDLY)** (e.g., running, jogging, hockey, football, soccer, squash, basketball, cross country skiing, judo, roller skating, vigorous swimming, vigorous long distance bicycling)	________
b) **MODERATE EXERCISE (NOT EXHAUSTING)** (e.g., fast walking, baseball, tennis, easy bicycling, volleyball, badminton, easy swimming, alpine skiing, popular and folk dancing)	________
c) **MILD EXERCISE (MINIMAL EFFORT)** (e.g., yoga, archery, fishing from river bank, bowling, horseshoes, golf, snow-mobiling, easy walking)	________

2. During a typical **7-Day period** (a week), in your leisure time, how often do you engage in any regular activity **long enough to work up a sweat** (heart beats rapidly)?

OFTEN	SOMETIMES	NEVER/RARELY
1. ☐	2. ☐	3. ☐

Table C5.

Inclusion Check List

Criteria	**Yes or No**
Did their first ankle sprain occur greater than 1 year ago?	
Did they score less than an 85% on the FAAM-Sport Scale?	
Did they score ≥ 10 on the IdFAI?	
Are they between the ages 18 and 40?	
Are they physically active for at least 20 minutes 3x per week?	

Exclusion Check List

Criteria	**Yes or No**
Are they currently seeking *Phys Ther* for their ankle?	
Have they had ankle surgery?	
Have they had an ankle sprain in the past 6 weeks?	
Have they had a fracture of their ankle?	
Do they have a current self-reported disability due to lower extremity pathology?	
Do they have any neurological or vestibular disorders?	
Do they have diabetes mellitus?	
Do they have lumbosacral radiculopathy?	
Are they pregnant?	
Do they have soft tissue disorders (Marfan's or Ehlers-Dandros syndrome)?	

Table C6.

Jump Landing Data Collection Sheets

Participant Name:

Age:
Height:
Weight:
Gender:
Right Ankle History:
1. How many times have you 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 you 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?

Subjective Questionnaires:

Name	Score
FAAM-ADL	
FAAM-Sport	
IdFAI (Only Pre-treatment)	
Global Rating Score (Only post-treatment)	
Godin Leisure-time questionnaire	

Table C7.

Range of Motion
Arthrokinematic restriction present? If yes, list joints:

Joint Mobilization Type/Grade	Sets	Duration (minutes)

Stretching exercises:

Stretch Position	Sets	Duration (seconds)
Seated Straight Knee		
Seated Bent Knee		
Standing Straight Knee		
Standing Bent Knee		

Strength

Exercise (circle appropriate)	Sets	Repetitions
Double legged/Single legged heel raises		
Double legged/Single legged forefoot raises		
4-way manual resistance		
D1/D2 PNF		
4-way walks		
Short Foot Progression		

Balance

Static Balance (circle appropriate phase) Goal 3x30 seconds	Sets	Duration (seconds)
1. Eyes Open Single leg balance		
2. Eyes Open Single leg balance on a (foam or ankle destabilization sandal)		
3. Eyes Open Single leg balance on (Dynadisc™ or ankle destabilization boot)		
Eyes Closed Progression		
1. Eyes Closed Single leg balance		
2. Eyes Closed Single leg balance on a (foam or ankle destabilization sandal)		
3. Eyes Closed Single leg balance on (Dynadisc™ or ankle destabilization boot)		

Reach Tasks (circle appropriate phase) Goal 2x10 each direction	Sets	Repetitions
1.Completing the exercise		

standing on a firm surface		
2. Completing the exercise on (foam or ankle destabilization sandal)		
3. Completing the exercise standing on (Dynadisc™ or ankle destabilization boot)		

Hop to Stabilization (circle appropriate phase) Goal is 10 consecutive trials	Repetitions Completed
1. 18 inch hop with arm assistance	
2. 18 inch hop with hands on hips	
3. 27 inch hop with arm assistance	
4. 27 inch hop with hands on hips	
5. 36 inch hop with arm assistance	
6. 36 inch hop with hands on hips	
Hops with (foam or ankle destabilization boot)	
1. 18 inch hop with arm assistance while jumping on to a (foam or ankle destabilization boot)	
2. 18 inch hop with hands on hips while jumping onto a (foam or ankle destabilization boot)	
3. 27 inch hop with arm assistance while jumping onto a (foam or ankle destabilization boot)	
4. 27 inch hop with hands on hips while jumping onto a (foam or ankle destabilization boot)	
5. 36 inch hop with arm assistance while jumping onto a (foam or ankle destabilization boot)	
6. 36 inch hop with hands on hips while jumping onto a (foam or ankle destabilization boot)	

<u>Functional Exercises</u>

Lunges (circle appropriate phase) Goal is 2x10 each leg	Sets	Repetitions
1.Complete lunges on a firm surface		

2.Complete lunges with (foam or wearing ankle destabilization sandal) beneath stance leg and lunge on top another (foam or wearing ankle destabilization sandal)		
3.Complete lunges with (Dynadisc™ or wearing ankle destabilization boot) beneath the stance leg and lunge on top another (Dynadisc™ or wearing ankle destabilization boot)		

Forward Step-ups and Step-downs (circle appropriate phase) Goals is 3x10	Sets	Repetitions
1. Step on and off a box		
2. Step on and off a box (foam or ankle destabilization sandal) on top and beneath it		
3. Step on and off a box (Dynadisc™ or ankle destabilization boot) on top and beneath		

Lateral Step-ups and Step-downs (circle appropriate phase) Goal is 3x10	Sets	Repetitions
1. Step on and off a box		
2. Step on and off a box (foam or ankle destabilization sandal) on top and beneath it		
3. Step on and off a box (Dynadisc™ or ankle destabilization boot) on top and beneath it		

Dot Jumping Drill (circle appropriate phase) Goal is 3x30seconds	Sets	Duration (seconds)
1. Double legged lateral to medial hops, double legged anterior to posterior jumps, double legged figure 8 jumps (shod or ankle destabilization boot)		
2. Single legged lateral to medial jumps, single legged anterior to posterior jumps, and single legged figure 8 jumps (shod or ankle destabilization boot)		

Walking (Condition) Time Speed

Table C8.

Muscle Volume Data Collection Sheets

Strength assessment using a hand-held dynamometer

Motion	Right Leg (kg)	Right Moment Arm (m)	Right Leg Muscle Volume for Muscles performing specific Motion (ml)	Left Leg (kg)	Left Moment Arm (m)	Left Leg Muscle Volume for Muscles performing specific Motion (ml)
Dorsiflexion						
Plantarflexion						
Inversion						
Eversion						

sEMG RMS Amplitude

Muscle	Right Leg (mV)	Muscle Volume (ml)	Left Leg (mV)	Muscle Volume (ml)
Anterior Tibialis				
Peroneus Longus				
Peroneus Brevis				
Medial Gastrocnemius				

Subject Height (m) = ____________

Subject Mass (kg) = ___________

Table C9.

<u>Gait Training Data Collection Sheets</u>

Participant Name:

Age:
Height:
Weight:
Gender:

Right Ankle History:

1. How many times have you 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 you 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?

Subjective Questionnaires:

Name	Score
FAAM-ADL	
FAAM-Sport	
IdFAI (Only Pre-treatment)	
Godin Leisure-time questionnaire	

Table C10.

Subject Study ID:____________________ TEST Limb ____________________

CAI Inclusion Check List

Criteria	Yes or No
Did their first ankle sprain occur greater than 1 year ago?	
Did they score less than an 85% on the FAAM-Sport Scale?	
Did they score ≥ 10 on the IdFAI?	
Are they between the ages 18 and 40?	
Are they physically active for at least 20 minutes 3x per week?	

Exclusion Check List

Criteria	Yes or No
Are they currently seeking *Phys Ther* for their ankle?	
Have they had ankle surgery?	
Have they had an ankle sprain in the past 6 weeks?	
Have they had a fracture of their ankle?	
Do they have a current self-reported disability due to lower extremity pathology?	
Do they have any neurological or vestibular disorders?	
Do they have diabetes mellitus?	
Do they have lumbosacral radiculopathy?	
Do they have soft tissue disorders (Marfan's or Ehlers-Dandros syndrome)?	

Table C11.
Subject Study ID:____________________ TEST Limb ___________________

Healthy Inclusion Check List

Criteria	Yes or No
Have they ever sprain either ankle?	
Did they score 100% on the FAAM-Sport Scale?	
Did they score 0 on the IdFAI?	
Are they between the ages 18 and 40?	
Are they physically active for at least 20 minutes 3x per week?	

Exclusion Check List

Criteria	Yes or No
Have they had ankle surgery?	
Have they had a fracture of their ankle?	
Do they have a current self-reported disability due to lower extremity pathology?	
Do they have any neurological or vestibular disorders?	
Do they have diabetes mellitus?	
Do they have lumbosacral radiculopathy?	
Do they have soft tissue disorders (Marfan's or Ehlers-Dandros syndrome)?	

Table C12.

Day	Band Color	Number of Sets Completed	RPE
Day 1			
Day 2			
Day 3			
Day 4			
Day 5			

APPENDIX D

Recommendations for Future Research

- Future studies should analyze the effects of comprehensive rehabilitation that is supplemented with biofeedback for proper jump landing mechanics in CAI patients.

- Future studies should include long-term (1 and 2 year minimum) follow-ups on self-reported function and ankle sprain status following intervention (comprehensive rehabilitation and gait training) studies for CAI patients.

- Future studies should analyze the combined effect of gait training and comprehensive rehabilitation on gait mechanics and self-reported function for CAI patients.

- Future studies should analyze the effects of gait training and jump landing training on the prevention of CAI following initial lateral ankle sprains.

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