LOWER EXTREMITY BIOMECHANICS AND CHRONIC ANKLE INSTABILITY

A Dissertation

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by

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ABSTRACT

Lateral ankle sprains (LAS) are the most common injury in active individuals. LAS often result in a condition known as chronic ankle instability (CAI). CAI is characterized by subjective feelings of instability and dysfunction within the individual. This includes muscle weakness and activation changes, range of motion and arthrokinematic alterations, proprioceptive and joint position sense changes and balance and postural control alterations. These deficits are hypothesized to play a role in the kinematics and kinetics during gait and jumping tasks in CAI patients. Previous studies have identified increased inversion and plantar flexion during gait and greater frontal plane motion during gait. Recently, novel statistical and non-linear techniques have been hypothesized to improve the analysis of the lower extremity biomechanics. The focus of manuscript one was to assess kinematics, kinetics and ground reaction forces (GRF) during walking and jogging gait between CAI and healthy controls using statistical parametric mapping (SPM). We found that CAI patients had greater ankle inversion during walking and jogging gait and greater eversion joint moments during jogging. No differences were found at the knee and hip. The purpose of manuscript two was to assess the impact of 4 weeks of comprehensive, progressive rehabilitation on lower extremity joint coupling in CAI patients. Rehabilitation including strength, balance and range of motion exercises is the standard of care for treating CAI patients. Rehabilitation has shown improvements in strength, balance and subjective function. We found that it also decreased variability between motion of the knee to the ankle and hip to the ankle during walking gait. The goal of manuscript 3 was to assess lower extremity joint coupling during a drop-vertical jump (DVJ) between patients with and without CAI. We found that CAI patients had higher variability, lower joint coupling magnitude and higher vector direction. These deviate from previous findings during gait and may represent the task constraint of DVJ on the sensorimotor function of CAI patients. CAI is an internal constraint that alters the lower extremity biomechanics during gait and DVJ. These changes may indicate an unhealthy motor control strategy that predisposes this population to instability and joint damage. Rehabilitation changes the joint coupling variability and may represent a protective organismic adaptation to create a stable joint.

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APPROVAL OF THE DISSERTATION

This dissertation, "Lower Extremity Biomechanics and 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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"*What looks large from a distance, close up ain't never that big.*"

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ABSTRACT

Background: Chronic ankle instability (CAI) is associated with changes in gait biomechanics which may be related to chronic dysfunction. Multivariate analysis of the lower extremity during gait may reveal unique biomechanical differences associated with CAI. The purpose of this study is to compare 3D biomechanics of the ankle, knee and hip and ground reaction forces (GRF) during gait. **Methods:** Forty young, active adults participated in this study (CAI: n=20, Control: n=20). Data was collected using a 3D motion analysis system while patients walked and jogged. Statistical parametric mapping (SPM) was used to assess 3D GRF, kinematics and kinetics of the lower extremity of CAI and healthy patients. **Findings:** During walking, the largest group difference was found in ankle frontal plane motion from 68-100% of the gait cycle with the CAI group having significantly more inversion ($p<0.001$, mean difference=3.2°,effect size:-0.95). During jogging, the greatest difference was found in subtalar frontal plane kinematics from 20-92% with the CAI group having greater inversion ($p<0.001$, mean difference=4.6°,effect size:-0.81). Greater plantar flexion moments were found from 65-71% ($p=0.05$, mean difference=347.4Nm/kg,effect size:-0.83) and greater eversion moments were found from 95-100% ($p=0.03$, mean difference=74.6Nm/kg,effect size:0.58) in the CAI group. No differences in GRF were found. **Interpretation:** Greater inversion may present a potentially injurious position. A faulty position of the rearfoot may require greater muscle function in order to correct the position of the joint resulting in greater eversion moments at the ankle. However, this kinetic change does not appear to correct the ankle position.
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Introduction: Lateral ankle sprains (LAS) are very common in active individuals and during sport.[1,2] The LAS results in damage to the lateral ankle ligaments and surrounding structures of the joint.[3] Sprains and strains to the lateral ankle complex are the most common outpatients conditions seen in United States emergency departments.[4] Following initial LAS, dysfunction often persists outside of the resolution of the injury.[5] Up to 70% of those that suffer a LAS will go on to have multiple sprains with 59% reporting long term disability.[6,7] Continued instability and subjective dysfunction outside of 12 months from the initial LAS associated with self-reported "giving way" has been defined as chronic ankle instability (CAI).[8] CAI has been associated with sensorimotor dysfunction and lower extremity changes including kinematics and kinetics.[9-13] Changes in the lower extremity biomechanics may play a role in continued instability and associated dysfunction.

Changes have previously been identified during the gait of CAI patients in frontal plane [9,14] and sagittal plane motion[9,11] of the ankle. CAI patients have been shown to have a more plantar flexion and inverted ankle position during gait. This position has been hypothesized to increase the risk for inversion mechanism of injury to occur.[15] Previous research typically only assessed a single joint or single plane of interest which may miss aspects of the joint motion contributing to instability of the ankle joint.

Proximal alterations in biomechanics have also been identified in CAI patients. Gribble et al[16] found less knee flexion in the CAI group compared to controls during single-limb jump landings. Brown et al[17], compared mechanically unstable and functionally unstable ankle groups to copers and controls and found that the mechanical instability group demonstrated greater hip flexion and external rotation during periods of a stop jump maneuver. During functional exercises, Feger et al[18] identified significantly less surface EMG activity in the peroneus longus, anterior tibialis, lateral gastrocnemius, rectus femoris, biceps femoris and gluteus medius in patients with CAI compared to controls. Monaghan et al[14], during walking gait, found CAI subjects had a higher rate of inversion immediately prior to initial contact while healthy patients were slowly everting. The CAI group also had higher eversion ankle joint moments post initial contact and were associated with changes in inversion position of the ankle. These changes in lower extremity kinematics and kinetics may indicate adaptive control mechanisms throughout the lower extremity in CAI patients.

Delahunt et al[19], compared 24 patients with ankle instability to 24 healthy control patients during a single limb drop jump The ankle instability group had an increase in vertical GRF and a more medially directed GRF 85 to 105 ms post-initial contact and a more posterior GRF from 75 to 90 ms post-initial contact. The functional instability group also reported less eccentric power generation post-initial contact.

Traditional analysis techniques of gait involve comparisons at specific discrete time points such as terminal swing and initial contact. These comparisons may limit the findings during a task by creating regional focus bias around only specific time points of the movement. Monaghan et al[20] identified differences at the ankle and found no differences at the knee and hip, however, only a period 100 ms pre initial contact to 200 ms post initial contact was analyzed. Comparisons of single plane kinematics and kinetics at specific joint segments may limit the findings during gait due to the complex nature of the task and multi-axial structure of the joints. Walking and running gait require the coordination of multiple segments throughout the lower extremity during the gait cycle in order to create effective and efficient movement in reaction to the task constraints.[21] Statistically, analysis of the entire gait cycle presents an issue of multiple comparison bias by comparing data across a large number of time points thus increasing the risk of statistical error. A multivariate method of analysis, statistical parametric mapping (SPM), minimizes multiple comparison bias and allows for assessment of multiple segments in three dimensions and motions across the entire gait cycle.[22] SPM has been validated previously in brain imaging studies[23,24] and has been suggested as a promising analysis tool for biomechanical measures.[25]

Our purpose was to compare kinematics, joint moments and ground reaction forces of the lower extremity during walking and jogging in CAI patients and healthy patients with no history of lower extremity injury. We hypothesized that the CAI group would have increased ankle frontal plane motion, decreased ankle sagittal plane motion, decreased knee sagittal plane motion and increased hip sagittal plane motion during walking and jogging. We also hypothesized that joint moments would be increased in the frontal and sagittal plane at the ankle but decreased at the knee and hip in CAI patients and that vertical ground reaction forces would not be different between groups.

Methods

Study Design: We conducted a descriptive laboratory study to analyze walking and jogging gait in patients with and without CAI. The independent variable was group (CAI, healthy controls). Groups were compared during two different gait speeds (walking, 4.83 km /hr, jogging, 9.66 km/hr). The dependent variables were the transverse, frontal and sagittal plane kinematics of the ankle, knee and hip, joint moments of the ankle, knee and hip, and ground reaction forces in the medial-lateral, anterior-posterior and vertical directions.

Patients: Forty young active individuals participated (CAI: n=20, Control: n=20) (Table 01). Inclusion criteria for the CAI group was a history of more than one ankle sprain with the initial sprain occurring greater than 12 months prior to the start of the study. CAI patients had to score at least <85% on the FAAM Sport sub-scale. Healthy patients had no history of ankle sprain. All patients had to be physically active exercises at least 3 times per week and have no history of lower extremity surgery or fracture, or any condition that would affect balance such as neuropathies or diabetes.[26] This study was approved by the Institutional Review Board (IRB# HSR-14893) and all subjects were consented prior to participation.

Table 01: Subject Demographics

Group	Control (n=19)	CAI (n=20)
Age (yr)	23.1±3.8	24.7±5.9
Height (cm)	170.0±10.4	170.4±9.2
Weight (kg)	67.3±14.4	69.9±13.1
Sex (m:f)	8:11	7:13
Godin	68.4±32.7	62.4±24.5
FAAM (%)	100±0.0	91.2±7.7
FAAMS (%)	100±0.0	74.7±8.8

Instruments: Motion analysis was assessed using a 12 camera Vicon system (Vicon MX t20, VICON Motion Systems, Inc., Lake Forest, CA) sampled at 250 Hz. Ground reaction forces were synchronized during data collection by 2 staggered multi-axis strain gauge force plates within the treadmill (AMTI OR 6-7, Watertown, MA). Ground reaction forces were sampled at 1000Hz with a threshold of 60N in order to identify initial contact and toe-off of walking and jogging strides. Three dimensional kinematics were collected using the Vicon PlugIn Gait (Oxford Metrics, London, UK).

Procedures: Thirteen retro-reflective markers were placed on the lower extremity of all patients; one each on the right and left thigh, knee joint, fibular head, tibial tuberosity, 4 marker cluster on the lateral shank, ankle, 1st, 2nd and 5th metatarsal and clusters on the posterior sacrum and each heel. All subjects wore customized running shoes (Brooks Sports, Inc., Bothell, WA). Portions of the shoes were removed on the posterior heel, medial and lateral metatarsal head regions in order to allow direct marker placement onto the foot without changing the structure of the shoe.[9] Ankle kinematics were calculated as 3D motion of foot markers and a 4 marker cluster placed on the posterior calcaneous relative to shank markers.[9]

All patients walked on the treadmill at a self-selected pace for 3 to 4 minutes as a warm-up. Following the warm-up period, subjects walked at 4.83 km/hr during which 3 fifteen second clips were collected. Patients were then allow to jog at a self-selected pace for 3-4 minutes and then speed was increase on the treadmill to 9.66 km/hr. During jogging, 3 fifteen second clips were collected. Following data collected, patients were released from the study.

Data Processing: During each task, the 15 second trials were visually inspected for completeness and one trial was selected for processing. The stride samples were filtered and normalized to 101 frames representing the percentages of the gait cycle using a customized MatLab program (MatLab 7.04, Mathworks, Inc., Natick, MA). Filtering and normalization was performed for each subject based on stride times and the initial contact and toe-off timing for each limb.[13] Ground reaction forces were calculated for the stance phase, normalizing the stance phase of each stride to 101 data points. Kinematics and kinetics were calculated over the entire gait cycle normalize the stance and swing phase to 101 points. Fifteen strides were extracted for each subject and used for statistical analysis.

Statistical Analysis: Statistical parametric mapping was performed on all data to explore group differences in kinematics, kinetics and ground reaction forces. Fifteen strides from each patient are used to calculate an ensemble mean for each variable across the gait cycle. Group matrices were then generated for the hip, knee and ankle kinematics and kinetics as 20x101x3 matrices representing the joint angles and moments in three planes across the gait cycle. GRF matrices were similar but only calculated during the stance phase of gait. Significant group differences were then assessed in each dimension of the data. Equation 1 is used to calculate the SPM t-statistics (SPM{t}). In the below equation, y_n and s_n represents group mean and SD respectively. J indicates the number of comparisons made, in this case 101 across the entire gait cycle.

Equation 1: $$SPM\{t\} \equiv t(q) = \frac{\overline{y_B}(q) - \overline{y_A}(q)}{\left(\sqrt{\left(\frac{1}{J}\right)\left(s_A^2(q) + s_B^2(q)\right)}\right)}$$

The significance of SPM{t} is determine based on random field theory (RFT) and on an α value set at 0.05.[27] When conducting multiple comparisons, higher t values will occur by chance and RFT takes into account this error and adjust the SPM{t} threshold based on the smoothness of the waveform and hence estimates the true number of comparisons made.[28]

Exploratory comparisons were made using SPM between CAI and healthy controls on the frontal, sagittal and transverse plane kinematics and joint moments of the ankle, knee and hip during the entire gait cycle. Ground reaction forces in the anterior-posterior, medial-lateral and vertical directions will also be compared between groups during the stance phase of gait. Effect sizes and 95% CIs were generated for the stance and swing phase of all vectors. Effect sizes and 95% CIs were also generated for all regions of significant differences as well as the stance and swing phase of all vectors. Vectors of the matrices that showed the greater difference were assessed to indicate group differences in each plane of motion. Mean differences were calculated between groups during regions where the SPM{t} was exceeded.

Results: The SPM technique was used to analyze the hip, knee and ankle kinematics, kinetics and GRFs. The greatest differences identified in single vectors were found in frontal plane ankle kinematics and frontal and sagittal ankle joint moments. Changes in ankle frontal plane motion and kinetics agree with our hypothesis, however, we found no group differences at the knee and hip. Effect sizes for stance and swing phase of gait were found for all vectors. (Table 02, 03, 04) No difference was found in GRF which agrees with our hypothesis.

During walking gait, the frontal plane ankle vector had the greatest differences, with the CAI group having greater inversion from 68-100% of the gait cycle (Mean difference 3.22°, p=0.05, effect size:-0.95) (Figure 01, Table 02). No kinematic or kinetic differences were found at the knee or hip (Figure 02, 03, Table 02). No differences were found in GRF during walking gait (Figure 04, Table 03).

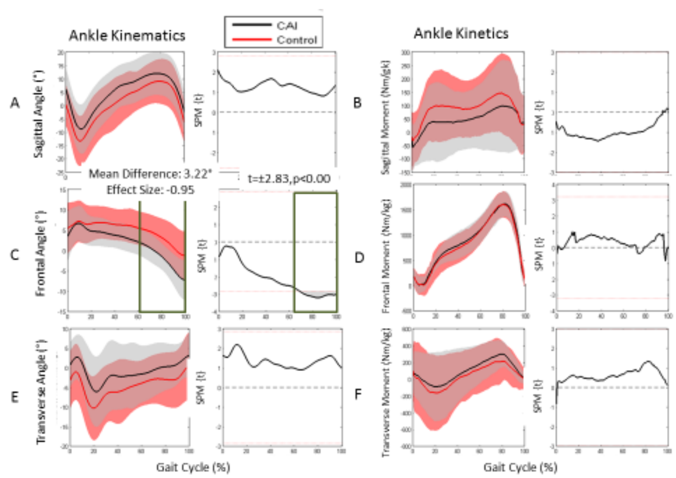

Figure 01: Walking ankle results. Means and standard deviations of kinematics and kinetics and SPM{t} graphs and thresholds. Periods of significance are boxed in red.

Table 02: Walking Gait Effect Size Means: Effect sizes of the stance phase and swing phase for the kinematics and kinetics in the sagittal, frontal and transverse plane.

Walking		Stance Phase			Swing Phase	
		Kinematics	Kinetics		Kinematics	Kinetics
Ankle	*Sagittal*	-0.32	0.14	*Sagittal*	-0.25	0.09
	Frontal	-0.37	-0.39	*Frontal*	-0.86	-0.29
	Transverse	-0.21	0.18	*Transverse*	-0.01	0.26
Knee	*Sagittal*	0.38	-0.15	*Sagittal*	-0.07	-0.34
	Frontal	-0.07	-0.24	*Frontal*	0.02	-0.09
	Transverse	-0.20	0.12	*Transverse*	-0.30	0.11
Hip	*Sagittal*	0.45	-0.10	*Sagittal*	0.34	0.12
	Frontal	-0.33	0.31	*Frontal*	-0.07	-0.42
	Transverse	0.15	0.06	*Transverse*	0.11	0.10

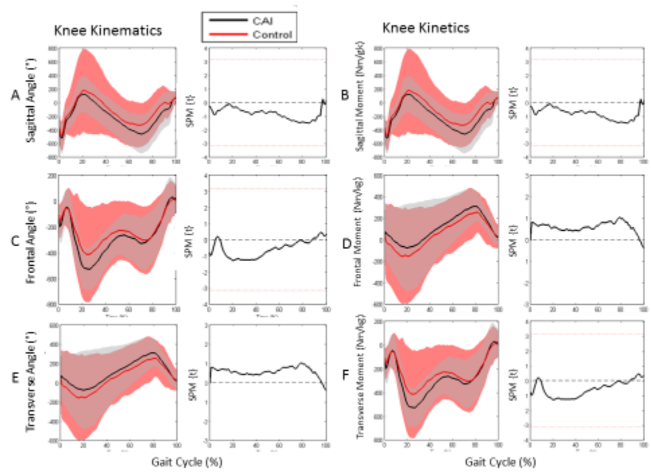

Figure 02: Walking knee results. Means and standard deviations of kinematics and kinetics and SPM{t} graphs and thresholds.

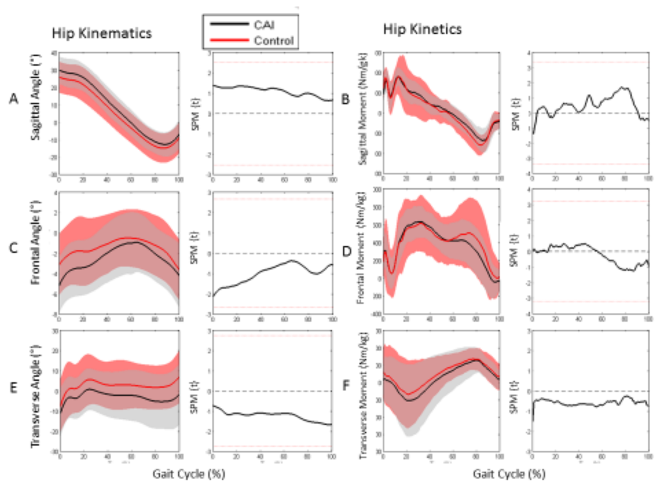

Figure 03: Walking hip results. Means and standard deviations of kinematics and kinetics and SPM{t} graphs and thresholds.

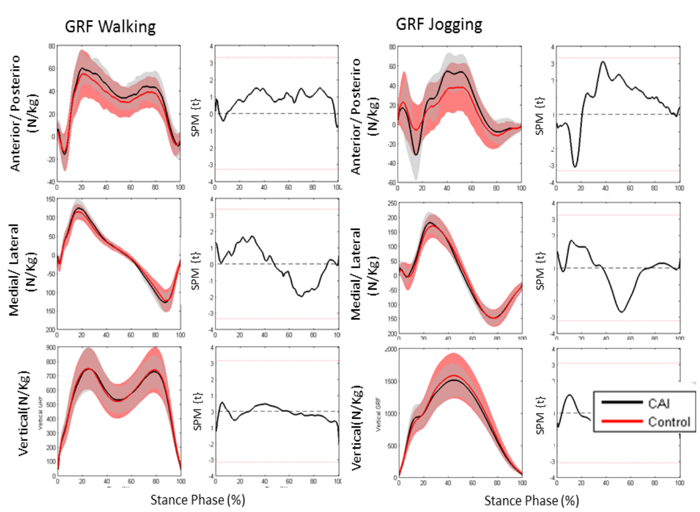

Figure 04: Walking and jogging ground reaction forces. Means and standard deviations of forces and SPM{t} graphs and thresholds.

Table 03: Ground reaction force effect size means: Effects sizes of the stance phase for walking and jogging gait in the sagittal, frontal and transverse plane.

GRF	Walking		Jogging	
Ankle	*Ant/Post*	-0.05	*Sagittal*	0.00
	Med/Lat	0.20	*Frontal*	0.00
	Vertical	-0.15	*Transverse*	-0.09

Table 04: Jogging Gait Effect Size Means: Effect sizes of the stance phase and swing phase for the kinematics and kinetics in the sagittal, frontal and transverse plane.

Jogging		Stance Phase			Swing Phase	
		Kinematics	Kinetics		Kinematics	Kinetics
Ankle	*Sagittal*	-0.06	-0.59	*Sagittal*	-0.03	-0.55
	Frontal	-0.64	-0.01	*Frontal*	-0.76	0.47
	Transverse	-0.01	0.10	*Transverse*	0.02	-0.05
Knee	*Sagittal*	0.34	0.13	*Sagittal*	0.04	-0.09
	Frontal	-0.19	0.00	*Frontal*	-0.12	-0.15
	Transverse	0.11	-0.07	*Transverse*	0.02	-0.32
Hip	*Sagittal*	0.43	0.22	*Sagittal*	0.37	-0.09
	Frontal	0.05	-0.19	*Frontal*	0.05	-0.19
	Transverse	-0.10	0.00	*Transverse*	-0.10	0.00

During jogging gait, the frontal plane ankle vector identified the greatest differences (Figure 05, Table 04). The CAI group had greater inversion from 20-92% of the gait cycle (Mean difference: 4.56°, p<0.00, Effect size: -0.81). Greater eversion moments at the ankle were greater in the CAI group from 95-100% of the gait cycle (Mean difference: 74.58Nm/kg, p=0.03, Effect Size: 0.58) (Figure 05). Greater plantar flexion moments were found in the CAI group from 65-71% of the gait cycle (347.38 Nm/kg, p=0.04, Effect size: -0.83) (Figure 05, Table 04). No significant differences in GRF were found during jogging (Figure 04, Table 03).

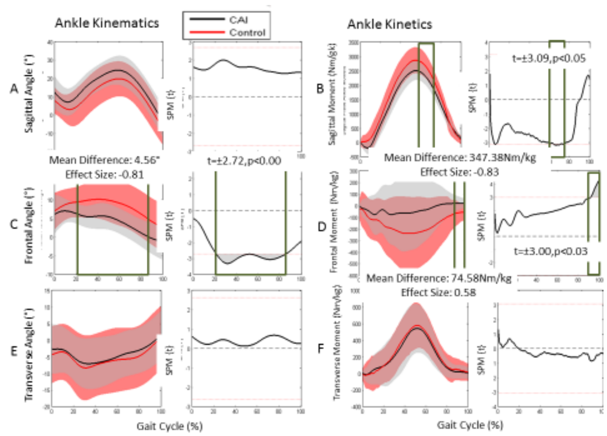

Figure 05: Jogging ankle results. Means and standard deviations of kinematics and kinetics and SPM{t} graphs and thresholds. Periods of significance are boxed in red.

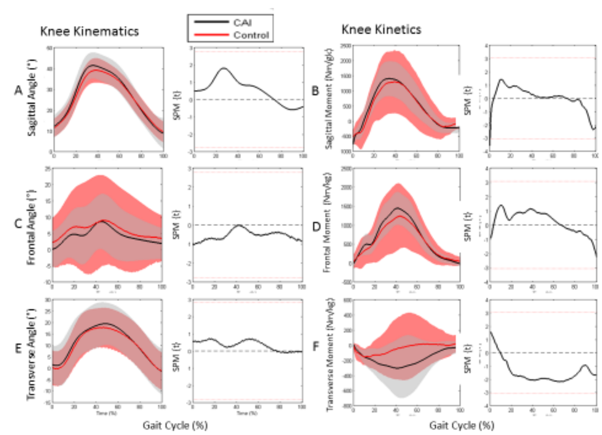

Figure 06: Jogging knee results. Means and standard deviations of kinematics and kinetics and SPM{t} graphs and thresholds.

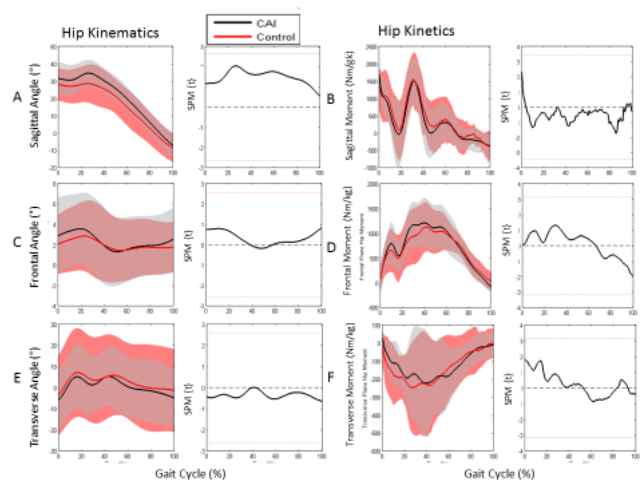

Figure 07: Jogging hip results. Means and standard deviations of kinematics and kinetics and SPM{t} graphs and thresholds.

Discussion: The SPM technique identified group differences in several specific vectors of the 3 dimensional lower extremity analyses. The exploratory technique identified periods of group differences in the ankle joint kinematics and kinetics. These differences, specifically greater inversion motion of the ankle in the CAI group, is consistent with previous findings, however, the portion of the gait cycle where differences were identified at longer periods of gait and the magnitude of the differences varied compared to previous literature. Changes in kinetics in the sagittal and frontal plane may be related to a control mechanism to correct faulty kinematic position associated with CAI.

Previously, differences between CAI and healthy groups in frontal plane kinematics during shod jogging gait were found from 11-18%, 33-39%, and 79-84% with mean differences of 3.9°, 4.8° and 5.7° of greater inversion in the CAI group, respectively. [9] Another study reported greater inversion before, at and following initial contact.[19] Drewes et al[12] identified a mean difference in inversion of 2.07° during barefoot walking across the entire gait cycle. During barefoot jogging gait, greater inversion in CAI patients was identified from 0-2% (mean difference:1.35°), 23-33% (mean difference:1.78°), from 42-58% (mean difference:1.57°), and from 78-100% (mean difference: 1.90°).[12] Our results indicate greater inversion in the CAI group from 68-100% of the gait cycle with a mean difference of 3.22° and large effect size during walking and from 20-92% with a mean difference of 4.56° and large effect size during shod jogging. The magnitude of this difference in the frontal plane was higher than previously reported by Drewes et al[12] but were similar to those reported by Chinn et al[9]. These studies used a confidence interval comparison to measure group differences. Chinn et al[9], using 90% confidence intervals and Drewes et al[12] using 95% confidence intervals. A potential explanation for difference is footwear. The Drewes et al[12] study collected data while barefoot compared to using standardized footwear in the current study and in the study by Chinn et al.[9]

Differences have been previously reported across different periods of the gait cycle. Our findings indicate greater inversion during terminal swing of walking and mid-stance to mid-swing phase of jogging gait. Wright et al[30], prospectively identified increased ankle sprain risk in those with increased supination angles in a biomedical modeling study. In a cadaver study, Konradsen et al[15], reported a position of 10° of inversion when the foot contacts the ground being enough to cause an inversion mechanism. In this study, inversion position ranged from 13° to 33° during mid-swing while healthy subjects ranged from a 0.6° of eversion to 19° of inversion. This position may indicate a higher risk for inversion mechanism at initial contact and would require greater dynamic control in order to protect the joint.

De Ridder et al[25,31] previously compared CAI, healthy and coper subjects during barefoot walking and jumping tasks using a multi-segment foot model and SPM analysis. The rearfoot was more everted during the stance phase of both walking and jogging. The medial midfoot was more inverted for running and walking in the ankle instability group. An everted rearfoot during stance phase seems counter to the mechanism of an LAS, however, Willems et al[32] did identified a medial loading of the foot and trend towards a higher eversion excursion in subjects at risk for an ankle sprain. No significant differences were identified during the impact phase of the jumping tasks in mean joint angles of the hip, knee and ankle.[31] However, they[25] did report that the CAI group demonstrated more rearfoot eversion during the stance phase. These results deviate from our current results and from other previous literature that reported greater inversion during stance phase in CAI patients.[9,12,14]

Kinetic differences between groups were identified during jogging. CAI patients had a greater eversion internal moments from 95-100% of the gait cycle during jogging with a mean difference of 74.58 Nm/kg compared to healthy patients. Higher eversion internal moments may indicate a control mechanism in order to correct faulty inversion positioning. The timing of the frontal plane kinematics and frontal plane kinetics indicate a potentially corrective motor control strategy where greater inversion during mid-stance through mid-swing was corrected by greater eversion forces prior to the subsequent initial contact. Previous findings have identified changes in evertor muscle function in CAI patients.[18,33,34] Changes in the eversion moment at the ankle may reflect alterations in neuromuscular control of peroneals in an attempt to protect the joint from deleterious positions.[18] Feger et al[18], identified an earlier onset of peroneal activation prior to initial contact and hypothesized that this was due to faulty inversion position of the ankle requiring greater peroneal activation. Earlier onset of the peroneal muscles may potentially fatigue this muscle more easily and decrease the ability to protect the joint leading to greater inversion position at initial contact.

CAI patients also were found to have greater plantar flexion moments from 65-71% of jogging. While we did not find kinematic differences in sagittal motion, the moments indicate a change in the force control during jogging gait. Sagittal plane kinematics identified relatively greater plantar flexion throughout the gait cycle but it never was found to be statistically significant (Figure 05). Previous assessments of sagittal kinematics have identified greater plantar flexion positioning during the swing phase of jogging gait.[9] These findings may indicate an attempt to prepare for ground contact forces at the ankle but potentially explain angles of greater plantar flexion previously reported during swing phase.[11]

Group differences in GRF forces were not identified during walking and jogging, which we hypothesized. Previous research has identified GRF differences during jumping tasks and balance[35-37] Using a jump landing task, Caulfied and Garrett[35] identified greater anterior force in CAI patients approximately 45ms following initial contact. Delahunt et al[36] found less posterior directed GRF during a lateral hopping task. A more anterior-lateral center of pressure has been found in CAI patients during single limb balance.[37] No group differences were identified during a walking task which may be related to the cyclical nature of the task or successful dynamic control of both groups during gait.

No differences were identified at the hip or knee for any kinematic or kinetic measures in this study. The larger joint motions that occur during gait at the knee and hip compared to the ankle may require higher sample sizes in order to identify group differences. Alternatively, hip and knee kinematics differences have only been identified in jumping and cutting studies.[16,17] During the stance phase of walking and jogging gait, moderate effect sizes were found in knee and hip kinematics indicating a potentially important differences at these joints. Future studies, if powered for kinematic hip and knee differences may identify group differences in CAI patients. The task of walking and jogging may not be challenging enough to require altered control strategies in the proximal joints of the lower extremity due to its primarily sagittal plane nature. The findings at the ankle indicate a position of inversion from mid to terminal swing in walking and from mid-stance to mid-swing during jogging gait. A position of inversion has been linked with CAI and as a risk factor for lateral ankle sprains and may result from a deficit in sensorimotor function around the joint following initial joint injury.[5] An inability to position the foot correctly results in multiple ankle sprain mechanism and potentially chronic degeneration of the joint.[38,39] Kinetic findings in this study indicate during jogging a potential protective mechanism of eversion but only during terminal swing. Interventions should address this inverted position during both the swing phase and stance phase of gait. The protective role of the evertors should also be emphasized as the primary mechanism to correct this position. Feger et al[18], hypothesized the early activation of the peroneals was a protective adaptation but may also lead to early fatigue and failure of the muscle during prolonged activity. Interventions to increase the strength and endurance of these muscles may support the protective adaptation.

The SPM technique provides a method of analysis for complex biomechanical data sets. The complex, continuous nature of human movement requires coordination across all lower extremity joints and in multiple planes of motion. Previously, continuous waveform analysis was primarily done by comparing means and confidence intervals for periods of overlap.[9,11] In this way, each point of gait is assessed independently from the surrounding data points and significance is based on only the mean, standard deviation and selected alpha level at that specific percentage of gait. SPM allows for multiple comparisons while taking into account the entire waveform.[22] This better represents the data of interest as no time point is truly independent of the rest of the gait cycle.

Limitations in this study include how our sample size was calculated, which was based on expected differences for the ankle kinematics. The knee and hip differences may be of smaller relative magnitude compared to the ankle, however, moderate effect sizes indicate that we may have been underpowered to detect group differences at these joints. Subjects all ran at only a controlled speed which may have been a novel task for patients in the study. Patients also wore standardized lab shoes which may have also presented a novel external condition for the patients.

In conclusion, CAI patients had greater inversion motion and altered ankle moments compared to healthy controls.

Conclusion: SPM identified changes when assessing 3 dimensional continuous data throughout the lower extremity. SPM should be considered when assessing complex biomechanical data. These results agree with previous findings but accounted for many statistically errors potentially limiting analysis of gait in CAI patients. This study presents the most comprehensive study of lower extremity gait mechanics related to CAI and provide a potential framework for clinical intervention in a CAI population.

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SECTION II: MANUSCRIPT II

EFFECTS OF REHABILITATION WITH AND WITHOUT DESTABILIZATION DEVICES ON LOWER EXTREMITY JOINT COUPLING IN CHRONIC ANKLE INSTABILITY PATIENTS

Abstract
Background: Chronic ankle instability (CAI) has been associated with kinematic changes in the lower extremity. Alterations in joint-coupling have been identified during gait in CAI patients compared to healthy patients. Conservative rehabilitation remains the gold standard for clinical treatment in CAI patients but little is known on the effects of rehabilitation on lower extremity joint-coupling. Previously, wearable destabilization devices have shown an increase in muscle activity during functional tasks potentially increasing the effects on musculature around the ankle. The purpose of this study is to analyze the lower extremity joint-coupling during walking gait prior to and following a 4-week comprehensive rehabilitation program performed with and without ankle destabilization devices. **Methods:** Twenty-six young active individuals with CAI were randomly assigned to receive 4 weeks of comprehensive ankle rehabilitation either with or without ankle destabilization devices. A 3D motion capture system was used to collect lower extremity kinematics during walking. A vector coding analysis was used to assess the lower extremity joint coupling variability of knee sagittal and hip frontal motion to ankle sagittal and ankle frontal motion. **Results:** Compared to the no destabilization device group, the group using destabilization devices for rehabilitation had significant decreases in hip frontal-ankle sagittal and knee sagittal-ankle sagittal joint coupling variability during periods of walking gait. **Conclusion:** This decrease in joint coupling variability may represent a change in sensorimotor organization following comprehensive rehabilitation. This decrease is indicative of an adaptation that may be protective from instability. Rehabilitation for CAI patients using destabilization devices may show greater sensorimotor improvements.
250/250

Introduction: Sprains to the lateral ankle joint complex (LAS) are the most common injury that occurs in active individuals.[1,2] LAS result from a mechanism of hypersupination of the ankle complex resulting in damage to the lateral ankle ligaments.[3] Chronic instability of the lateral ankle complex following an initial sprain are common with up to 70% of patients suffering recurrent sprains and 59% reporting long term disability.[6,7] Chronic instability and dysfunction after LAS has been labelled chronic ankle instability (CAI).[5,8] CAI is defined as subjective instability following an initial LAS outside of 1 year and associated with subjective instability and feelings of "giving way".[8]

CAI has been associated with gait alterations and landing biomechanics changes compared to healthy patients.[9-14,16,17] Frontal plane differences at the ankle have been identified during walking and jogging gait with CAI patients having significantly greater inversion at different time periods during the gait cycle.[9,14] Similarly, sagittal plane differences at the ankle have been found during walking and jogging gait with CAI patients exhibiting less dorsiflexion.[9,11] More recently, alterations have been identified multivariate, non-linear analyses including joint coupling.[12,13] Using both continuous relative phase and vector coding, alterations in joint coupling have been identified in patients with CAI.[12,13]

Differences in joint coupling associated with CAI may indicate alterations in coordination of the lower extremity segments due to the internal constraint of CAI.[12,13] Dynamical systems theory describes the central organization of movement based on the conditions of the individual.[39] This includes internal constraints (the health and function of the individual), external constraints (the environment the individual is in), and the task constraints (the action being performed). The initial LAS injury results in a constraint on the neuromuscular function and sensorimotor control of the patient.[40,41] These sensorimotor deficits are characterized by decreases in muscle function[42-44] and deficits in postural control and balance.[36,45] Deficits in sensorimotor control may lead to biomechanical alterations and result in a deleterious movement strategy based on this constraint of ankle instability. Previous research has identified a less variability between shank-rearfoot joint coupling between CAI patients and healthy controls.[13] This decrease represents a more rigid coupling pattern during the stance phase of walking and may be related to the CAI patient's inability to explore alternate movement patterns during the loaded phase of gait. Changes in external or task constraints may lead to instances of instability or excessive repetitive loading of tissues. Over time, excessive loading of similar joint structures may be related to long term joint degeneration seen following ankle sprains.[46]

A progressive balance training program has been shown to improve subjective function and balance in patients with CAI.[47] McKeon et al[48], identified a decrease in shank-rearfoot joint coupling variability following a 4-week progressive balance training program. Improved balance and decreased ankle joint coupling variability after rehabilitation may represent an improved control strategy and be related to the improvement in subjective function in these patients. Movement variability has been hypothesized to be a reflection of sensorimotor health.[49] Higher variability has been associated with a healthy movement pattern which appears to contradict the findings of McKeon et al.[48] Previous research on joint coupling has identified the ability of adjacent joints to adapt to alterations at other joints in the upper extremity.[50] While McKeon et al[48], found a decrease in shank-rearfoot coupling variability following the balance training, coupling was not assessed at the knee or hip. Alterations in control strategies and potential changes in variability at these proximal joints may improve movement strategies in this population.

Conservative rehabilitation, including balance training, is considered sound clinical treatment for CAI but there is limited research assessing gait outcomes following a comprehensive rehabilitation program. Hale et al[51] found 4 weeks of comprehensive rehabilitation improve dynamic balance and subjective function. Mattacola and Dwyer[52], in a review of literature made clinical recommendations for acute and chronic ankle rehabilitation to include range of motion, strength training, and proprioceptive training in the early and intermediate time periods. McKeon et al[47,48] identified joint coupling changes, balance and functional changes following a progressive balance program. Destabilization devices, such as foam pads or balance discs are commonly used to add an external constraint to subjects. Recently, destabilization devices defined as footwear with an articulating heel (Myolux Footwear, Cevres Santé, Le Bourget-du-Lac, France) have shown increases in sEMG measures of the peroneus longus and gastrocnemius during balance tasks, functional exercises and walking.[53,54] Increased muscle activity during rehabilitation exercises may increase the capabilities of these muscles improving their function during gait. Use of external devices during 4 weeks of comprehensive rehabilitation was also shown to improve self-reported function and balance.(Donovan et al, Dissertation) No differences were found in single plane gait kinematics.(Donovan et al, Dissertation) Use of destabilization devices may challenge patients with ankle instability and force internal adaptations to protect the joint and has been hypothesized to increase the stability of the ankle.[53]

The purpose of this study was to assess the lower extremity coupling of the hip and knee to the ankle before and after 4 weeks of comprehensive rehabilitation performed with or without destabilization devices. The destabilization devices were footwear that had articulating heels aligned with the approximate axis of the subtalar. A vector coding technique was used to assess lower extremity joint coupling variability during walking. We hypothesize that following rehabilitation all patients will have increased variability in all joint coupling pairs with patients in the devices group will have greater magnitude of change in variability. An increase in joint coupling variability will indicate an increase in sensorimotor adaption capability in CAI patients to potentially protect them from further instability episodes by better exploring movement strategies following rehabilitation.

Methods:

We performed a randomized controlled trial with two independent variables of time (pre-rehabilitation, post-rehabilitation) and group (no device, device) in a sample with CAI. The dependent variable was joint coupling variability across the entire walking gait cycle. The following coupling pair were investigated:

1) Knee sagittal plane motion-ankle frontal plane motion
2) Knee sagittal plane motion-ankle sagittal plane motion
3) Hip frontal plane motion-ankle frontal plane motion
4) Hip frontal plane motion-ankle sagittal plane motion

This dependent variable was assessed between pre-rehabilitation and post-rehabilitation in patients with CAI for both groups (no device, devices).

Participants: Twenty-six, young active adults with CAI were recruited and participated in the study (Table 01). The effect of rehabilitation programs on measures of self-reported function, range of motion, strength, and balance in these same subjects have been previously reported. (cite Donovan et al) Inclusion criteria for CAI patients was a history of at least 1 significant ankle sprain taking place at least 12 months prior to recruitment. CAI patients scored at least <85% of the Foot Ankle Ability Measure-Sport (FAAM-S) scale and ≥10 on the Identification of Functional Instability scale (IdFAI).[8] The FAAM-S assesses the self-reported function of patients with CAI and IdFAI is used to determine the presences of CAI. Both questionnaires are valid and reliable.[55,56] All subjects were physically active (≥20 minutes of exercise at least 3 days per week). Patients had no history of lower extremity injury in the past 6 weeks and no history of lower extremity fracture or surgery. All patients had no history of balance disorders, neuropathies, diabetes or any condition outside of CAI that may affect balance. These inclusion and exclusion criteria are based on current recommendations for research on patients with CAI.[8] This study was approved by the institutional review board (IRB-HSR 17361) and all patients were consented prior to participation in the study.

Group	No Device (n=13)	Device (n=13)
Age (yr)	21.31±3.4	21.5±2.8
Height (cm)	168.81±6.9	169.1±10.6
Weight (kg)	66.12±12.9	75.30±13.7
Sex (m:f)	4:9	3:10
Godin	79.70±31.7	58.8±16.4
IdFAI	23.23±5.2	22.90±1.7
Pre-FAAM (%)	85.76±7.3	87.60±7.9
Pre-FAAMS (%)	67.07±13.4	65.90±18.2
Post-FAAM (%)	95.97±4.5	95.60±3.3
Post-FAAMS (%)	85.82±8.3	86.80±11.4

Table 01: Subject Demographics (Mean±SD)

Instruments: Three-dimensional kinematics were measured using the Flock of Birds (Ascension Tech., Inc., Burlington, VT) electromagnetic motion analysis system using Motion

Monitor software (Innovative Sports Training, Inc., Chicago, IL). A forceplate was used to assess inital contact and toe-off to allow timing of the gait cycle (Bertec Corp., Columbus, OH). Ankle destabilization devices included the Myolux Athletik and Myolux II footwear for the device group. Foam pads (Airex AG, Sins, Switzerland) and DynaDisc (Exertools, Inc., Petaluma, CA) were used in the no device rehabilitation group.

Procedure: All patients completed injury history questionnaires and self-reported function scales (FAAM-S, IdFAI). Gait trials were then captured using 10 sensors total. On each leg, a marker was placed on the lateral mid-thigh, lateral mid-shank, posterior calcaneus, dorsum of the foot, lumbar spine and thoracic spine. Digital sensors were then generated on the C7 spinous process, T12 spinous process, bilateral ASIS, medial and lateral knee joint line and medial and lateral ankle joint in order to generate joint centers of the ankle, knee and hip. All participants then completed 15 walking trials on the both the right and left limb across a 6 meter walk-way at a self-selected pace. The force plate was located in the middle of the walkway and foot contact with the forceplate was used to identify initial contact of the middle stride which was used for data processing. Researchers monitored walking speed and timing of each trial to ensure consistency. Trials where the subject missed the force plate were not used and trials were then repeated.

Rehabilitation was started within 48 hours of initial data collection. Three sessions per week were completed for 4 weeks to total 12 sessions of rehabilitation for all patients. All rehabilitation sessions lasted approximately 1 hour and were supervised by a single certified athletic trainer, who was blinded to all data collection. Rehabilitation included exercises to address range of motion, strength, balance and functional activity. The supervising clinician recorded exercises and progressions. The rehabilitation program progressions have been described in detail elsewhere. (Donovan et al, Dissertation)

Range of motion exercises: Arthrokinematics were initially assessed at the talocrural joint, tibiofibular, proximal tibiofibular and calcaneocuboid joints. If necessary, joint mobilizations were then performed for 2 sets of 2 minutes of grade III mobilizations based on previous recommendations.[57] Seated and weight bearing calf stretches were performed with both straight and bent knees. Stretching exercises lasted approximately 5 minutes.

Strength Exercises: Exercises addressing muscles of the lower leg included calf raises, toe raises, 4-way manual ankle resistance, D1 and D2 PNF patterns and 4 positioned walks were performed. Manual 4-way and PNF strengthening exercises were performed addressing both concentric and eccentric strength. Strength exercises started at 2 sets of 10 repetitions and progressed by increasing sets as deemed by the supervising clinician. The 4 positioned walks consisted of patients walking on their heels, toes, medial foot and lateral foot for 10 meters. Adding additional laps of 10 meters were repeated in order to progress the exercise. Strength exercises took approximately 10 minutes and progressions were based on patient feedback and the success of the required trials.

Balance Exercises: Balance exercises were based on similar progressions by McKeon et al.[47,48] which has been shown to improve self-reported function and balance and alter joint-coupling variability. Both static and dynamic balance exercises were performed including single-leg balance, single-leg balance and reach and hop to stabilization. Single-leg stance was performed with eyes open and eyes closed for 3 sets of 30 seconds in each task. Single-leg stance and reach exercises consisted of sets of 10 reaches using the adapted three direction Star Excursion Balance Test (SEBT) in the anterior, posterior-medial and posterior-lateral directions.[58] Hop to stabilization exercises were performed in sets of 10 with the patient performing a distance single-leg hop and balancing before hopping to the start position and stabilizing again. Ten repetitions were performed. Progression of all balance exercises consisted of changes in the surface or footwear. Stage 1 was performed on the ground with stage 2 adding a standard foam pad for the no device group or the Myolux II for the device group. Stage 3 of the balance progression was performed on the DynaDisc balance disc or the Myolux Athletik.

Functional Exercises: Patients performed lunges, box step-ups and step-downs and lateral step-ups and step-downs, forward running, dot jumping drills and gait training. Lunges were performed on both legs in sets of 10 ensuring the legs reached a depth of 90° of knee flexion with the knee just above the ground before returning to the starting position. Step-ups and step-downs, both forward and lateral were performed on a standardized 30cm box. Patients were directed to step up and down leading with the CAI leg. Sets of 10 repetitions were performed adding up to 3 sets for a progression. Sets were increased for lunges and step-ups and step-downs adding additional sets and using foam and the DynaDisc or each of the Myolux devices. Quick dot jumping drills were performed on a 4 quadrant square marked using tape. Participants completed 30 second bouts of bilateral medial/lateral, anterior/posterior and figure 8 hops. Up to 3 sets of these 3 directions of hops were added to challenge the patients. Further progression involved moving to unilateral hops for the 3 directions.

Walking Gait Training: Walking on a treadmill at a self-selected pace was performed by all subjects. Subjects were blinded to the speed and asked to increase the speed until they were at a normal walking pace where they felt comfortable. Patients progressed by5 minutes of walking up to 15 minutes. Patients in the device group performed the same progression but wearing devices.

Follow-up testing was completed within 48 hours of the last rehabilitation session. Participants completed the same motion capture process of 15 strides on each leg walking at a self-selected pace.

Data Processing: Joint kinematics were extracted and normalized. Strides were reduced to 100 frames representing percentage points of the gait cycle. Kinematic data was extracted for the ankle, knee and hip for each stride. A vector coding analysis was performed to compare the joint couples of interest. A custom processing code was used for all analysis (MatLab 7.04, MathWorks Inc., Natick, MA). A vector coding analysis was performed on each individual stride for all patients.

Vector coding is a technique for the quantification of the stride-to-stride variability (VCV) in the vector magnitudes and directions of two distinct joint motions. The calculations were based on methods described previously.[59] The vector direction is generated using previously described methods by Heiderscheit et al.[60] and adjusted based on the technique of Ferber et al[61] to fall between 0-90°. The vector magnitude was generated using Pythagorean Theorem at each point of the gait cycle. VCV is calculated as the stride to stride consistency of the vector magnitude and direction on a scale from 0 to 1 with 1 representing complete randomness and 0 representing no differences between trials.

Statistical Analysis: Groups means and 90% confidence intervals were generated for VCV across the entire gait cycle. Pre to post rehabilitation comparisons were made for both the no device and device groups.Any region where the confidence intervals did not overlap for at 3% points were considered significant.[13] Mean differences were then generated for the significant regions.

Results:

Hip-ankle results: No differences were identified in the hip frontal-ankle frontal (HFAF) coupling comparison between time points in either the no device or device group (Figure 01). No differences were identified in the no device rehabilitation group in hip frontal-ankle sagittal couple (HFAS) (Figure 02). In the device group, lower variability was identified post-rehabilitation from 44% to 47% (mean difference: 0.11±0.02) and 67% to 70% (mean difference: 0.12±0.05) (Figure 02).

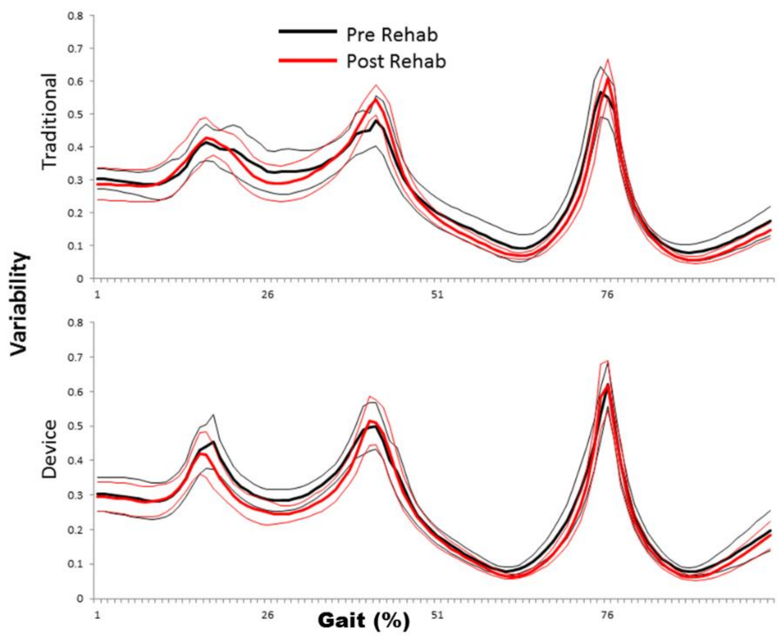

Figure 01: Hip frontal-ankle frontal joint coupling variability results. Means and 90% confidence intervals are presented across the gait cycle.

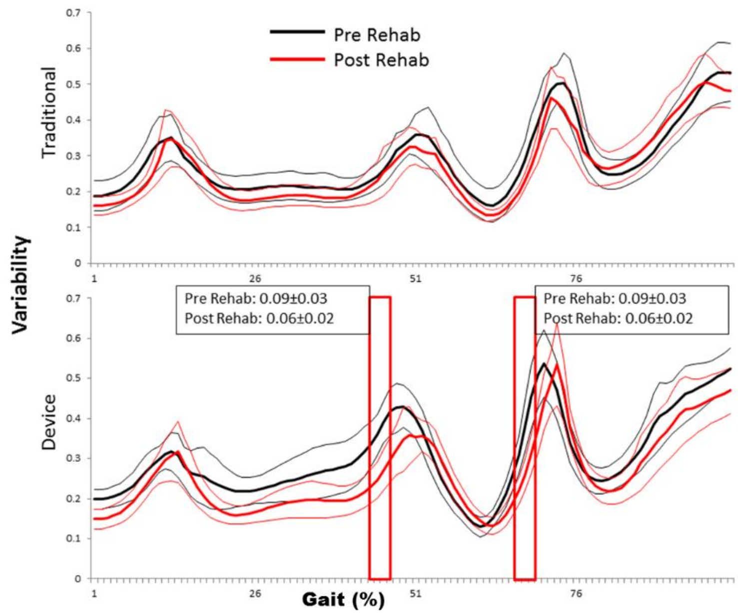

Figure 02: Hip frontal-ankle sagittal joint coupling variability results. Means and 90% confidence intervals are presented across the gait cycle. Periods of significant difference are boxed in red.

<u>Knee-ankle results</u>: No differences were identified in the knee sagittal-ankle frontal (ASAF) plane comparison in either no device rehab or using devices (Figure 03). In the no device rehab group, no differences were identified in knee sagittal-ankle sagittal (KSAS) couple (Figure 04). The device group had significantly less variability from 1-5% (mean difference: 0.19±0.05) and 63-66% (mean difference: 0.09±0.03) of gait in the KSAS group (Figure 04).

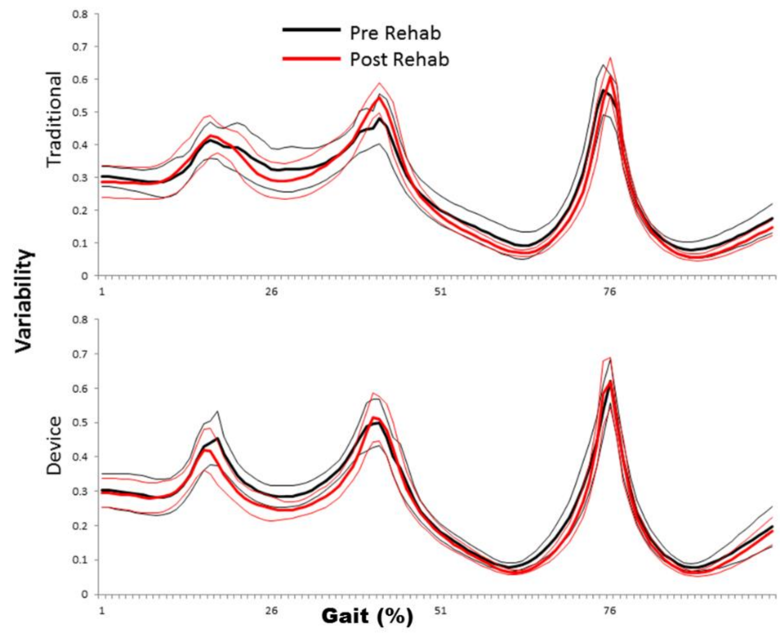

Figure 03: Knee sagittal-ankle frontal joint coupling variability results. Means and 90% confidence intervals are presented across the gait cycle.

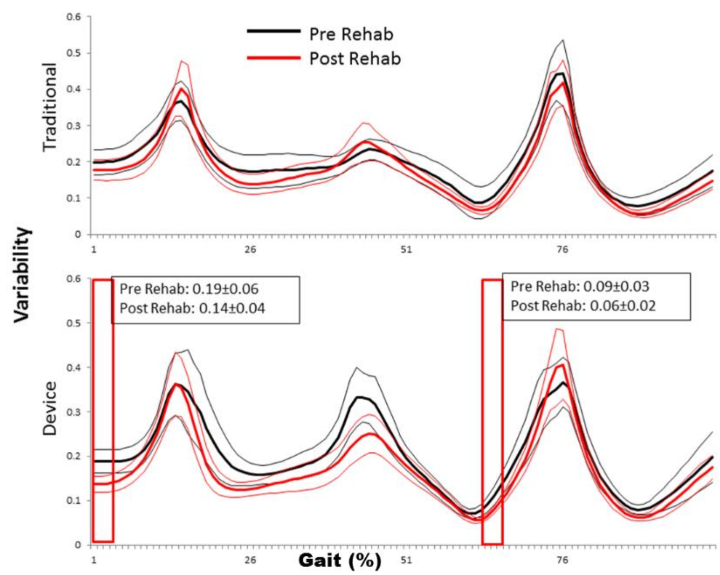

Figure 04: Knee sagittal-ankle sagittal joint coupling variability results. Means and 90% confidence intervals are presented across the gait cycle. Periods of significant difference are boxed in red.

Discussion:

A decrease in joint coupling variability was identified in KSAS and HFAS group in the device group. This decrease in joint coupling variability may reflect a change in the coordination of the lower extremity following 4 weeks of rehabilitation using destabilization devices. The rehabilitation protocol included range of motion, strength, balance and functional exercises. This data set was previously assessed measuring subjective function pre to post-rehabilitation and patients had a significant improvement in function, strength and balance (Donovan et al, 2015 UNDER REVIEW). This rehabilitation protocol did not directly address gait mechanics as part of the intervention but changes in variability during gait may indicate improving strength and balance may have the ability to alter sensorimotor function indirectly change the coordination of the hip-ankle and knee-ankle joint coupling.

McKeon et al[48] found a decrease in joint coupling of the shank-rearfoot and an increase in subjective function following a balance training protocol. Sekir et al[62] found that 6 weeks of isokinetic ankle strengthening improved strength, joint position sense and single leg balance compared to the contralateral limb. Comprehensive rehabilitation has been recommended as clinical intervention for those with ankle instability.[52] Hale et al[51] performed 4 weeks of comprehensive rehabilitation including range of motion, strength, neuromuscular training and functional tasks and found CAI patients had improvements in subjective function and dynamic balance. Joint mobilization and stretching exercise can improve the arthrokinematics and osteokinematics in patients with CAI and has been shown to improve postural control and subjective function.[51,57,63] Addressing specific impairments in CAI patients appears to alter the gait variability and also improve overall subjective function.

The protocol in this study used similar exercises to McKeon et al[48] and all patients were progressed based on each individual's ability during the balance exercises. In our study, we used different tools to challenge the patients. Only the group that used the destabilization devices was found to have changes in the joint coupling variability after rehabilitation. Balance training appears to alter the joint coupling around the ankle and joint coupling with the destabilization devices alters the variability at knee and hip. This may be related to novelty of the devices. Devices may present a challenging and new external constraint to the patients forcing them to develop changes at the hip and knee resulting in alterations in the joint coupling behavior.

Dynamical systems theory describes the ability to increase the function of sub-systems (neuromuscular function, strength, balance, etc) degrees of freedom in order to improve the function of the system as a whole. By increasing the strength of muscles of the lower extremity, improving motion and flexibility at the ankle, and increasing balance and postural control the joint coupling flexibility of the lower extremity during walking gait may be changed without directly targeting gait training. A decrease in variability was found in both groups particularly during stance phase and mid to late swing phase but was not significant in the no device rehab group. The destabilization device group may have had intervention during the walking portion of rehab due to the novelty of the footwear compared to the no device group as they wore sneakers. This may have forced the device group to further develop a sensorimotor adaptation which carried over into the data collection walking task.

Herb et al[64], identified a decrease in shank-rearfoot joint coupling with the application of ankle taping across the entire gait cycle in CAI patients. The external constraint of tape may protect the ankle joint by creating consistent motion during gait; however, limiting exploration of alternate movement patterns through the ankle tape theoretically may create a movement pattern reliant on the tape. CAI patients and healthy patients may be protected from lateral ankle sprains through the use of tape but may be at a higher risk when not taped. A rehabilitation program that addresses limitations seen in CAI patients may allow the patient to develop an internal protective mechanism to avoid lateral ankle injury. Both tape and comprehensive rehabilitation have been shown to decrease the joint coupling variability potentially indicating a protective role of these interventions.[48,64] While rehabilitation using destabilization devices, only decreased variability of the hip frontal-ankle sagittal and knee sagittal-ankle sagittal coupling during small regions of the gait cycle compared to ankle taping, it represents an organismic adaptation. By developing better strength, balance, and function, CAI patients have developed a different strategy to potential decrease the risk of injury. Taping, as an external constraint, may lead to the development of a reliance on tape during gait.

This rehabilitation protocol did not directly address gait training. Changes were seen in walking joint coupling variability by addressing other limitations of those with CAI but not walking directly. Future research should look at the impact of gait training on joint coupling variability. It is also unknown how long these adaptation will last, if they do represent a protective mechanism it needs to be determined how long the changes will last following rehabilitation. Lower extremity loading and kinetics have been shown to be changed through gait re-training intervention using re-time visual feedback. Potentially addressing the dorsiflexion deficits and inversion position may alter the biomechanics during walking gait using real time feedback.

Conclusion: Our findings indicate the 4 weeks of comprehensive rehabilitation using destabilization devices decreased lower extremity joint coupling variability during walking gait. Rehabilitation using no device rehab tools had no impact on joint coupling variability. The decrease in variability may represent an internal protective mechanism to ensure consistency in lower extremity coordination during walking gait.

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SECTION II: MANUSCRIPT III

CHRONIC ANKLE INSTABILITY PATIENTS EXHIBIT HIGHER VARIABILITY IN LOWER EXTREMITY JOINT-COUPLING VARIABILITY DURING DROP VERTICALJUMPS

Abstract:

Background: Chronic ankle instability **(**CAI) has been associated with biomechanical alterations during landing tasks. Joint-coupling analysis assesses associated motion of two body segments around different axes of motion. While joint-coupling differences have been reported during gait in patients with CAI, there is no known research assessing joint-coupling during drop-vertical jump (DVJ). The purpose of this study was to compare lower extremity joint-coupling during a DVJ between CAI and healthy patients. **Methods:** Twenty-eight young, active individuals (CAI:n=14,Control:n=14) participated in the study. A 3D motion-capture system was used to collect kinematics during 15 DVJs. A vector-coding analysis was used to assess the following joint-couples: knee sagittal-ankle frontal, knee sagittal-ankle sagittal, hip frontal-ankle frontal, and hip frontal-ankle sagittal. Measures of the magnitude, ratio, and variability of coupled motion were compared between groups. **Results:** The CAI group had higher variability in hip frontal-ankle sagittal, knee sagittal-ankle frontal and knee sagittal-ankle sagittal planes both prior to and following ground contact during the DVJs. Lower magnitude was found in the CAI group in knee sagittal-ankle frontal coupling before ground contact and in hip frontal-ankle frontal coupling after contact. The CAI group also exhibited a greater ratio of knee sagittal-ankle frontal motion compared to the control group both before and after landing. **Discussion:** CAI patients had higher variability, lower magnitude and higher ratio during the DVJ. These changes indicate potential adaptations to the constraint of CAI and the task of the DVJ. Clinicians should consider the challenges of DVJ during rehabilitation as is creates unique task constraints.
250/250

Introduction:

Lateral ankle sprains (LAS) are the most common injury in sports and physically active individuals.[1,2] Approximately 70% of individuals that suffer a lateral ankle sprain will go on to have multiple LAS and 59% report long term disability.[3,4] Chronic ankle instability (CAI) is a condition resulting from one initial LAS that results in long term disability and subjective instability outside of 12 months from the initial LAS.[5] Alterations associated with CAI include changes in neuromuscular function[6,7], balance and postural control[8], biomechanics during gait[9-11] and landing tasks[12,13].

Previous kinematic assessments have identified greater inversion[9,11], less dorsiflexion[9,10], and alterations in joint-coupling of the shank and rearfoot[14,15] during gait. Alterations in kinematics during gait and landing tasks have been hypothesized to be related to continued instability in this population associated with the position of the ankle during these tasks. However, there is only limited research during more sport specific tasks such as jumping and landing tasks. Brown et al[12,13] identified differences in frontal and sagittal plane motion of the ankle and frontal and sagittal plane motion of the hip in mechanically and functionally unstable and healthy patients during single leg drop jump tasks. In another study, Brown et al[16] found greater frontal plane motion variability, as defined by coefficient of variation of the joint angles, during a stop jump task. During a single limb drop jump, Delahunt et al[17] found greater inversion motion in individuals with functional instability. CAI patients appear to have altered biomechanics during jumping tasks.

The drop-vertical jump (DVJ) is a commonly used evaluation tool that simulates the landing and propulsion mechanics required during sport and athletic function.[18,19] The DVJ consists of jumping from a 30cm box a distance of half the individual’s height onto a target and then immediately performing a maximal vertical jump. This task has primarily been used to assess knee joint pathologies including anterior cruciate ligament injuries in patients following reconstruction.[18] There is little research using the DVJ as a tool to measure the movement strategy in patients with CAI.

Joint-coupling has been used to analyze movement variability and coupling relationship of multiple segments during human motion.[14,15,20,21] Movement variability has been studied as a reflection of sensorimotor health associated with injury but typically during continuous movement task such as walking or jogging gait.[15,21,22] Vector coding assessment of joint-coupling has been used to assess the magnitude and ratio of relative motion between two segments as well as the vector coding variability (VCV) between segments during gait in patients with CAI.[23] This vector coding variability (VCV) measure allows for information on the trial to trial consistency of intersegmental coordination as well as the relationship in motions occurring between the segments. The assessment of joint-coupling associated with CAI may present more information on lower extremity coordination at multiple segments during sport functional task such as DVJ.

Previously, Herb et al[15] identified a decrease in the variability of shank transverse plane to rearfoot frontal plane coupling during walking gait in patients with CAI compared to healthy controls. This decrease may indicate a constrained sensorimotor system in this population resulting in a more consistent gait pattern around the ankle joint. This reduced variability potentially protects the ankle joint by loading the joint in a consistent manner during gait; however, it also may represent a decrease in adaptability. Dynamical systems theory describes a healthy system as an adaptable system with the sensorimotor capabilities to alter movement patterns based off internal, external and task constraints.[24] A decrease in variability may reflect the internal constraint of CAI.[15,25] Further task or external constraints may require adaptations that a CAI patient is not capable of adapting during movement. This lack of adaptability may result in periods of instability or increases in variability and may place them at risk for further lateral ankle sprains.[24]

The purpose of this study is to assess lower extremity joint-coupling and variability between CAI patients and healthy controls during a DVJ. A vector coding assessment will analyze joint-coupling between: knee sagittal-ankle frontal plane motion, knee sagittal-ankle sagittal plane motion, hip frontal-ankle frontal plane motion, and hip frontal-ankle sagittal plane motion. We hypothesize that the CAI group will have higher VCV during the task compared to healthy controls indicating an unhealthy joint-coupling strategy as well as significantly greater magnitude and significantly lower ratio indicating greater relative joint-coupling motion and greater ankle motion respectively.

Methods:

We performed a descriptive laboratory study with one independent variable of group (CAI, Healthy). The dependent variables will be the vector coding measures of variability (VCV), magnitude and direction (θ) for all coupling pairs:

1) Hip frontal plane motion-ankle frontal plane motion (HFAF)
2) Hip frontal plane motion-ankle sagittal plane motion (HFAS)
3) Knee sagittal plane motion-ankle frontal plane motion (KSAF)
4) Knee sagittal plane motion-ankle sagittal plane motion (KSAS)

Participants: Twenty-eight, active adults (18-40 years) were recruited and participated in the study (CAI: n=14, Control: n=14) (Table 01). Inclusion for patients with CAI was a history of at least 1 significant lateral ankle sprain at least 12 months prior to the study and continued subjective instability. CAI patients scored at least 85% on the Foot and Ankle Ability Measure-Sport subscale (FAAM-S) and ≥10 on the Identification of Functional Ankle Instability (IdFAI). The FAAM-S assesses the self-reported function of patients during sport related activity such as running and jumping and has been shown to be valid in the assessment of functional impairments associated with ankle instability.[26] The IdFAI has been shown to be valid in the assessment of the presence of CAI.[27] Healthy control subjects had no history of lower extremity injury and scored a 100% on the FAAM-S and a 0 on the IdFAI. All subjects were physically active and participated in at least 20 minutes of physical activity at least 3 times per week and had no history of lower extremity fracture or surgery. All patients reported no history of balance disorders, neuropathies, diabetes or any condition outside of CAI that may affect balance. These inclusion were based on current recommendations for research on patients with CAI.[28]

Group	CAI (n=14)	Healthy (n=14)
Age (yr)	21.00±3.3	22.7±3.5
Height (cm)	170.63±8.8	170.0±12.1
Weight (kg)	69.46±12.63	66.16±14.3
Sex (m:f)	5:9	5:9
IdFAI	22.64±2.8	0±0
FAAM (%)	84.79±8.0	0±0
FAAMS (%)	63.62±15.4	0±0

Table 01: Subject Demographics

Instruments: Three dimensional kinematics were collected using the Flock of Birds (Ascension Tech., Inc., Burlington, VT) electromagnetic motion analysis system using motion monitor software (Innovative Sports Training, Inc., Chicago, IL). A forceplate was used to assess initial contact of all DVJ timing (Bertec Corp., Columbus, OH). All patients wore standardized footwear (Brooks Sports, Inc., Seattle, WA). Shoes had a section of the heel cut out to allow direction marker placement onto the rearfoot and working with the shoe company was ensured not to effect the structure of the shoe.[9]

Procedure: This study was approved by the institutional review board and all patients were consented prior to participation in the study (IRB-HSR #17361). Following consenting, all patients completed injury history questionnaires (FAAM, FAAM-S, IdFAI, Godin Leisure). Jump trials were captured using 10 sensors, including markers on the lateral mid-thigh, lateral mid-shank, posterior calcaneus, and base of 2nd metatarsal, T12 spinous process and C7 process. Digital sensors were generated on the head, ASIS, PSIS, knee joint and ankle joint in order to generate joint centers for the ankle, knee and hip. A 30cm box was position half the patient's height from the center of the forceplate. All patients then completed 15 DVJ. Patients were directed to drop off of the box landing on both legs with the limb of interest landing on the forceplate and then jumping directly up toward a mark on the ceiling directly above the forceplate. All patients took 3 practice trials. Researchers monitored trials to ensure consistency and trials were repeated if patients did not hit the forceplate.

Processing: Joint kinematics were extracted for the ankle, knee and hip. Trials were filtered and normalized to 100 points representing 100ms prior to initial forceplate contact to 200ms post initial forceplate contact (33%). A vector coding analysis was performed to compare the joint-coupling of the lower extremity. All analysis was done using a custom written MatLab code (MathWarks, Inc., Natick, MA).[15] For presentation of results purposes, normalized data was returned to the time domain.

Vector coding calculations were performed for all subjects on each trial of the drop-vertical jump. It is the calculations and quantification of the trial-to-trial consistency (VCV) of the vector magnitude and vector angle (θ) and is scaled from 0-1 with 0 representing no differences from trial-to-trial and 1 representing complete randomness.[15,29] The magnitude is calculated as the length as the resulting hypotenuse based off the excursion of each segment using the Pythagorean Theorem at each percentage of the drop-jump task (Equation 1).

Equation 1:

$$m = \sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2}$$

The vector angle ratio (θ) is generated based on methods described previously and adjust to fall between 0-90° using Equation 2.[21,30]

Equation 2:

$$\theta_{i = abs[tan^{-1} y_{i+1} - y_i / x_{i+1} - x_i]}$$

The calculations are based on previous vector coding methods described by Tepevac and Field-fote.[31]

Statistical Analysis: For all dependent variables, group means and 90% confidence intervals (CI) were generated throughout the entire drop-jump trial. Any region where group CIs do not overlap for at least 3% points was considered to be significantly different.[23] During periods of significant differences, mean differences between groups were generated.

Results:

Hip-Ankle Coupling

In HFAF, no differences were found in the VCV or ratio measures (Figure 01). The CAI group had significantly lower magnitude during from 100ms pre-contact to 10ms pre-contact (mean difference: 0.11±0.08).

In HFAS, CAI patients had higher VCV 82ms prior to landing 31ms prior to landing mean difference: 0.13±0.03) and 146ms post-landing to 161ms post-landing (mean difference: 0.12±0.06) of the trial (Figure 04). No differences were found in magnitude or ratio measures.

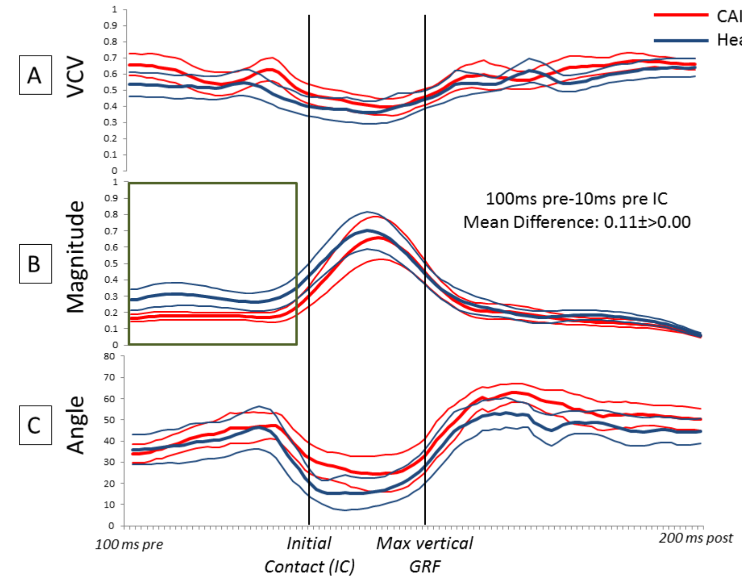

Figure 01: Hip Frontal-Ankle Frontal Results. Group means±90% Confidence intervals compared from 100ms pre initial contact to 200ms post initial contact. Vertical lines identify initial point of contact and the instance of maximal vertical GRF.

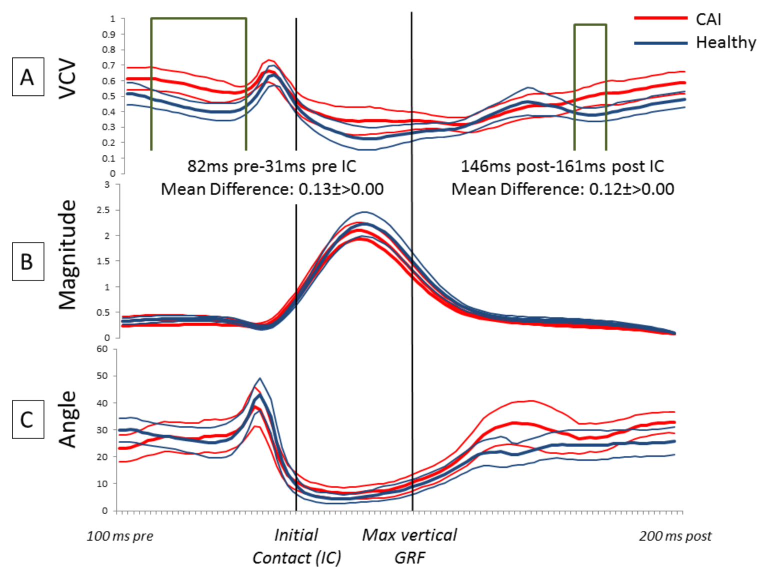

Figure 02: Hip Frontal-Ankle Sagittal Results. Group means±90% Confidence intervals compared from 100ms pre initial contact to 200ms post initial contact. Vertical lines identify initial point of contact and the instance of maximal vertical GRF.

Knee-Ankle Coupling

In KSAF, the CAI patients had higher VCV from 100ms pre landing to 76ms pre landing (mean difference: 0.14±0.04) and from 107ms post landing to 191ms post landing (mean difference: 0.14±0.06) (Figure 03). The CAI group had lower magnitude from 128ms post landing to 146ms post landing (mean difference: 0.15±>0.00) and higher ratio from 60ms prior to landing to 8ms post landing (mean difference: 36.14±3.74) and from 80ms post landing to 122ms post landing (mean difference: 3.74±3.95).

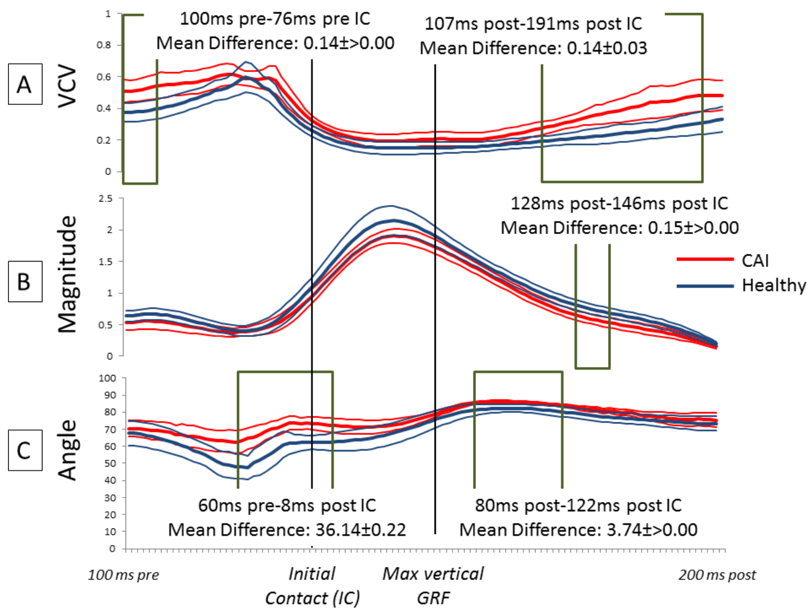

Figure 03: Knee Sagittal-Ankle Frontal Results. Group means±90% Confidence intervals compared from 100ms pre initial contact to 200ms post initial contact. Vertical lines identify initial point of contact and the instance of maximal vertical GRF.

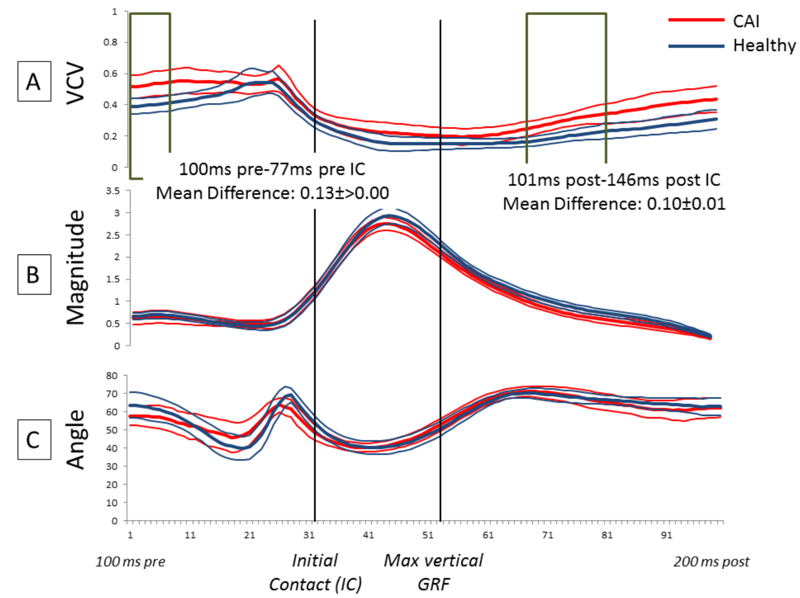

Figure 04: Knee Sagittal-Ankle Sagittal Results. Group means±90% Confidence intervals compared from 100ms pre initial contact to 200ms post initial contact. Vertical lines identify initial point of contact and the instance of maximal vertical GRF.

In KSAS, CAI patients had greater VCV from 100ms pre landing to 77ms pre landing (mean difference: 0.13±0.07) and from 101ms post landing to 146ms post landing (mean difference: 0.10±0.03) (Figure 04). No differences were found in the magnitude or ratio.

Discussion:

Changes in lower extremity joint-coupling were identified between CAI and healthy patients during a DVJ. Overall, there was higher VCV prior to and after landing of the task in the CAI patients. Lower magnitude of coupled motion was found in the joint couples of ankle frontal plane motion potentially indicating a constrained pattern of rearfoot motion in the CAI group during a DVJ. Higher ratios of coupled motion were found in the CAI group at and following initial contact which indicates greater relative motion at the ankle, in relation to the more proximal joints, compared to the healthy patients. Differences were identified prior to and after landing. The timing of these results may indicate potential differences in how CAI patients prepare for landing and coordinate motion during loading following the landing. Altered landing may predispose this population to recurrent LAS and changes in force dissipation during landing may stress the structures of the joint.

During a single limb jump landing task, Brown et al[32] found decreased variability at the knee and hip in patients with CAI. Task differences may have impacted the disagreement in variability findings between these studies; however, analysis techniques were most likely the cause for these differences. Brown et al[32] used a linear analysis technique assessing the coefficient of variation compared the vector coding which is a non-linear assessment technique of kinematics.

Previously, lower VCV has been identified during walking gait in shank-rearfoot coupling.[15] Herb et al,[15] did not find similar differences during jogging gait. This was hypothesized to be due to the increase in the task constraints of jogging gait. Lower VCV of the knee-ankle and hip-ankle during walking gait was previously reported.[33] In our study, CAI patients were found to have higher VCV of hip-ankle and knee-ankle during the drop-vertical jumping task. Shank-rearfoot coupling was not assessed during this task. The differences in the task requirements of walking gait and drop-vertical jumping may explain the differences in our findings compared to gait findings.

Dynamical systems theory describes the range of variability as a bell curve.[24] Low variability may represent a lack of adaptability to constraints and high variability may represent a of lack coordination. If we assume that healthy patients have a healthy range of joint-coupling variability then we can assess how patients with CAI relate to this range during different tasks. Increases in variability between the knee-ankle and hip-ankle may potentially be related to the constraint of CAI and the constraint of the task of the DVJ. The increases of VCV in the hip-ankle and knee-ankle coupling during DVJ may be related to a decrease at the ankle, however, there is little research assessing joint-coupling around the ankle during a DVJ task. Higher VCV during a DVJ, may reflect a lack of coordination during the task. An inability to control the lower extremity especially during a non-cyclical task such as DVJ may allow for trials where the limb is in a faulty position and injury may result. Cyclical tasks, such as gait, may allow for more opportunities to adapt a lower extremity position over successive trials.

Lower magnitude was found in the HFAF and KSAF couples during the DVJ. In HFAF, magnitude changes were found prior to landing as the CAI patient prepared for landing. Lower magnitude is indicative of less relative motion of the hip and ankle compared to the healthy patients. Less relative motion was also found during the swing phase of walking in shank-rearfoot coupling and was hypothesized to be in an attempt to create a stable limb in preparation for ground contact.[15] In KSAF, less magnitude was found following landing on the forceplate. A decrease in the magnitude during this period may be related to less motion between knee flexion and ankle frontal plane motion during this loading phase of the landing (Figure 05). Similar to the findings at the HFAF, it may represent an attempt by the CAI group to stabilize the limb and control the forces following landing in an attempt to create a stable joint. No differences were found in magnitude in any couple involving ankle sagittal motion. This may be related to the sagittal nature of the DVJ and potentially explain why the magnitude confidence intervals were so tight in the HFAS and KSAS coupling.

In the KSAF, ratio differences were found. Before, during and after initial contact the CAI group had greater amount of rearfoot motion relative to the knee sagittal motion compared to healthy patients. The CAI group also had higher ratios from 59-75% following landing on the forceplate. Greater ankle frontal plane motion relative the knee sagittal plane motion found in the CAI group may indicate a control strategy that places these subjects at a higher risk for inversion ankle sprains. Previously, Brown et al[32], identified greater frontal plane motion in CAI patients during jumping tasks. Our findings indicate that the coordination of the ankle and the knee motion is also different compared to healthy patients and may indicate a change in coordination during the task.

Based off these findings, further research should be done to assess potential interventions on this pathology and the changes to lower extremity joint coupling during DVJ task. Both CAI and healthy patients were assessed based on subjective reports of function potentially limiting our findings. Standardized footwear was used for all jumping tasks and may have presented a novel constraint depending on the familiarity with the shoe. All patients jumped from a 30 cm box regardless of height. This DVJ task was previously reported[34] and methods were the same in this study but the jump task may have challenged subjects based off their experience or size.

Conclusion:

Our findings indicate the CAI patients have higher VCV during DVJ representing a more varying coordination strategy between the hip and knee and the ankle. This may indicate an adaptation based off the constraint of CAI and a lack of coordination between the hip and the ankle and the knee and ankle. Magnitude changes were found with CAI patients having lower magnitude of coupled motion. This agrees with previous findings during gait. Ratios were higher in CAI patients in the KSAF joint couple. This indicates greater relative ankle motion compared to the knee in CAI patients versus healthy patients. Our findings indicate changes in lower extremity joint coupling coordination during a DVJ in patients with CAI that may be related to the condition. Further, inquiry into joint coupling and variability should be performed in different more functional tasks.

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SECTION III: APPENDICES

APPENDIX A

The Problem

Statement of the Problem

Lateral ankle sprains (LAS) are the most common injury in active individuals and sports. The condition of chronic ankle instability (CAI) commonly results from LAS and is associated with chronic lateral ankles sprains, loss in function during activities of daily living and sport and long term joint degeneration. Research has shown changes in neuromuscular function including activation and strength of the peroneal musculature. Decreases in balance and proprioception measures have been shown in CAI patients compared to healthy patients. These findings indicate an overall decrease in sensorimotor function in this population. This change in sensorimotor health is hypothesized to result in changes in kinematics and kinetics in these patients. These changes include decreases in eversion moments and force as well as increased inversion angles and dorsiflexion position. Intervention on this population often includes addressing the deficits previously identified in these patients. Improvements with balance training and strength training in isolation have driven clinical use of balance training and strength work. However, current clinical practice also includes range of motion work, balance training and functional exercises. Little is known on the effectiveness of these comprehensive rehabilitation protocols.

Human movement involves the complex organization of multiple body segments using varying muscular control based of sensory information from varying sources of neural signals. Previous assessment is often limited by to assessing single plane kinematics or single joint motion. Statistical limitations often lead to minimizing movement assessment to small portions of the task. These limitations may result in limitations in the current findings of biomechanical assessments in CAI patients. Statistical parametric mapping (SPM) is a technique to assess multivariate, multiplanar human movement while limited statistical sources of error and may allow for a more accurate assessment of CAI patients during gait. Joint coupling assessment takes into account movement of two segments in two planes during movement. Vector coding is a non-linear technique to assess joint coupling and has previously shown deficits during gait in CAI patients.

Research Question and Experimental Hypothesis

Manuscript 1: Gait kinematics and kinetics in patients with chronic ankle instability and healthy controls: a statistical parametric mapping analysis

Research Question: What are the differences in hip, knee and ankle kinematics and kinetics and ground reaction forces between CAI and healthy patients during walking and jogging gait using a statistical parametric mapping technique?

Research Hypothesis:

CAI patients during walking and jogging will have:

-Greater ankle frontal plane motion

-Less ankle sagittal plane motion

-Less knee sagittal plane motion

-Greater hip sagittal plane motion

-Differences in hip and knee kinetics

-No differences in ground reaction forces

Manuscript 1: Effects of Progressive Comprehensive Ankle Rehabilitation With and Without Destabilization Devices on Lower Extremity Joint Coupling in Patients with Chronic Ankle Instability

Research Question: What is the effect of 4 weeks of comprehensive rehabilitation with and without destabilization devices in CAI patients on lower extremity joint coupling during walking gait?

Research Hypothesis:

Following rehabilitation, CAI patients will have a decrease in magnitude, angle and VCV regardless of with rehabilitation devices they used.

Manuscript 3: Lower Extremity joint coupling during drop-jump in Chronic ankle instability and Healthy Control Patients

Research Question: What are the differences in lower extremity joint coupling between CAI and healthy patients during a drop-vertical jumping task?

Research Hypothesis:

Patients with CAI will have lower VCV, magnitude and angle compared to healthy patients before landing and after landing.

Assumptions

- Biomechanics of treadmill jogging/walking were similar to flat ground jogging/walking during activities of daily living.
- Retro-reflective markers affixed to the skin and electromagnetic markers are indicative of motion of the underlying bony structures.
- Participants responded truthfully to questionnaires regarding lower extremity injury history.
- Participants provided full effort during gait and DVJ trials.
- Kinematics and kinetics calculated by the Vicon and Flock of birds system is accurate to actual body movement.
- Gait kinematics and kinetics were not affected by any other reasons besides CAI.

Delimitations

- Participants were recreationally active.
- Participants were between the ages of 18 and 40 years.
- All participants were recruited from a sample of the community.
- Healthy participants had no history of lower extremity joint injury of fracture.
- CAI inclusion was limited on FAAM-S and IdFAI scores.

Limitations

- Participants in the rehabilitation had a range of experience with rehabilitation and physical therapy.
- Subjects walked or ran on a treadmill or walked across a 6 meter stage which may be different from over ground gait.

- Subjects were recreationally active, however, no other measure of physical activity was collected and subjects may have a wide range of activity levels.
- Treadmill speed was standardized for all participants.
- Footwear was standardized for all participants.

Operational Definitions

Chronic Ankle Instability- Repetitive occurrences of lateral ankle sprains resulting in instability and based on a subjective complaint of “giving way” along with scores below 90% on the Foot and Ankle Disability Index (FADI) and scores below 80% on the the FADI Sport.

Constraints- Boundaries or limits that affect the biological system. They reduce the availability of degrees of freedom in motion of the system limiting the strategies of movement and are classified as organismic, task, and environmental.

Drop vertical jump- A bilaterally jumping task in which the patient jumps down onto a target and then immediately jumps maximally in the vertical direction.

Dynamical Systems Theory- Theory that the body accomplishes tasks by using available degrees of freedom which are altered by constraints placed upon the body. Assumes that variability is a required part of human movement and develops as the body learns to accomplish tasks.

Gait Cycle- The period during locomotion from initial contact of a foot to the contact of that same foot following the stance phase and swing phase.

Initial contact- first point during gait or DVJ trials in which the vertical ground reaction force is between 10% and 20% of the body mass. In walking gait this is presented as the first percentage of gait but during out DVJ trials it is the 33% point of the trial.

Lateral Ankle Sprain- Inversion stress resulting in damage to the lateral ligaments of the ankle. Often result in chronic ankle instability.

Out-of-Phase- Coupling of two segments that move in an asynchronous way more often compared to an unconstrained population.

Recreationally active- participating in at least 30minutes of moderate to vigorous physical activity 3 times per week.

Significant difference during gait-Waveforms of the groups being compared are plotted across the trial. Means and 90% confidence intervals are generated. Any region where the confidence intervals do not overlap for at least 3% points is considered significantly different.

Stance Phase- Weight bearing phase of gait. The foot goes from heel strike thru foot flat, heel off and ends with toe off.

Statistical parametric mapping- multivariate method to analyze complex dynamic, 3 dimensional, multi-segmental biomechanical systems. Alpha level used for comparison is based on random field theory that takes into account multiple comparisons.

Swing Phase- Period of the gait cycle from toe off to heel strike during which the foot swings under the body.

Vector Coding- Method of analyzing coordination of two segments during the gait cycle. Angle-angle plots are constructed and transformed into a chain of points. The points are then analyzed looking at the line and direction between to consecutive points.

Significance of the Study

This study analyzed the biomechanics of the entire lower extremity (hip, knee, ankle) during gait. This study used a statistical technique that may account for previous bias in kinematic and kinetic waveform analysis. Previously, analysis limitations and statistical bias as confounded waveform analysis by limiting the time period or plane of comparison. SPM is a technique that has recently been applied to biomechanical research. This study identified novel results that expand on previous findings and may indicate the use of SPM in this field of research. The study assessed the impact of comprehensive rehabilitation on walking gait joint coupling using a non-linear analysis technique. Comprehensive rehabilitation has been shown to improve balance, strength and subjective function but not to alter joint kinematics. Joint coupling variability was shown to be changed through four weeks of rehabilitation. These results indicate that sensorimotor alterations can occur through rehab and that those changes impact gait. Finally, this study explored joint coupling during a drop vertical jump task. LAS often occur during landing tasks but there is limited research on these tasks in CAI patients. These changes indicate that joint coupling variability is different in CAI patients and may be related to continued instability in this population.

APPENDIX B

Literature Review

Introduction: Lateral Ankle Sprain

A lateral ankle sprain (LAS) is one of the most common musculoskeletal injuries in athletics and active individuals.[1,2] Sprains and strains was the most common outpatient condition reported in the United States emergency departments with 4.4 million visits per year and ankle sprains are estimated to be 7-10% of emergency department videos.[4,65] These account for only reported ankle sprains and the actual number is estimated to be significantly higher. Nearly half of all ankle sprains occur during athletic participation with the majority occurring in individuals under the age of 35 years.[66,67] Disability and long term sequelae can result from an initial ankle sprain including a loss of time from sport and work and the development of chronic ankle instability and osteoarthritis.

A mechanism of hypersupination of the ankle complex and adduction of the foot results in damage to the lateral ankle ligaments.[3] Sometimes external rotation of the lower leg with respect to the ankle complex may occur.[3] The restoration of full function following acute ankle sprains often does not occur with resolution of the acute symptoms following a primary lateral ankle sprain. It has been reported that between 40% and 70% of patients that suffer an ankle sprain will go on to have multiple ankle sprains.[6,68] The presence of continued instability and subjective giving way at least one year out from the initial sprain and self-reported giving way has been identified as chronic ankle instability (CAI).[8] CAI is associated with changes in sensorimotor function at the joint and the lower extremity.[5] These changes are reported to result in disability including neuromuscular alterations,[40] balance and postural control deficits[69], and biomechanic changes including changes in movement variability[9,11,70]. All of these differences identified in those with CAI may be associated with the continued instability in this population. The purpose of this literature review is to review the condition of CAI and associated biomechanical changes associated with the condition, alterations in lower extremity joint coupling and movement variability and discuss the condition from the perspective of dynamical systems theory.

Ankle Joint Complex and Pathomechanics of Lateral Ankle Sprains

The ankle joint complex consists of the talocrural or tibiotalar joint and the subtalar joint and the distal articular of the tibia and fibula. The talocrural joint is considered to be a hinge joint, however, due to the ligamentous, tendonous and bony anatomy the degrees of freedom of the joint exist outside sagatal plane motion alone.[71] The subtalar joint consist of the articulation of the calcaneus, navicular and talus. The axis of rotation at the sub-talar joint is aligned in approximately 40° above horizontal and 23° internally rotated away from the midline of the foot.[72] Biomechanically these joints allow for multiple planes of motion requiring coordination of the muscles in multiple planes and patterns in order to effectively and efficiently control the joint. The supination of the ankle joint complex consists of talocrural dorsiflexion and subtalar inversion and internal rotation coupled with proximal shank external rotation. The multiplanar position of these two joints allow for more combined motion throughout the ankle joint complex in the three planes of motion than from each joint combined.[73]

The musculature surrounding the ankle is separated into four regions based on fascial tissue separation. The anterior compartment consist of tibialis anterior, extensor hallucis longus, extensor digitorum longus and fibularis tertius. All musculature is innervated by the deep tibial nerve and acts to primarily dorsiflex the ankle. The posterior compartment includes both deep layers including flexor hallucis longus, flexor digitorum longus and tibialis posterior and all act to plantar flex and invert the foot. The superficial layer includes the primary plantarflexors of the foot, including the gastrocnemius, soleus and plantaris muscles. The posterior compartments are innervated by branches of the tibial nerve. The lateral compartment includes the peroneal longus and brevis musculature and act to evert the foot. The lateral compartment is innervated by the superficial peroneal nerve. The peroneal musculature, due to its action of eversion has been research to play a role in the condition of CAI.

The ankle joint is supported by ligaments of the subtalar and lateral ankle joint. Intrinsic subtalar ligaments, interosseous, cervical and the deep fibers of the extensor retinaculum , all support act to stabilize the subtalar joint.[74] Peripheral ligaments supporting the subtalar joint include the calcaneofibular, lateral talocrural and fibulotalocalcaneal. Lateral ankle ligaments include the anterior and posterior talofibular ligament. The combined support of these ligaments act to resist inversion, internal rotation and supination of the ankle joint complex.[74] The bifurcate ligament also acts as a static stabilizer of the complex consisting of two branches, dorsla calcaneocuboid and dorsal calcaneonavicular. The articulation of the tibia and fibula is supported by the syndesmosis and tibiofibular ligaments.

The pathomechanics of a lateral ankle sprain occur with excessive supination of the rearfoot, internal rotation of the foot and external rotation of the shank.[3] Recent video analysis of lateral sprain mechanisms has identified inversion angles of as high as 142° and inversion velocities of up to 1,752°/sec.[75] Fuller[76] suggested an increased supination moment at the subtalar joint to ultimately be the cause for lateral ankle sprains. Damage has been shown to initially occur to the anterior talofibular ligament (ATFL).[77] Disruption of the ATFL allows for greater amounts of internal rotation placing remaining structures at risk for injury.[78] The remaining ligaments have been shown to incur damage upon disruption of the ATFL. Damage to the ankle complex joint capsule and subtalar joint stabilizers has also been to shown including 80% of ankle sprains involving the subtalar ligaments.[79]

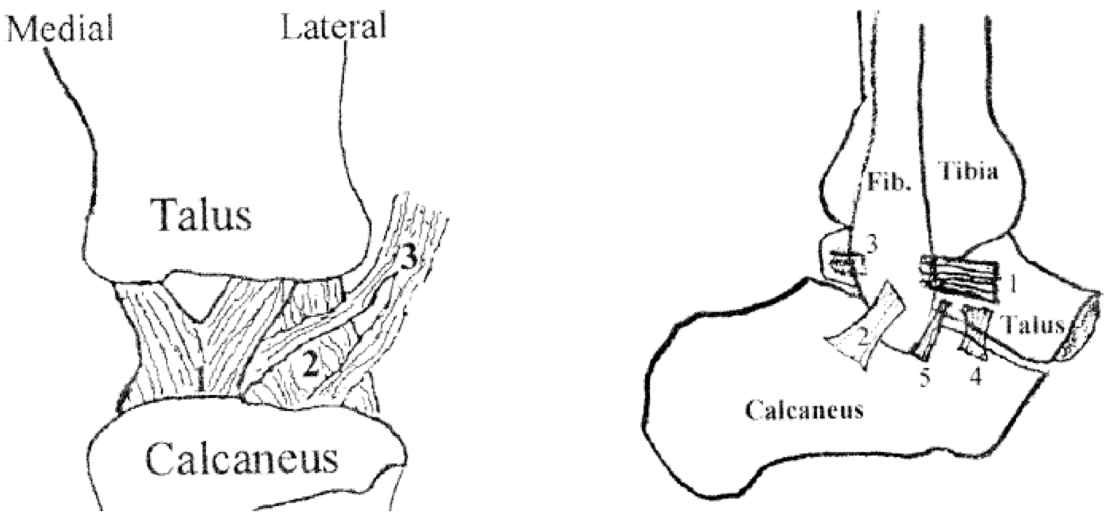

Figure B01: Ligamentous structures often suffer damage during a lateral ankle sprain resulting in ankle joint complex instability.

Damage to the musculotendonous structures may also occur. Peroneal tears were reported in 25% of patients and 54% of patients had peroneal retinacular damage associated with lateral ankle sprains in 61 patients undergoing ankle reconstruction.[80] The ability of the peroneal musculature to respond to rapid inversion has been hypothesized as a protective mechanism in lateral ankle sprains.[81] Konradsen reported a need 126 milliseconds of response time, including 54 milliseconds for reaction time and electromechanical activity generation and 72 milliseconds of electromechanical delay prior to the generation of force.[81] Compared to 1,752°/second velocity of an ankle sprain there appears to be no capacity for this musculature to protect the joint during an inversion mechanism without any preparatory activity.[3] Denver et al[82] recently identified that foot position affected the response time in the peroneal musculature, delaying reaction time in of individuals in a pronated or supinated foot position compared to neutral position.

The mechanism of inversion will stress the supporting structures of the ankle complex and if the external forces exceed the tensile strength of these structures, damage will occur. Damage to the lateral ankle ligaments was hypothesized initially by Freeman[68] to be of importance in the chronic lateral ankle sprain population. Damage to these ligaments is associated with loss of afferent sensory information from the indwelling mechanoreceptors.[5,68] There are more free nerve endings located within the anterior talofibular, calcaneofibular, and posterior talofibular ligaments compared to other ligaments within the ankle joint complex.[83] Hubbard et al[84] reported that healing to the lateral ankle ligaments may began to heal as early as 6 weeks but at up to 1 year up to 31% of patients still had mechanical laxity. Ultimately, the healing time is not congruent with recommended immobilization time to return to play. Professional American football players have been reported to miss only 1.1 practices and only 0.04 missed games after ankle sprain.[85] Following an acute lateral ankle sprain, the typical sequelae include swelling, tenderness and pain with movement and weight bearing. Resolution of these symptoms is often the primary determinant in return to play, often overlooking joint instability which may still be present following a lateral ankle sprain.

The leading risk for a recurrent ankle sprain remains a history of previous ankle sprain.[8] Deleterious changes following the initial ankle sprain are thought to predispose these patients to recurrent sprains and the development of chronic ankle instability (CAI).[86] Joint mechanic changes associated with ligamentous laxity and functional changes due to alterations in sensory information from the joint both play a role in the development of the chronic ankle instability.[3] While the influence of mechanical and functional deficits have been thought to play a role in the condition, Hubbard et al[87] stated that the conditions were not dichotomous due to a the presence of functional disability regardless of the presence of mechanical instability in 30 subjects with diagnosed CAI.

Chronic Ankle Instability

CAI has recently been defined as instability and subjective feelings of “giving way” at the ankle at least 12 months out from an initial ankle sprain.[8] Being at least one year removed from the initial sprain will help to separate patients with CAI from those with long term symptoms associated with the acute sprain. Patients should include subjective complaints of dysfunction and questionnaires can be used to help characterize the patients’ dysfunction.

The Foot and Ankle Ability Measure (FAAM) and the sport subscale (FAAMS) have been shown to be valid in the assessment of dysfunction associated with CAI.[55] The Identification of Functional Ankle Instability (IdFAI) has also been shown to be a reliable tool in identifying those with CAI.[88] The ankle instability instrument (AII) and Cumberland ankle instability tool (CAIT) are subjective tools to identify feelings of instability associated with the condition.[8] These questionnaires should be used to identify and characterize the condition of CAI in this population.

Beyond subjective dysfunction, alterations in mechanical stability and laxity have been identified in part of this population. Laxity is a predictor of the development of CAI.[89] Arthrokinematics changes and joint laxity have been reported in patients with recurrent ankle sprains and CAI.[74,84,90] Denegar et al[90] reported a deficit in posterior talar glide but not in ankle dorsiflexion in patients following at ankle sprain. The restoration of osteokinematic motion was present in spite of the arthrokinematics restrictions. Mechanical laxity may allow aberrant motion at the joint due to alterations in the position of the talus within the joint. The mechanism of a lateral ankle sprain may pull the talus anteriorly out of its arthrokinematics position. This positional fault has been hypothesized to play a role in biomechanical changes and be related to the kinematic findings seen during gait.[91]

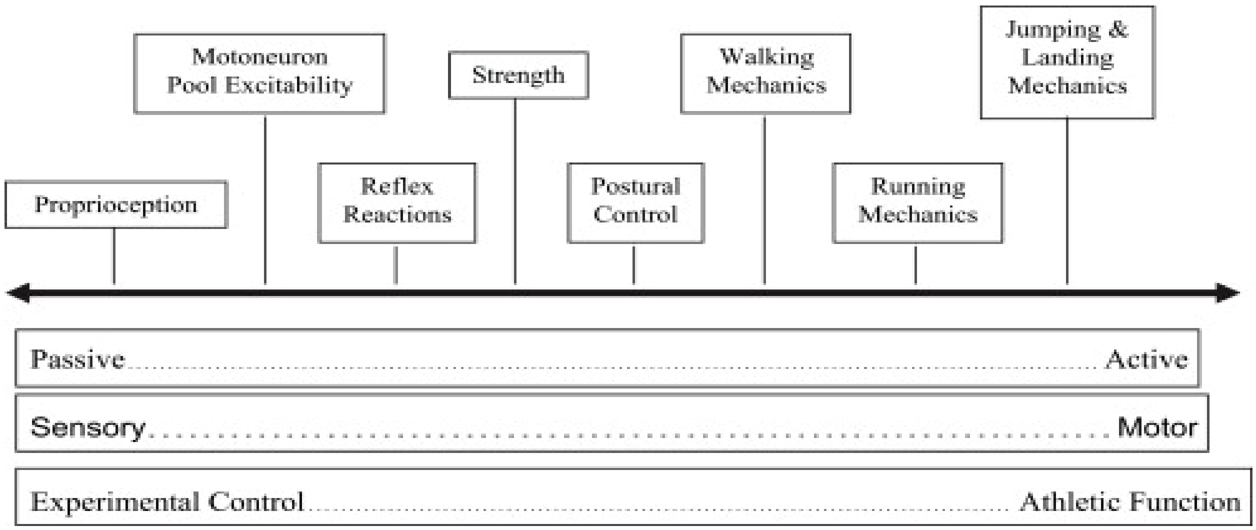

Figure B02: Dysfunction and limitations previously identified in patients with CAI. Hertel 2008

Damage to the mechanoreceptors within the lateral ankle ligaments was hypothesized by Freeman to lead to functional disability at the ankle joint.[68] The loss of afferent information has been linked with changes in neuromuscular function[40], balance and postural control[69], as well as kinematics and kinetics.[9,11,92] The initial healing process to the lateral ligaments may occur, however, the sensory receptors within the ligaments may not return to function. This change may alter the mechanics of the joint as the healing ligaments may never return to the original structural condition but also the loss of sensory information will change in the afferent input on joint position, velocity, and force as sensed by mechanoreceptors of the ankle. These changes have been directly associated with deficits in proprioception in this population but do not entirely explain the deficits seen this this population.[3]

Proprioceptive deficits have been seen in joint angle replication measures[93] and kinesthesia.[94,95] The surround ankle musculature may be able to compensate for changes in the ligament mechanoreceptors but have also been shown to be altered in the CAI population.[96]

These changes may be related to muscle function including eversion strength[97] and efferent motor control.[41] Beyond muscle and ligament receptors cutaneous sensation[98,99] and nerve conduction velocity have also be identified following ankle sprains and may explain some changes leading to chronic instability.[100]

Neuromuscular alterations have been reported in the CAI population. These have often targeted the peroneus longus due to its mechanism of eversion and protection from an inversion mechanism. The study of the ankle musculature typically occurs during a perturbation or trapdoor mechanism. Kavanagh et al[101], identified a slower motor time for the peroneus longus but not the anterior tibialis in patients with CAI. Gutierrez et al[102], identified a preparatory response in the peroneals and increased reactive time in patients with ankle instability compared to healthy controls while landing on an inversion trap door. This preparatory response has also been identified during gait. Feger et al[103] reported an earlier onset of activation prior to initial contact during a walking task in CAI patients. This may indicate a mechanism to protect the ankle joint prior to initial contact but it was hypothesized that this may create a mechanism of fatigue in the peroneal which may place these individuals at risk following fatigue.[103]

Changes in supraspinal control of the musculature may explain alterations in activity of the peroneals. CAI patients had higher reported thresholds for activation using transcranial magnetic stimulation.[104] Using the Hoffman Reflex technique, similar findings were present in the soleus musculature following acute ankle sprains.[105] Neuromuscular changes in patients following LAS may help explain the development of CAI. Changes in afferent sensory function due to damage to the ligaments along with neuromuscular changes may present a constraint to the sensorimotor system and may lead to CAI.

Rehabilitation and Chronic Ankle Instability

Management following LAS or in those with CAI commonly attempts to return the patient to previous function but also to prevent subsequent ankle sprains. Mattacola and Dwyer[52] recommends clinical use of range of motion, strength and proprioception exercise for patients following acute sprains and in those with CAI. Use of these interventions directly addresses many of the previously reported limitations and deficits identified in CAI patients.

Recently, Donovan and Hertel[106] have described a new paradigm to guide clinical intervention on LAS and in those with CAI (Figure 03). Due to the multifaceted condition of CAI, certain deficits should be treated only if they are found in the patient. The categories include range of motion, strength, balance and functional movement.The paradigm describes a cycle of assess, intervene, and reassess in order to best determine deficits in this patients and provide the appropriate care. The paradigm also guides clinicians through reassessment following initial intervention.

Improvements in dorsiflexion range of motion has been shown with intervention of static stretching[107] and through joint mobilization of the talocrural joint.[108] Using resistance tools to perform multi-directional strength was shown over a four week program to improve strength and proprioception.[109] Following a 6 week strength training program, Docherty et al[110] found improvement in not only eversion strength but also joint position sense. Balance training has also been used in this population and shown to be a useful tool in rehabilitation.[111]

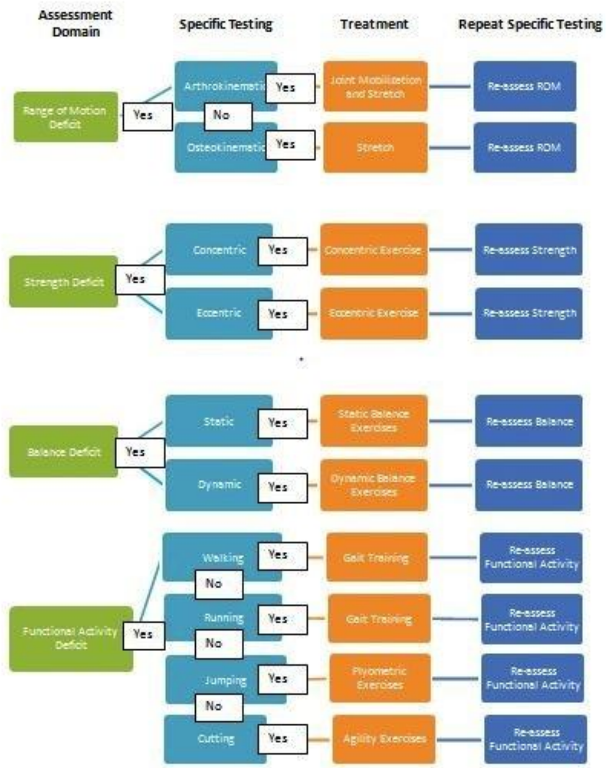

Figure B03: Paradigm for intervention for LAS and CAI. Donovan and Hertel 2012

McKeon et al[47,48] previously report improvements in subjective function and balance along with gait parameters following progressive balance training in patients with CAI.   These findings included changes in joint coupling variability which was decrease following the balance training. Hale et al[51] completed a 4 week comprehensive rehabilitation program and found it improved dynamic balance and subjective function. Clinical practice recommends the use of tools to challenge patients during rehabilitation. This includes, changing surfaces or task requirements.

Destabilization devices such as foam pads or balance disks are used clinically to challenge patients during single limb balance. One issue with these is that are challenging to adapt to more dynamic task such as walking. Recently, destabilization footwear has been used to create an unstable foot surface during (Myolux Footwear, Cevres Sante, Le Bourget-du-Lac, France). The design of the shoe creates an unstable heel that has an approximate axis parallel with the subtalar joint axis. [112] In this way it requires muscular activation to sense the position of the foot and counter the position resulting from having a destabilization shoe.[112] The footwear is worn similar to a sandal and can be used during walking or more functional tasks, including jumping and lunges.[53,54] Increases in surface EMG amplitudes of musculature surround the ankle through the use of this footwear may indicate a role in rehabilitation. Donovan et al[53,54], found increases in a CAI group during walking and lunges and step-up with novel use of the devices. Use of these devices over a period of time may be able to further challenge the musculature around the ankle as well as challenge the proprioceptive capabilities of this population.

Gait and Chronic Ankle Instability

Changes in gait have been reported in patients with CAI compared to healthy controls. These changes have been linked with the constraints previously presented. These constraints may be associated with alterations in motor control and biomechanics during gait that are associated with continued instability and dysfunction. The purpose of the following section is to present previously identified findings during gait and to discuss theories on the role of motor control changes on the condition of CAI.

De Ridder et al[113], analyzed a multisegmented foot model to analyze the kinematics within the foot during walking and jogging gait. The rearfoot was more everted during the stance phase of both walking and jogging. The medial midfoot was more inverted for running and walking in the ankle instability group. An everted rearfoot during stance phase seems counter to the mechanism of an LAS, however, Willems et al[31] did identified a medial loading of the foot and trend towards a higher eversion excursion in subjects at risk for an ankle sprain.

This study used a statistical parametric mapping (SPM) technique to assess the multiple segments within the foot. This technique was proposed to remove the assumptions typically associated with waveform analysis. The time differences of early midstance versus late stance phase gait indicate the importance of assessing the entire waveform and not just the early loading phase.[113] De Ridder[113] argued that this may indicate the time period of ankle sprains during gait appear to be the mid to late stance and not the loading phase following initial contact as previously described.

Alterations at the ankle have been reported during task such as jogging, walking, and initiation and gait termination. These differences have been identified during different periods of the task. Drewes et al[11], found less dorsiflexion during jogging from 9-25% of the gait cycle in patients with CAI compared to healthy controls. During this period of gait, maximum dorsiflexion is expected. These differences were expected to be the result of alterations in the arthrokinematics in the CAI patients preventing the ankle from reaching a maximally closed packed position. This hypothesis agrees with findings of decreased posterior glide in CAI.[114] Chinn et al[9] found during walking from 42-51% the CAI group was less dorsiflexed and during jogging was more plantarflexed from 54-68%. During walking a lack of 3° of dorsiflexion during mid to late-stance phase agreed with the findings of Drewes et al.[11] During jogging, the CAI group was also more plantarflexed during swing phase. These findings were hypothesized to decrease the floor foot clearance in this population. Konradsen et al[15], hypothesized that early foot contact during swing was a risk factor for inversion mechanisms at the ankle. Brown et al[10], identified a decrease in clearance in an ankle instability group 250ms prior to initial contact.

Chinn et al[9], also identified differences in jogging in the frontal plane. The CAI group had more inversion throughout the gait cycle and periods of significantly more inversion during parts of the stance phase, swing phase and at toe off. Drewes et al[12] reported similar findings during during a jogging task in patients with CAI, however, differences were significant throughout the entire gait cycle. Greater inversion during gait may put these individuals at risk for inversion. The study by Drewes et al[12] were found in a barefoot condition while Chinn et al[9] differences were found while in a shod condition. These findings indicate that the presence of shoes changes the kinematics and should be taken into consideration in interpreting kinematics to clinical practice. Monaghan et al[14] and Delahunt et al[40] have also reported greater inversion in patients with ankle instability during gait around initial contact. These kinematic alterations were reported with changes in kinematics at the ankle joint.[14]

Biomechanical assessment has also been identified during gait initiation[115] and unplanned gait termination.[116] Hass et al[115] assessed the center or pressure (COP) trajectory and peak COP excursion in 20 CAI and 20 healthy subjects during gait initiation. Significant findings indicated a group x limb interaction suggesting supraspinal motor control differences in subjects with CAI. The CAI group had a decrease in the COP measures in the involved limb which may indicate a potential constraint of the condition. In an attempt to limit and potentially protect the ankle joint, CAI patients may limit the COP over the injured limb. Higher level control mechanisms may lead to alterations in the control mechanism around the joint.[115] Wikstrom et al[116] assessed 20 patients with CAI and 20 healthy controls during a self-selected pace walking task that required unplanned gait termination. The CAI group was found to have significantly higher braking and propulsive forces during planned and unplanned gait termination. These findings indicate alterations in the biomechanical control strategies during gait initiation and termination.

The inconsistencies in these kinematics findings during gait may be a result in differences in methods. Previous studies have varied in their assessment of the condition of CAI as well as their inclusion and exclusion criteria. Gribble et al[8], recently published the position statement on selection criteria for future research in this population which should improve the consistency in identifying CAI in both clinical and laboratory settings. Method differences and task differences also may explain differences in findings at the ankle. Foot wear is important and may explain biomechanical differences by altering the external constraint on the patients, both CAI and healthy patients. Task differences include the speed of gait and whether it was self-selected on normalized speed. The use of treadmills during gait compared to motion capture across flat ground may also result in differences in the task constraints and may limit findings of previous research. Despite these differences, previous findings indicate a central control mechanism in the biomechanics of the ankle during gait and these control mechanisms may explain continued instability in this population.

Lower extremity changes outside of the ankle have also been reported in patients with CAI and agree with the potential central motor control difference previously hypothesized. Decreased knee flexion was reported in patients with CAI while landing during a jump landing task which was associated with decreased in anterior-posterior stability in dynamic balance.[16] This strategy was hypothesized to be a strategy to lengthen the force absorption period during landing. Centrally mediated neuromuscular control may be a strategy to compensate for dysfunction at the ankle as previously found during gait termination[116] and gait[14]. Caulfield et al[117] reported greater knee flexion in the CAI group 10ms prior to and 20ms post initial contact during a drop landing task. These findings indicate a movement strategy difference in preparing for contact and during contact.

While these findings were not performed during gait, they explain a centrally mediated control strategy in the CAI patients that result in alterations throughout the lower extremity.

These changes may indicate a proximal strategy to account for faulty patterns at the ankle. Little research has been done looking at these proximal segments during gait. The kinematic alterations at the ankle have only been analyzed at the frontal and sagittal plane. The multiplanar motions that occur at the ankle may mask some differences in the motions at the ankle joint and may require complex motor control throughout the lower extremity in order to account for errors in ankle position. Drewes et al[12], used a continuous relative phase analysis to analyze the coupling between shank internal and external rotation and rearfoot inversion and eversion during walking and jogging gait in patients with CAI. Altered joint coupling has been used to gain insight on the centrally controlled coordination of the ankle. CAI patients showed more out-of-phase coupling during gait compared to healthy controls. Out-of-phase coupling may be indicative of altered coordination and control. Herb et al[13], used a vector coding method to analyze the shank rotation and rearfoot inversion/eversion in patients with CAI. The vector coding method allows for the analysis of both movement variability between the segments and relative motion between the segments. Findings indicate difference during both walking and jogging in the relative motion between the segments. Variability differences were only identified during walking. These findings of joint coupling between shank rotation and inversion/eversion of the rearfoot identified differences during gait in the fine motor coordination between segments around the ankle. The changes in shank rotation would, theoretically, affect the motions of the knee and require a more complex motor control around the knee joint as well. These alterations may need to be explored as motor control throughout the lower extremity may be altered. The dynamical systems theory of motor control has recently been used to describe the organization of human movement related to injury and may help describe associated changes in patients with CAI.

One consideration for the assessment of the knee and hip in those with ankle instability is statistical in nature. Motions of the hip and knee are larger, especially during gait, compared to the ankle. Due to this fact, statistical power must be taken into account in order to identify differences at the knee and hip. Larger sample sizes may be required in order to find significance at proximal joints during gait.

Jumping Tasks and Chronic Ankle Instability

During sporting tasks, jumping and landing tasks present a high risk for ankle injury and possibly explain the high number of injuries in sports such as basketball and volleyball.[2] Jump landing requires coordination of multiple joints across the lower extremity to control the forces of the body on the ground and the returning forces onto the body. This control requires effective postural control and neuromuscular activity in order to complete the task. Brown et al[118] found differences in kinematics in CAI patients during walking, a single leg drop jump and a stop jump task. Delahunt et al[19] identified kinematics, kinetic and surface EMG measures during a single leg drop jump task. Greater inversion angles were identified prior to initial contact which was associated with lower integral EMG measures in the peroneus longus. Brown et al[118] identified changes in the frontal and sagittal plane motion between both functionally unstable patients and mechanically unstable individuals compared to copers and healthy controls. Mechanically unstable patients had greater plantar flexion and higher maximal eversion prior to initial contact. Both of the studies identified similar findings during a single leg drop jump task. During this task patients dropped off a normalized height box, landing on a force plate and maintained balance. This task requires the effective postural control and force absorption during landing. However, it does not reflect the force generation task that also occurs during a jumping task.

A bilateral drop vertical jump (DVJ) where patients land on both feet and immediately perform a maximum vertical jump has been used to assess the biomechanics of force absorption and generation during functional activity. Previous papers have reported slightly varying methods of the drop vertical jump but they consistently report jumping from a box simultaneously leaving each leg, hitting a force plate and immediately perform a bilateral maximal vertical jump. The landing error scoring system (LESS) is a valid and reliable clinical tool used to assess the risk factors for lower extremity injury and has been researched in those following anterior cruciate ligament repair (ACL-R)[119] or healthy individuals.[120] The drop vertical jump has been used to assess lower extremity movement patterns and load deformation. Due to the task requirements of the DVJ, the patient must control forces of the initial jump, generate forces to perform the vertical jump and then land again. This provides a very functional task that requires coordination of the lower extremity through all phases of the task.

Associated with ACL injury are changes in kinematics of the hips and knees in patients at risk for injury.[119] These findings indicate that the task challenges the entire lower extremity and changes following joint injury. The constraint of an ACL injury and repair require alterations in the control of the hip and knee and the uniqueness of the DVJ task may require altered biomechanics. Ligamentous injury at the ankle is associated with changes during a single limb drop jump and findings during a bilateral drop vertical jump may help identify the impact of CAI on functional task.

Compared to gait, DVJ represents a non-cyclical task in its use in a controlled laboratory setting. The task would be performed in discrete trials. Measures of variability may be limited during discrete tasks, however, the ability to coordinate and control movement of multiple segments of the lower extremity may reveal differences in the control strategy of these patients.

Mullineaux et al[121], previously assessed joint coupling variability during a task of basketball free throw shooting and found interesting changes at the elbow in order to better position and control motion at the wrist and hand. These findings indicate that the study of joint coupling throughout the extremity may reveal information on the control mechanism during tasks.

Dynamical Systems Theory and Chronic Ankle Instability

The dynamic systems approach to human movement characterizes human movement as a non-linear system changing over time.[39] This theory of human movement assumes two types of behavior; short intervals behaving in deterministic ways and long intervals behaving in complex and chaotic ways. Small changes in initial conditions lead to what may seem to be small changes in short term cyclical behavior but may lead to dramatic changes over longer time scales. Dynamic systems involve the control of state variables such as displacement and velocity or any variable that can result from computation. These variables are subject to physical laws but can be altered based on parameters of control. Parameters include equations of physics, properties of the object (mass, length) and can also be controlled through central nervous system control. The parameters can be altered, changing initial conditions of the system that lead to changes in the state variables. Analysis of state variables allows for the interpretation of parameters. Changes in the initial conditions of the system can be the result of injury or central control. [122] Gait represents a cyclical task that requires control of the complex lower extremity by neuromuscular control. The study of gait, specifically movement variability allows for the assessment of human movement control from a dynamical systems theory perspective.[39]

During gait, the state variables include the position, velocity and forces of the lower extremity. These state variables are subject to mechanical limitations based on the parameters of the organism. State variables are easily assessed during research. The parameters include joint range of motion, neuromuscular capabilities and health of the structures. The physical limitations of the body can alter the influence that the parameters have. These state variables may include the limitations present in those with CAI or result from lateral ankle sprains. Central control is also subject to input from the peripheral input and experience in completing gait. The application of dynamical systems on human movement may better explain the control and coordination of movement as well as the alterations associated with injury. Particularly characteristics of control such as variability and stability of gait may allow for the study of human movement related to injury and external constraints.

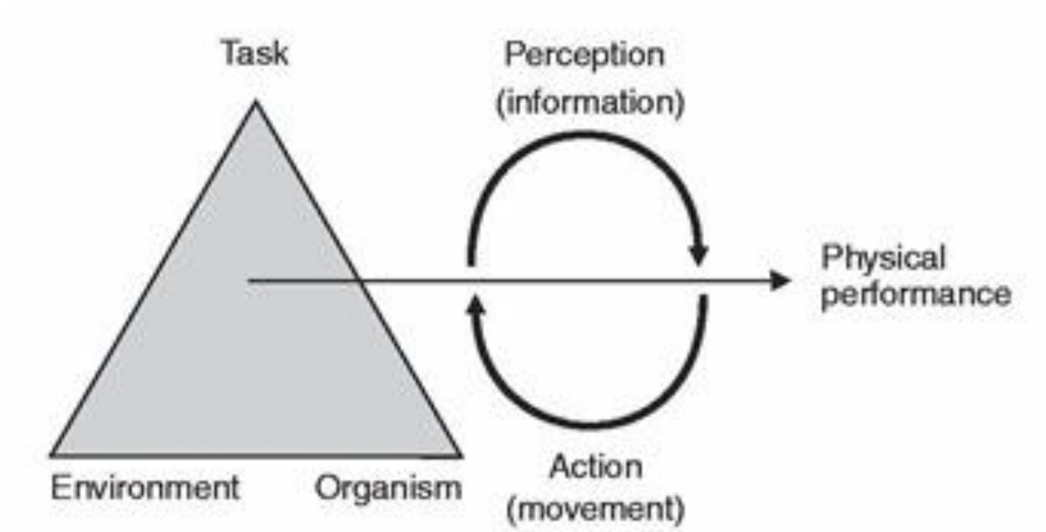

Figure B04: Newell's model of constraints in a dynamical system.

A constraint is a limitation or adaptation to a biological system that alter the ability of that system to find an optimal state of organization.[123] In the example of human gait, efficient and effective gait involve the cyclical control of the extremities and involve the use of numerous muscles in order to move the bones through an almost infinite coordination of movements. The control of these sub-systems (muscular, nervous) represents the parameters and the outcome of this control result in the state variables. The state variables are typically the measures of interest in research; measuring the kinematics or kinetics represent measures of position, velocity and forces within the joints. Constraints represent an alteration in the parameters of the task and can include any change to the individual, the task of gait or the environment that the individual is in. Changes to the conditions such as a loss of sensory information from the ankle ligaments create changes to the initial condition parameters of the system. Task changes such as speed of gait, can also change the systems control of gait. Finally, alterations in the environment such as changes in the surface can constrain the system forcing control adaptations to occur. The study of an organism's state variables as related to an organismic constraint, such as injury, allows researchers to reflect on the control of the parameters of the system.

Chronic ankle instability represents an organismic constraint that alters the initial conditions and changing the parameters of the system. These parameter changes result in alterations to state variables including the kinematics of the lower extremity and kinetics during gait which have been measured in previous research. In the CAI population, changes to sensory function and neuromuscular control represent an organismic constraint which alters the parameters of the system. A change in these parameters may be associated with central alterations in movement coordination and result in mechanical and functional disability.[124] For this reason, the study of CAI and its impact on movement variability may better explain the condition and human movement. Movement variability is a manifestation of central control mechanisms altering the cyclical consistency of joint kinematics and kinetics.[39] The study of movement variability in joint segment motion reflects the changes in the parameters as an attempt to control for alterations in the system.

Joint Coupling

A study by Drewes et al[12] used a continuous relative phase (CRP) method to analyze the joint coupling of the shank and rearfoot during walking and jogging gait. The CRP analysis allows for the measure of movement variability between these two segments as it is related to CAI.[125] Continuous relative phase analysis compares the velocity and position of two segments. In this study, Drewes et al[12] compared tranverse plane motion and velocity of the tibia to frontal plane motion velocity of the rearfoot. These two phase-planes, which take into account position and velocity of the two segments, are then analyzed against each other to determine when the motions of inversion and external rotation were coupled or eversion and internal rotation were coupled. During periods of highly coupled motion during gait, the segments are considered to be in phase and when inversion occurs with internal rotation or eversion with external rotation, the motions are considered to be out of phase.[125] The CAI group was identified to have more rearfoot inversion and shank external rotation during walking and jogging and was found to be more out of phase during terminal swing in both walking and jogging. These findings indicated altered joint coupling coordination compared to healthy patients. The CRP method does have assumptions and limitations that create challenges in interpreting the measure.[126] A big assumption in this method is that the data (segment kinematics) are sinusoidal in nature.[125,126] This may not be true during complex tasks such as gait particular in joint motion of the ankle where motion does not occur in smooth arcs that have equal magnitude of both flexion and extension. When the phase-planes are not sinusoidal, normalization can limit the interpretation of data as well by minimizing the impact that certain motions have on the phase plane of the two segments.[126] Due to these limitations another method of joint coupling analysis may provide a more accurate and more interpretable method.

McKeon et al[48], found changes in the shank-rearfoot joint coupling following balance training in patients with CAI. Following, 4 weeks of progressive balance training patients had a more stable coupling pattern measured by a continuous relative phase technique. No differences were found between pre and post balance training in frontal ankle motion or shank rotation in this study, however, the CRP analysis found lower phase-plane values during gait between time periods.

Vector coding is a vector based analysis technique that compares the direction and magnitude of a motion vector that is generated between two segments over multiple strides.[59] Vector coding compares the position of two segments against each other, generating an angle-angle plot of the kinematics across the gait cycle. The angle-angle plot is generated by plotting kinematics of the distal segment on the y-axis and proximal segment motion on the x-axis. This method has been previously used to compare different lower extremity pathologies.[13,49] The angle-angle plots are then used to compare each percentage of the trial, comparing the direction and magnitude of the vector during this period of the task. The variability of magnitude and direction of the vector over multiple trials reflect the ability of an individual to coordinate the intersegmental motion during the task in the presence of the constraint of CAI. The magnitude of the vector is the length of the vector and reflects the total motion between the segments. Magnitude does not take into account the impact that each segment has on the vector length as task constraints may require one segment to dominate the couple. The direction of the vector has been reported as the value of θ.[13] The θ value represents the ratio of one segments motion compared to the other. A value of 45° represents an equal ratio of motion between the 2 segments. Values greater than 45° indicate greater distal segment motion and values of lower than 45° indicate greater proximal segment motion.

Herb et al[13], used a vector coding technique to compare the transverse plane motion of the shank against the frontal plane motion of the rearfoot during walking and jogging gait. During walking gait, the CAI group had lower variability during mid to late stance phase compared to healthy controls. During this period of gait, the CAI group had lower θ and greater magnitude compared to healthy controls. These findings indicate greater rearfoot motion and greater overall motion during stance phase. During swing phase, no variability differences were found. Magnitude and θ differences were found with the CAI group having lower magnitude and lower θ. During swing, the CAI group continues to have more rearfoot motion but also lower overall motion between the segments. The CAI group was hypothesized to rely more on bony support by limiting the amount of relative rearfoot motion during the stance phase and a more rigid joint coupling coordination resulting in lower variability. During the jogging task, variability and magnitude was not significantly different between groups. Differences in θ were identified during mid-stance and mid-swing phases of gait. During these periods, the CAI group had greater rearfoot motion compared to controls. Greater rearfoot motion may be related to an inability to control the position of the ankle consistently during gait.

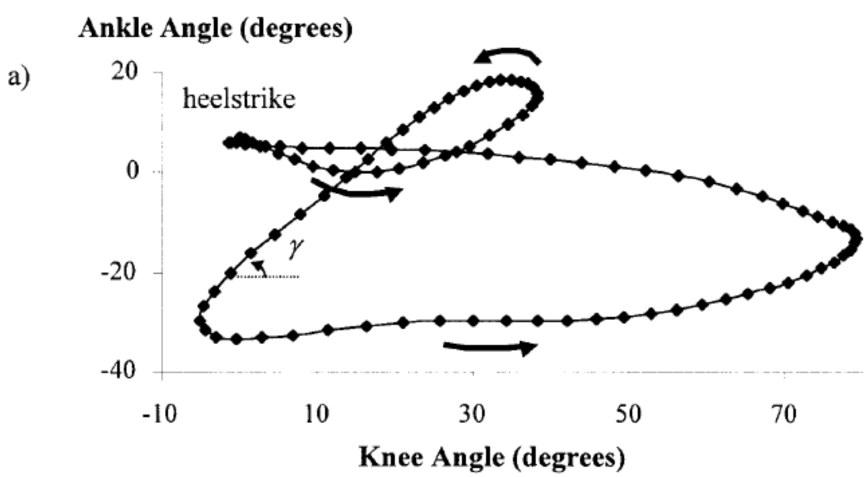

Figure B05: Example of an angle-angle plot allowing for the measure of vector angle and vector magnitude of multiple trials.

The analysis of joint coupling, may present more information on the sensorimotor function and motor control in the CAI population. Changes in shank to rearfoot coupling may also indicate proximal changes above the ankle joint during gait as changes in transverse plane motion of the shank would require neuromuscular control at the knee and potentially the hip. Assessment throughout the lower extremity may provide further information on how this population is coordinating motion. Findings by Herb et al[13] indicate that CAI patients may adapt a more deterministic movement pattern during the stance phase in order to minimize the stress placed on the unstable joint. This may result from alterations in the neuromuscular control, ligamentous stability and sensory function around the joint changing the control parameters of the system and altering the kinematics to protect the joint. Based on these findings, however, the CAI patient may be less adaptable to environmental and task constraints and be at a greater risk for instances of "giving way". Repetitive loading of tissues in the joint may also lead to faster degeneration of the joint and lead to early onset of post-traumatic osteoarthritis. The fact that these findings were during walking also indicate that simple activities of daily living in this population are affected and not only sport function.

Joint coupling assessment also provides multi-planar analysis. The mechanical structure of the ankle joint is truly multiplanar and single plane assessment of the lower extremity may miss subtle differences in lower extremity movement during gait. Beyond the ankle joint, motions of the hip and knee also require complex coordination in multiple planes. Changes at the knee have been identified in the CAI population.[92] Little, however, has been done during walking and jogging gait or jumping trials in assessing the knee and hip biomechanics as it is related to CAI. Future studies of human movement associated with CAI should take into account the multiplanar, multi-segmental alterations that exist in patients with CAI.

Statistical Parametric Mapping

The method of statistical parametric mapping (SPM) may allow for the analysis of multi-segmental, spatiotemporal analysis of lower extremity movement in 3 dimensions.[22] Commonly used in the analysis of brain mapping, SPM uses Random Field Theory (RFT) to make inferences about topological features of statistical processes in continuous functions over time. Random field theory is a field of research in stochastic processes that involves underlying parameters be multidimensional vectors on some manifold and not simple or real integers.[127] Pataky et al[22] stated that SPM is effective in analysis of complex biomechanical systems as they are continuous waveforms that are time dependent. This includes lower extremity kinematics and kinetics during gait. SPM considers the covariance of test statistics, the smoothness and size of waveforms, and random behavior when computing p-values.[22] Comparable to a 2-sample t-test, SPM can compare waveforms of gait data. First, as with a t-test, the means and standard deviations are calculated for the wave forms of interest. The below equation then allows for the generation of test statistic (SPM{t}) across multiple time points of interest (q) such as the 100 points of a time normalized gait cycle between two groups of interest (A,B).

$$SPM\{t\} \equiv \frac{t(q) = \overline{y_B}(q) - \overline{y_A}(q)}{(\sqrt{(\frac{1}{J})}(s_A^2(q) + s_B^2(q))}$$

Based on the selected α level and t distribution the critical t value specific regions of the gait cycle (specific values of q) of difference between the two groups (A,B) can be identified. Unlike, a 2 sample t-test which would reject a null-hypothesis based of the entire waveform crossing the critical t-value, SPM allows for specific regions of the waveform to be analyzed in order to identify time points when the null can be rejected or accepted. SPM employs a RFT correction for the α value based on the size of the waveform and the waveform smoothness.

SPM has many potential advantages in the study of lower extremity biomechanics during gait. Besides the use of a corrected threshold for the α value, it considers the entire waveform across an entire gait cycle. Unlike discrete scalar analysis which often focuses on specific time periods or has a regional focus bias.[22] SPM also allows for multidimensional data sets to be compared. Gait is in its nature a continuous, multidimensional data set that is highly dependent on time. Previous comparison techniques often simplify this data through normalization, binning or comparisons are made that create excessive statistical bias in the comparison. SPM appears to provide an appropriate technique to analyze complex biomechanical systems including, kinematics, kinetics, and ground reaction forces while minimizing statistical bias.

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APPENDIX C

Additional Methods

Figure C01: Godin Leisure-Time Exercise

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. ☐

Figure C02: Identification of Functional Ankle Instability

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

Figure C03: Foot and Ankle Ability Measure- Activities of Daily Living and Sport Subscale

Foot and Ankle Ability Measure (FAAM)

Activities of Daily Living Subscale

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

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

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

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

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

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

__ __ __ . 0 %

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

Foot and Ankle Ability Measure (FAAM)
Sports Subscale

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

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

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

__ __ __ . 0%

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

☐ Normal ☐ Nearly Normal ☐ Abnormal ☐ Severely Abnormal

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

Figure C04: Rehabilitation Sheets

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)	

Functional Exercises

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

Figure C05: SPM Inference Code

```
[Y0,Y1,Y2] = spm1d_util_get_dataset('speed-kinematics-categorical');


%(1) Conduct SPM analysis:

options   = struct('two_tailed',1);
SPM       = spm1d_stats_ttest2(Y1, Y2);
SPMi      = spm1d_inference(SPM, 0.05, options);


%(2) Plot:
close all
%create figure and axes
figure('Position',[100,100,800,350])
ax0 = axes('Position', [0.10,0.15,0.35,0.8]);
ax1 = axes('Position', [0.55,0.15,0.35,0.8]);
%plot mean & SD curves:
axes(ax0)
[hA0,hA1] = spm1d_plot_meanSD(Y1);
hold on
[hB0,hB1] = spm1d_plot_meanSD(Y2);
set(hA0, 'color','k')
set(hB0, 'color','r')
set(hB1, 'facecolor', 'r')
legend([hA0 hB0], 'Normal', 'Fast', 'Location','SouthWest')
xlabel('Time (%)')
ylabel('\Delta \theta   (MF - MT)')
%plot SPM results:
axes(ax1)
spm1d_plot_SPMi(SPMi)
```

```
spm1d_plot_SPMi_label_threshold(SPMi, 50, 3)
text(80, 4.2, sprintf('p = %.03f',SPMi.p))  %p value
xlabel('Time (%)')
ylabel('SPM \{ t \}')
```

Figure C06: Vector Coding Code

```
% function yarray_output=ttb_readin %bigoutput num_strides

clear all
close all

%-----------------------------------------------------------------------

prompt={'Enter data path:','Enter filename for txt file:',...
   'Enter first trial','Enter last trial, or 0 for maximum','Print each graph (Y or N)', 'Enter sf', 'Enter cf'};
title='Data start menu';
lines=1;
def={'C:\Herb_Vector_Coding\vector_coding_m_files','cai_keyfile.txt','1','1','Y','240','6'};
answer=inputdlg(prompt,title,lines,def);

pathname=char(answer{1});
filename=char(answer{2});
starttrial=str2num(char(answer[61]));
endtrial=str2num(char(answer{4}));
eachgraph=char(answer{5});
sf=str2num(char(answer{6}));
cf=str2num(char(answer{7}));

% set data path
scrsz = get(0,'ScreenSize');
data_path=[pathname];
cd(data_path);
% [filename,pathname]=uigetfile(filetype, ['Select ' filetype ' file'],'Location',[0.5*scrsz(3) 0.5*scrsz(4)]);
data_path=[pathname];
cd(data_path);

fileloc=pathname;
keyfile=filename;
%-----------------------------------------------------------------------
% set data path; evaluate; load keyfile
data_path = [fileloc];
```

```
eval(['cd ' data_path]);

% load keyfile, and assign each column to different variables
[filedir subdir2 subdir3 subdir4 subdir5 subdir6 subdir7 subdir8 subjectnum cai speed condition trial suffix extra1 extra2
   =textread(keyfile,'%s %s %s %s %s %s %s %s %s %s %s %s %s %s %s %s %s %d %f %f');
%Make second "s" a "d" if underscore is not used.

% C:\                                                          HS_TTB\   none       none        none    GF

%C:\                                                           Gait_     analysis_  Australia\  002\    00



% control trials to analyze (e.g. trials 1 to 2)
[nr0 nc0]=size(filedir);
if endtrial<1
endtrial=nr0;
end

%------------------------------------------------------------------------
% define variables before loop

fltshankang1 = repmat(NaN,101, endtrial);
fltankleang1 = repmat(NaN,101, endtrial);
% yarray_output=repmat(zeros,endtrial-starttrial+1,14);

% filedir subdir2 subdir3 subdir4 subdir5 subject walking num prepost suffix extra1 extra2 extra3

%------------------------------------------------------------------------
% start loop to load each file in turn. Combine keyfile info to get filenames etc
for p=starttrial:endtrial                                      % end at bottom
   fileloc=char(strcat(filedir(p,:),subdir2(p,:),subdir3(p,:),subdir4(p,:),subdir5(p,:), subdir6(p,:), subdir7(p,:), subdir8(p,:)))
fileloc=strrep(fileloc,'none','');                              %replaces text
fileloc=strrep(fileloc,'_','_');                                %replaces text
vcfile=char(strcat(subjectnum(p,:),cai(p,:),speed(p,:),condition(p,:),trial(p,:),suffix(p,:),extra1(p,:),extra2(p,:)));
vcfile=strrep(vcfile,'none','');                                           %replaces text
vcfile=strrep(vcfile,'_','_')                                              %replaces text
vcfile=strrep(vcfile,'space',' ');                             %replaces text
data_path = [fileloc];
% eval(['cd ' data_path]);
p

% rightleft(p,:), extra4(p,:), rightoff(p,:), leftoff(p,:)));
```

```
vc=dlmread([data_path vcfile]);
% vc=load('C:\Gait_analysis_Australia\037\037 walking 1 pretest.txt');



shank = vc(:,1);
shank = shank*-1;
ankle = vc(:,2);
shankang = shank - mean(shank);
ankleang = ankle - mean(ankle);

n = length( ankle);
dt = 1 / n;
t=( 0: dt : (dt * (n-1)))';

i = 1:n;

if cf>0  %smooth data
   fltshankang=mybutter(2,cf,sf*0.8,'low',shankang,1); %(butterorder,CF,SF,type,data,damped);
    fltankleang=mybutter(2,cf,sf*0.8,'low',ankleang,1); %(butterorder,CF,SF,type,data,damped);
end

% fltshankang(1) = (shankang(99)+shankang(100)+shankang(1)+shankang(2)+shankang(3))/5;
% fltshankang(2) = (shankang(100)+shankang(1)+shankang(2)+shankang(3)+shankang(4))/5;
% fltshankang(100)= (shankang(98)+shankang(99)+shankang(100)+shankang(1)+shankang(2))/5;
% fltshankang(99) = (shankang(97)+shankang(98)+shankang(99)+shankang(100)+shankang(1))/5;
% for i=3:98;
%     fltshankang(i) = (shankang(i-2)+shankang(i-1)+shankang(i)+shankang(i+1)+shankang(i+2))/5;
% end
%
% fltankleang(1) = (ankleang(99)+ankleang(100)+ankleang(1)+ankleang(2)+ankleang(3))/5;
% fltankleang(2) = (ankleang(100)+ankleang(1)+ankleang(2)+ankleang(3)+ankleang(4))/5;
% fltankleang(100)= (ankleang(98)+ankleang(99)+ankleang(100)+ankleang(1)+ankleang(2))/5;
% fltankleang(99) = (ankleang(97)+ankleang(98)+ankleang(99)+ankleang(100)+ankleang(1))/5;
% for i=3:98;
%     fltankleang(i) = (ankleang(i-2)+ankleang(i-1)+ankleang(i)+ankleang(i+1)+ankleang(i+2))/5;
% end

fltshankang1(:,p) = fltshankang;
fltankleang1(:,p) = fltankleang;
% figure
% plot(fltshankang, fltankleang);
```

```
% figure
% plot(fltankleang);
% figure
% plot(fltshankang);
end
% plot(fltshankang1, fltankleang1);
% end
VC1=repmat(NaN,101,endtrial/3)

%VCTO = repmat(NaN,endtrial/3,1);
for jj=1:3:endtrial
% switch char(suffix(jj))
%    case '.txt'
angle1=fltshankang1(:,jj:jj+2);
angle2=fltankleang1(:,jj:jj+2);


%VC_temp=myVC(angle1,angle2,3); % type: 1 VC_tepavac; 2 VC_heider 3 VC_mullineaux
%this replaces m file myVC

% %-----------------------------------------------------------------------
% angle data
Data1=angle1;
Data2=angle2;

% %-----------------------------------------------------------------------
% calculations
[nrrows numtr]=size(Data1);

% %-----------------------------------------------------------------------
% differentiate
% Data1diff=mydifferentiate(1,Data1); %(SF, data); use SF=1
% Data2diff=mydifferentiate(1,Data2); %(SF, data); use SF=1
Data1diff(2:nrrows,:)=Data1(2:nrrows,:)-Data1(1:nrrows-1,:);
Data2diff(2:nrrows,:)=Data2(2:nrrows,:)-Data2(1:nrrows-1,:);
% add first row (POSSIBLY should not do this as not real data, but keeps it same length as raw data)
Data1diff(1,:)=Data1diff(2,:);
Data2diff(1,:)=Data2diff(2,:);

% %-----------------------------------------------------------------------
% using circular statistics calculate 'mean vector angle'
ResultDiff=sqrt(Data1diff.^2+Data2diff.^2);
CosTheta=Data1diff./ResultDiff;
```

```
SinTheta=Data2diff./ResultDiff;
MeanCos=mean(CosTheta,2);
MeanSin=mean(SinTheta,2);
ResultA=sqrt(MeanCos.^2+MeanSin.^2);% use ResultA to calculate VC_heider as below

% %------------------------------------------------------------------------
% normalize vector magnitude to maximum vector magnitude (for each row)
MaxRes=max(ResultDiff,[],2);
MaxRes=repmat(MaxRes,1,numtr);
DiffRatio=ResultDiff./MaxRes; %so max is 1

% %------------------------------------------------------------------------
% calculate variabilty
SDdiff=std(DiffRatio,0,2);
% calculate max SD for normalized data (dependent on odd/even trial numbers)
denom=(0.5*sqrt((numtr+mod(numtr,2))/(numtr+mod(numtr,2)-1)));
% normalize SD to max possible SD
M1=SDdiff/denom;
Mfinal=ones(nrrows,1)-M1; %inverts so range 0 max to 1 no variability

% %------------------------------------------------------------------------
% FINAL VC values
% switch type
%    case 1
% % calculate Tepavac and Field-Fote VC (range 0 max to 1 no variability)
% VC_tepavac=(ResultA.*Mfinal);
% VC=[VC_tepavac, 1-ResultA, 1-Mfinal];
%    case 2
% % calculate Heiderscheit VC (range 0 none to infinity variability)
%VC_heider=(sqrt(2*(1-(1*ResultA))))*(180/pi);
% VC=VC_heider;
%    case 3
% calculate Mullineaux VC (range 1 max to 0 no variability)
VC_mullineaux=1-(ResultA.*Mfinal); % same as 1-VC_tepavac;
VC=VC_mullineaux;
end

%------------------------------------------------------------------------
% consider smoothing VC in main m file (not here)
VC1(:,(jj+2)/3)=VC(:,1);
% end
%vc value at toe off
% switch char(rightleft(jj))
```

```
%     case 'R'
%         VCTO((jj+2)/3) = VC1(round(rightoff(jj)),(jj+2)/3);
%     otherwise
%         VCTO((jj+2)/3) = VC1(round(leftoff(jj)),(jj+2)/3);
% end

plot(VC1);
VC1ind = VC1(1,:)';
VC1up = VC1';
meanVC = mean(VC1)';
meanHSinterval5 = mean(VC1(1:5,:))';
meanHSinterval95 = mean(VC1(97:101,:))';
meanHSinterval = (meanHSinterval5 + meanHSinterval95)/2;
% final_output = [VCTO, meanVC, VC1ind, meanHSinterval];
```

Figure C07: Customized shoes and marker set up for manuscripts 2 and 3 data collection.

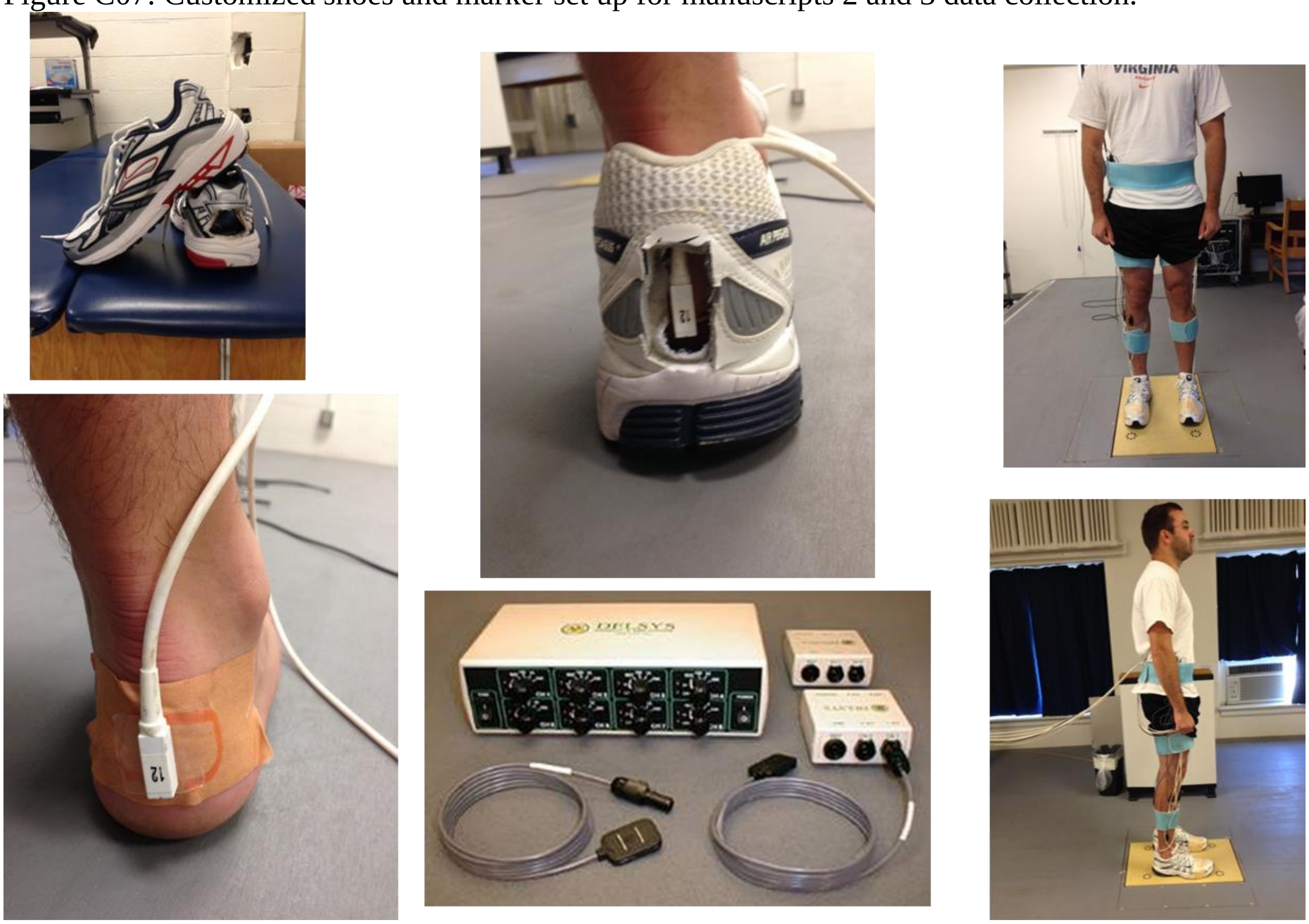
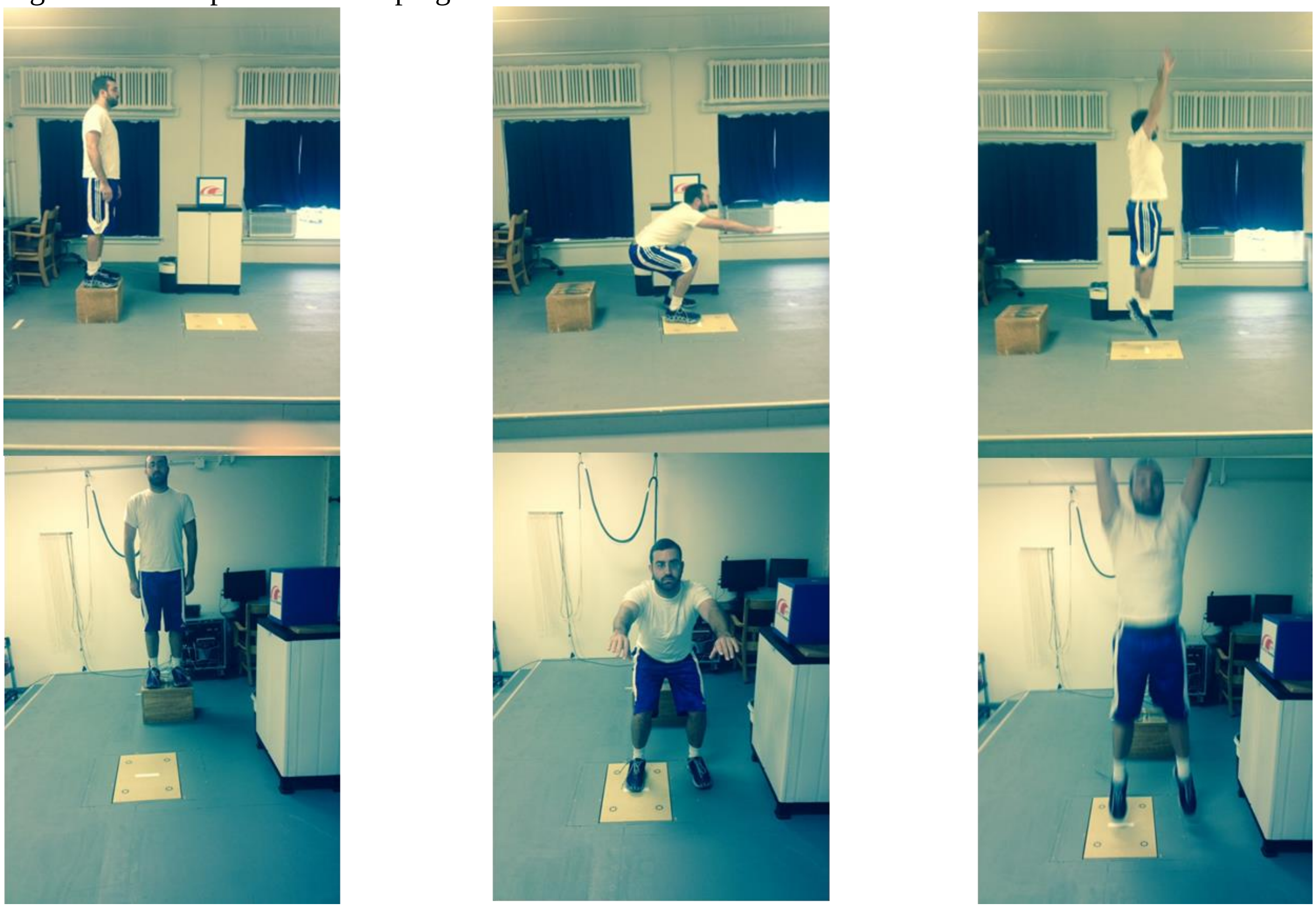


Figure C08: Drop Vertical Jumping Task



APPENDIX D

Additional Results

Figure D01: Hip frontal-ankle frontal angle-angle plots for Manuscript 2. Pre versus post rehabilitation in device and no device groups.

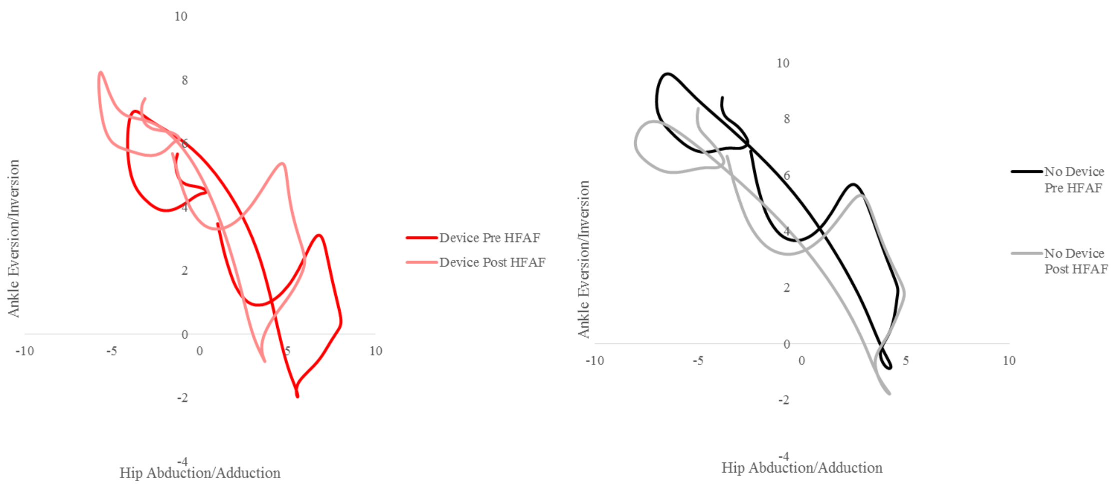


Figure D02: Hip frontal-ankle sagittal angle-angle plots for Manuscript 2. Pre versus post rehabilitation in device and no device groups. Regions of significance are highlighted with blue circles.

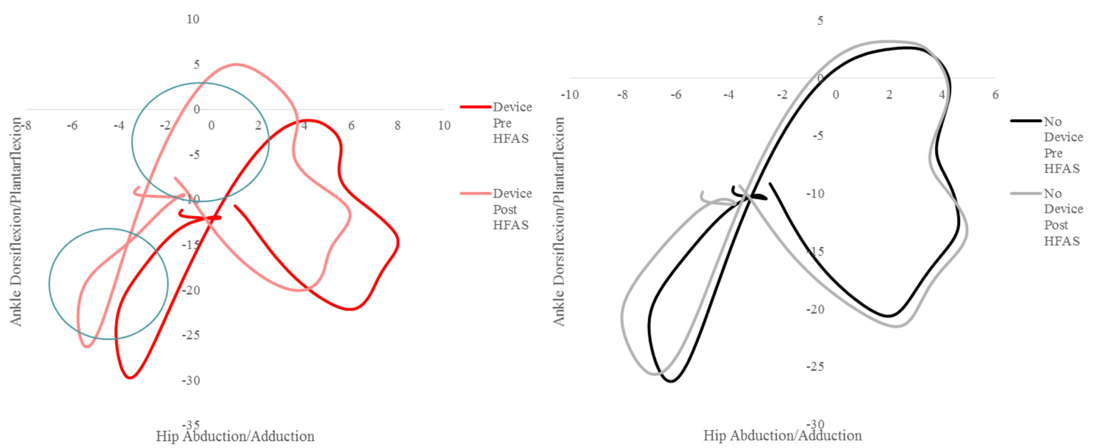


Figure D03: Knee sagittal-ankle frontal angle-angle plots for Manuscript 2. Pre versus post rehabilitation in device and no device groups.

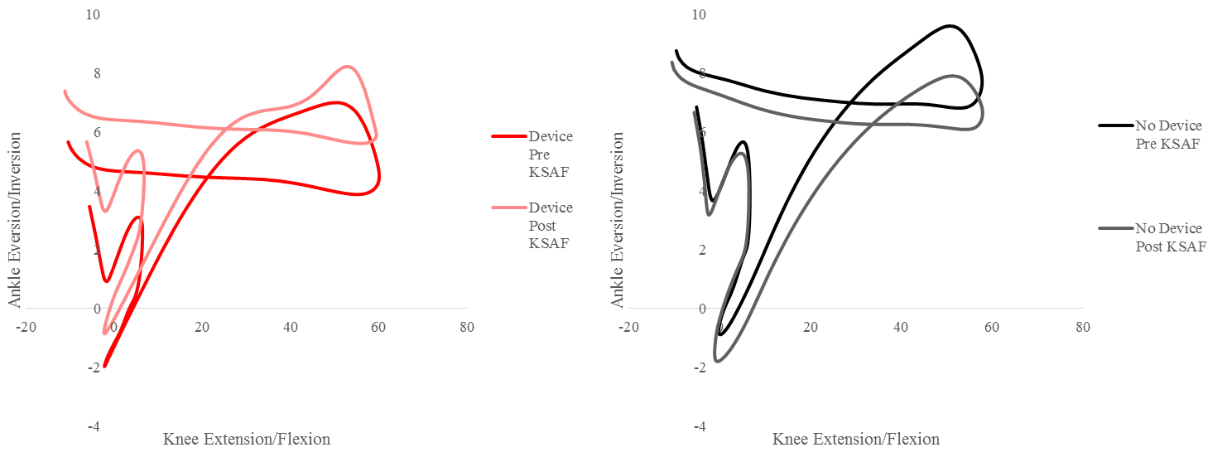


Figure D04: Knee sagittal-ankle sagittal angle-angle plots for Manuscript 2. Pre versus post rehabilitation in device and no device groups. Regions of significance are highlighted with blue circles.

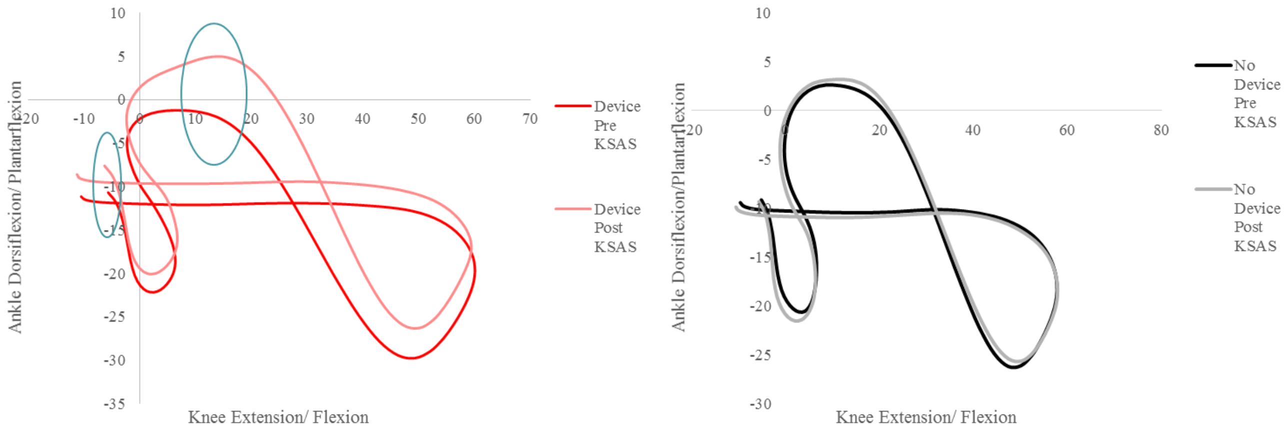
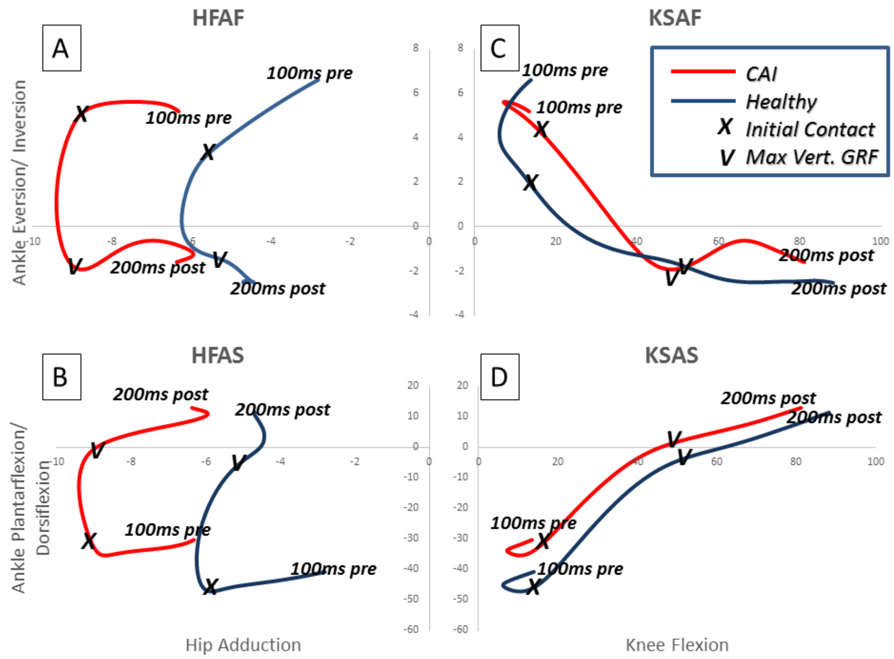


Figure D05: Angle-angle plots for Manuscript 3. A) Hip frontal-ankle frontal B) Hip frontal-ankle sagittal C) Knee sagittal-ankle frontal D) Knee sagittal-ankle sagittal. Group mean kinematics with ankle segment on the Y axis and knee or hip segment on the x axis. X indicates initial contact and V indicates the maximum vertical GRF point.



APPENDIX E

Back Matter

Recommendations for Future Research

1. Do patients with chronic ankle instability exhibit differences in biomechanics during drop vertical jump when assessed using statistical parametric mapping?

2. Can ankle kinematics be altered through progressive gait training and comprehensive rehabilitation?

3. Is joint coupling variability a predictor of joint injury?

4. Is joint coupling variability altered following a first time lateral ankle sprain?

5. Can joint coupling variability predict the development of CAI in patients that suffer a first time lateral ankle sprain?

6. Can joint coupling variability be predictive of subjective function in CAI patients?

7. Is there a relationship between joint coupling variability of the hip, knee and ankle and is the relationship associated with history of injury?